Final Report

MECHANICS OF GECKO-INSPIRED DRY ADHESIVES

Principal investigator: **Dr. Attila KOSSA**
Project Identifier: **FK 128662**

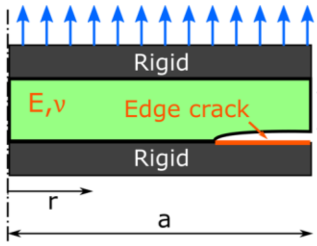
1 Introduction

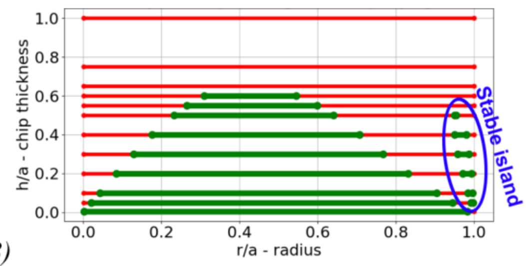
The project focused on the mechanical characterization of dry adhesives, which are usually fibrillar structures. In order to understand the underlying phenomena during the attachment and detachment of fibrillar structures, we needed to perform experimental tests, analytical calculations, and numerical simulations. Since the fibrillar structures are made of polymer materials we had to pay particular attention to the accurate constitutive modeling of the material behavior. A large number of finite element simulations had to be performed with self-developed automated Python scripts. The new scientific results were published in 11 papers (6 among them have IF) and were presented in 8 conference talks. We consider the research to be successful. Our new results can be directly applied in other projects. It is important to note that one of the researchers involved in the project, finished his PhD studies and received the PhD degree during the research years. The support of the current project helped him significantly. The main results are described in the following section.

2 Energy release rate calculation

An accurate description of the stress distributions along the interface of adhesive structures is required for the proper understanding of the attachment. However, stress is not the only crucial quantity when we analyze the performance of an adhesive structure. For application purposes, we need to understand the behavior of the detachment behavior. There are problems where unstable detachment is required, but the stable detachment mechanism can also be desired in other cases. The detachment mechanism can be analyzed with the help of the energy release rate. Calculating the strain energy release rate can be performed using the J-integral, but the variation of the stored strain energy can also be used to determine its value by performing numerical differentiation.

We proposed an elementary approach for calculating the strain energy release rate. Python scripts were created to build the particular FE models with different initial crack lengths. Another Python script was used to extract the strain energy values from the database file and to perform the numerical differentiation. The results were compared with the J-integral calculation and we concluded that our method gives the same accuracy. It is important to emphasize that our method can be more easily implemented for a parameter-sweeping calculation. More than 100 000 FE calculations were performed! The energy release rate calculations were completed for the poker-chip problem, composite fibrils, and mushroom fibrils. Our results revealed stable domains, which have not been identified and published before. The new stable domains might be used to explain the transition between finger crack and edge crack. Our approach can be generalized to arbitrary geometries and can be used in designing new fibrillar structures.



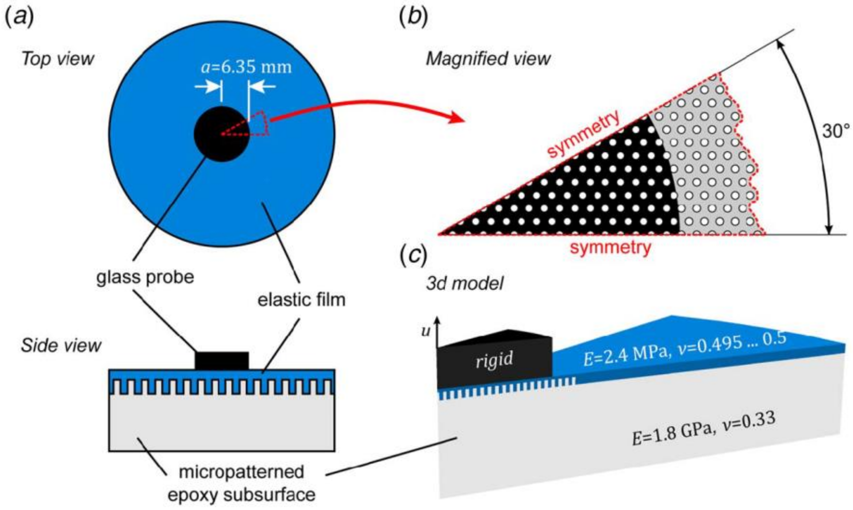


1. Figure: Schematics of the axisymmetric problem (A); Stability map for edge crack (B)

3 Subsurface microstructure

It is a common strategy to use adhesive layers in applications. These adhesive layers are confined materials, where the overall adhesive behavior depends mainly on the layer thickness, the Young modulus, and the Poisson's ratio. Using various subsurfaces beneath the adhesive layer might improve the adhesive properties.

A special micropatterned subsurface embedded into an adhesive layer was designed and the performance of the new structure was investigated by experiments and numerical simulations. Three-dimensional finite element models were created with various number of underlying fibrils. An extensive number of 3D FE calculations were performed and the normal stress distributions were obtained along the interfaces.

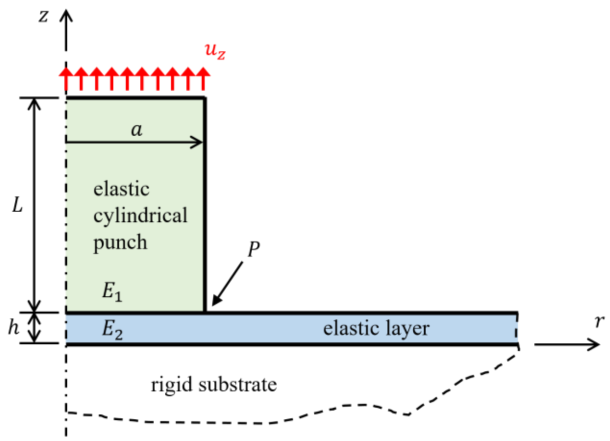


2. Figure: Illustration of the problem and three-dimensional model for numerical simulations

4 Adhesion of elastic punch

In most cases in modeling, we consider one of the connected bodies to be rigid. This approximation is used because the elastic modulus of one body is usually significantly larger than that of the other material. However, this approximation can cause errors that can lead to misinterpretation of the actual mechanical phenomenon.

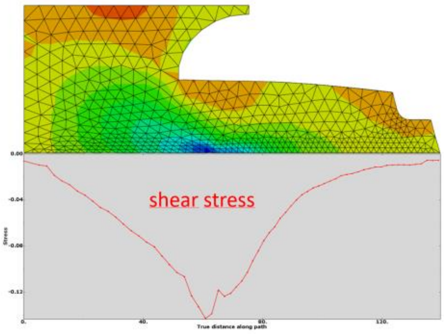
In this research, we investigated how the stress distributions change when elastic deformation is allowed for both contacting bodies. The new results are an extension of one of our previous papers. Our calculations revealed the effect of the ratio of the Young's moduli and the ratio of the Poisson's ratios. The numerical results can be used to optimize the material parameters for a particular geometry.



3. Figure: Geometry of the investigated axisymmetric problem

5 Funnel shaped fibrils

Adhesion in underwater environments can be significantly improved by using funnel-shaped geometries. In this case, the deformation of the structure is large, which is modelled using hyperelastic material models. Several finite models have been developed, taking into account geometric nonlinearities in order to accurately determine the stress distributions along the interface to optimize the geometry. The new scientific results have not yet been published in a scientific paper but were presented in a workshop. We paid particular attention to the shear stress distribution, because according to our hypothesis, the shear stress also plays an important role in addition to the normal stress distribution.

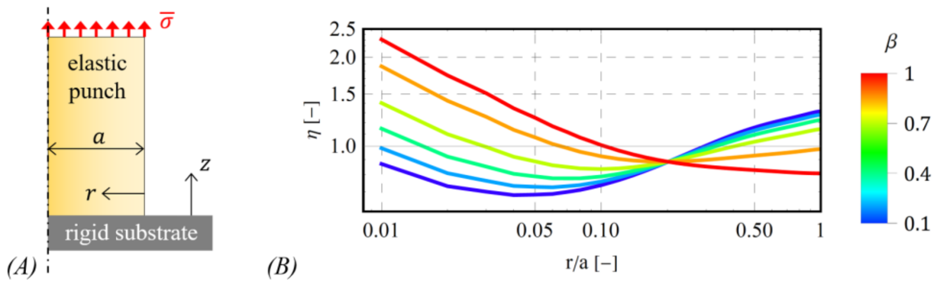


4. Figure: Shear stress distribution along the interface of an attached funnel-shaped fibril. Axisymmetric view.

6 Cylindrical punch with varying elastic modulus

One of the goals in designing fibrillar adhesive structures is to reduce the stress values around the perimeter of an individual stalk. This can lead to better adhesion. Using mushroom-shaped punches, we can significantly lower the stress values in the so-called singularity zone. Another strategy is the application of a soft tip at the end of the fibril. These approaches were already published in the literature.

We proposed a new concept to reduce the stress in the critical stress-singularity zone. We analyzed the stress distributions along the interface of a cylindrical punch with elastic properties that vary spatially in a gradual manner. The new results revealed that the varying elastic modulus could also be used to reduce the stress in the singularity domain significantly. The new observation can be used in the design and fabrication of new types of fibrillar structures. In addition, we also carried out a detailed analysis of the mushroom fibrils with varying elastic modulus.

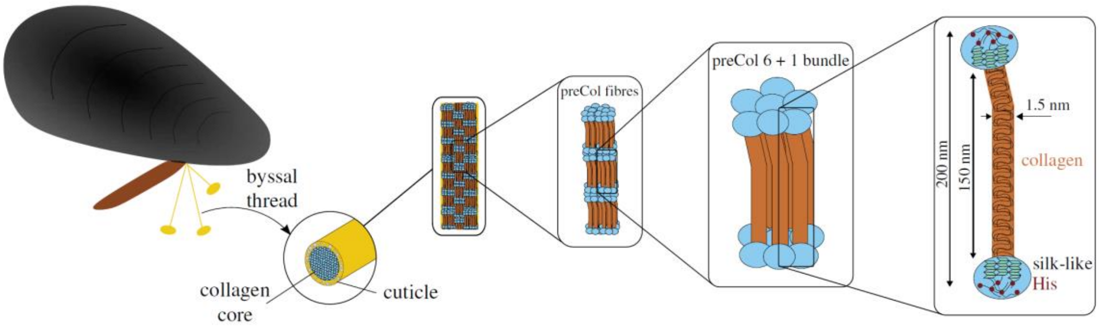


5. Figure: Schematics of the problem (A); Normalized normal stress distributions along the interface for different values of parameter β (B).

7 Attachment of mussel threads

Mussels use byssal threads to secure themselves to rocks and as shock absorbers during cyclic loading from wave motion. They have very strong attachments to objects in the underwater environment. This extraordinary skill would be beneficial for industrial applications.

To properly understand the mechanism behind the strong adhesion of mussels' byssal threads we carried out a detailed analysis of the viscoelastic properties of the byssal threads. We fitted viscoelastic models to the experimental data obtained in different environments. The parameters of the generalized Maxwell model were used to predict the damping characteristic of the material. The new results provide insight into the mechanics of the adhesion of mussels' byssal threads. This information can be directly used in the design of artificial structures.

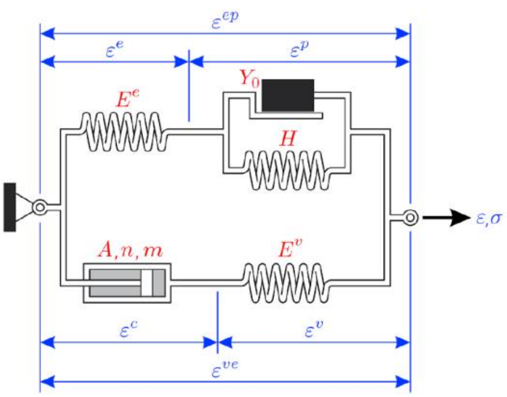


6. Figure: The hierarchical assembly of mussel byssal threads spans multiple length scales.

8 Advanced viscoelastic/viscoplastic material model

In most cases, the structures used for adhesion are made from a polymeric material. Consequently, the time and temperature dependence of the material can be significant. If the deformation is large, these effects are more dominant and the classical Hooke's law cannot be used to calculate the stresses accurately. In this research, we needed a complex material model that could describe the nonlinear viscoelastic and viscoplastic properties accurately, even at elevated temperatures. Such a universal material model does not exist.

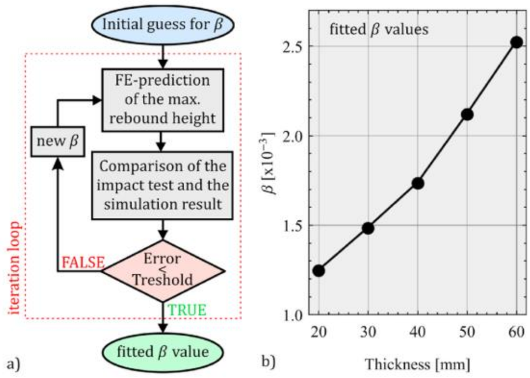
We have chosen the two-layer viscoplastic material model family available in the Abaqus finite element software. The plastic material behavior was modeled using the Mises yield criterion and isotropic linear hardening rule. The nonlinear viscoelastic property was described using strain-hardening and time-hardening nonlinear dashpots in the viscoelastic branch. Several experiments were performed on polymeric materials at different temperatures, and the parameters of our material model were determined via parameter-fitting procedures. The accuracy and performance of the model were verified by a detailed analysis. The resulting constitutive equation has no closed-form stress solution. To overcome this difficulty, we proposed and published our numerical integration scheme. In addition, we have created a self-developed calibration software with a graphical user interface in a Python environment. This software is freely available to researchers and can be downloaded by anyone from our website. The experimental, theoretical, and numerical results obtained from the material model development have been published in two distinct papers in the D1-ranked journal "Polymer Testing".



7. Figure: One-dimensional idealization of the TLVP model.

9 Material damping

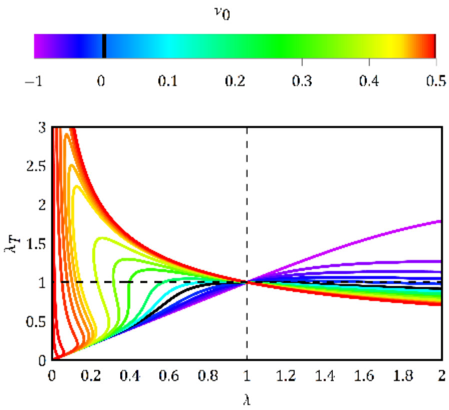
The polymer materials used for adhesive structures show viscoelastic behavior. The viscoelastic nature of the material generates internal damping in dynamical loadings. The material modeling of the internal damping is very challenging as the damping characteristics are usually frequency-dependent. However, the numerical simulations require a reliable damping modeling strategy with a limited number of additional material parameters to investigate different phenomena quickly. The materials we were interested in can exhibit large (finite) deformations, where the elastic behavior is modeled using hyperelastic material models. We combined the “classical” Rayleigh-damping method with hyperelasticity to model the internal damping of the material. We wanted to analyze the accuracy and performance of this strategy in applications where low and very high strain-rates are also present. For this reason, we investigated the impact of hollow rubber balls and a static steel wall. We captured an extensive number of high-speed camera recordings and analyzed the motion with self-developed motion-tracking codes. Dynamic explicit finite element models were created to simulate the impact phenomena. The inbound and outbound velocities were used to determine the parameters of the damping model using constrained minimization. The resulting hybrid material model (hyperelasticity + Rayleigh damping) showed satisfactory accuracy to our expectations. In addition, we combined the damping modeling strategy with the hyperfoam hyperelastic model to simulate the damping behavior of closed-cell polymeric foams in falling weight impact tests. Our conclusion is that the proposed strategy provides results with reasonable accuracy. Consequently, we can use this approach to analyze adhesive structures under dynamical loadings.



8. Figure: a) Flowchart for the fitting strategy b) Fitted stiffness proportional damping ratio.

10 Compressible neo-Hookean model

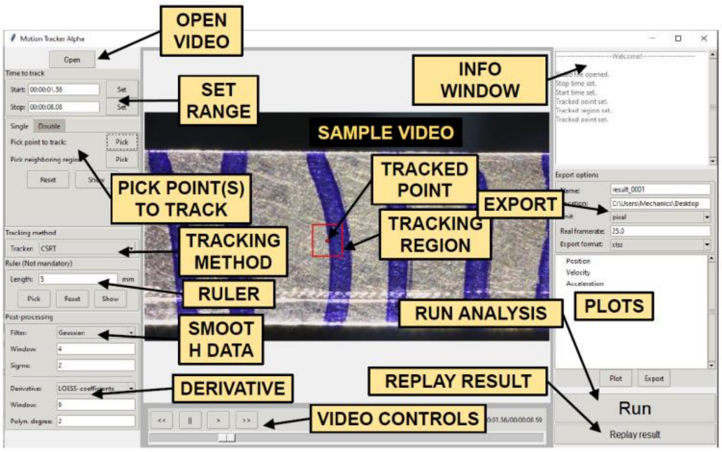
The generalization of the numerical models proposed for “small-strain” problems to “finite-strain” problems requires the replacement of the Hooke’s law with a hyperelastic model. Among many available hyperelastic models, the neo-Hookean model is a standard and preferable thanks to its simple structure. It contains only two material parameters similar to the Hooke’s law. Although the closed-form stress solutions in homogeneous loading modes are known for the incompressible case, the stress solutions for the compressible version cannot be obtained analytically. In our analysis of adhesive structures, the ground-state Poisson’s ratio plays an important role. In finite strain problems, the current/apparent Poisson’s ratio is dependent on the magnitude of the deformation. We extended the calculations to the finite strain regime, and this approach required the proper calculation of the current/apparent Poisson’s ratio. Our literature survey revealed that even though the neo-Hookean model is the simplest hyperelastic model, a detailed analysis of its compressible version is still missing in the literature. We obtained the stress solutions for the compressible neo-Hookean model in uniaxial loading, equibiaxial loading, and uniaxial loading in plane strain. These are the standard loading modes we use for experiments to determine the material parameters. Our numerical analysis revealed the domains in the parameter space, where the model response is stable. For the finite element simulations, it is required to use material parameters, which result in stable material behavior. The new results form a basis for the analysis of other compressible hyperelastic models.



9. Figure: Transverse stretch as a function of longitudinal stretch in uniaxial stress.

11 Motion tracking software

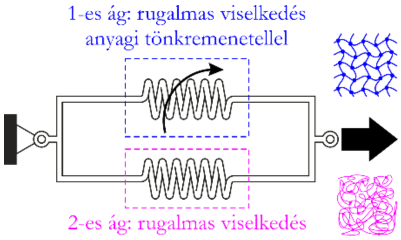
In material testing, the displacements can be measured with designated equipment (such as an extensometer). Yet, video analysis has become very popular in the past years thanks to the high-resolution videos we can capture even with standard DSLR cameras. During our experiments, we sometimes needed to measure the displacement and therefore strains using video recordings. Measuring the displacement needs a motion-tracking procedure, where the spatial position of a selected object is tracked during the event. There exist dedicated (commercial; not free) motion tracking software, which can be used for this purpose, but our analysis needed to control some parameters during the motion tracking. We decided to develop a new open-source motion tracking software in Python with a graphical user interface. Finally, we developed a stand-alone motion-tracking software, which is free to download for researchers. We used this software for some of our experiments.



10. Figure: GUI of the software.

12 Hydrogel structures

The researchers also plan to use artificial adhesion structures in tissue engineering. Due to the interaction with biological tissues, the adhesion material cannot be arbitrary. Recently, various hydrogels have been proposed due to their biocompatible properties. Double-network hydrogels are proving to be particularly promising as they are tough materials compared to ordinary hydrogels. When describing the mechanical behavior of these materials, material degradation, known in the literature as the Mullins phenomenon, cannot be neglected. The research has also addressed the question of how to accurately describe the Mullins phenomenon for double-network hydrogels using constitutive models. Using measurement data available in the literature, hyperelastic material models were fitted to model the Mullins phenomenon. The resulting mechanical model proved to be promising.



11. Figure: Proposed model.

13 Modeling material ageing

Polymer structures that provide adhesion are subject to ageing over time, which can alter their mechanical properties. This also has a direct impact on adhesion properties, as altered elasticity can cause a different type of stress distribution. Understanding the phenomenon of ageing is particularly important at higher operating temperatures. Ageing can also be caused by mechanical or chemical effects. In collaboration with Czech researchers, a model for mechanical modeling of the ageing process has been developed and published.

14 Publications

This section lists only the publications, where the NKFIH support is mentioned in the corresponding Acknowledgements. **11 scientific papers** were published. 8 papers are listed in the WOS system and 6 papers have IF (sum of impact factors is 26.1). We must emphasize that we published **<u>2 D1 papers</u>** during the project. Furthermore, we published 2 Hungarian papers too. **8 scientific conference talks** were held even though the COVID situation made it complicated to visit international conferences. 6 of the talks were presented at international conferences. In addition, the principal investigator held **10 seminar talks** corresponding to the project.

Journal Papers:

1. Berezvai, Sz., Kossa, A., 2020. *Performance of a parallel viscoelastic-viscoplastic model for a microcellular thermoplastic foam on wide temperature range*. Polymer Testing 84, April 2020, 106395. DOI: 10.1016/j.polymertesting.2020.106395, IF=4.282.
2. Samri, M., Kossa, A., Hensel, R., 2021. *Effect of subsurface microstructures on adhesion of highly confined elastic films*. Journal of Applied Mechanics, Mar 2021, 88(3): 031009. DOI: 10.1115/1.4049182, IF=2.794.
3. Kossa, A., Horváth, A. L., 2021. *Powerful calibration strategy for the two-layer viscoplastic model*. Polymer Testing 99, July 2021, 107206, 1-13. DOI: 10.1016/j.polymertesting.2021.107206, IF=4.931.
4. Heczko, J., Kottner, R., Kossa, A., 2021. *Rubber ageing at elevated temperature – model calibration*. European Journal of Mechanics / A Solids 89, August–October 2021, 104320. DOI: 10.1016/j.euromechsol.2021.104320, IF=4.873.
5. Areyano, M., Valois, E., Sanchez, I.C., Rajkovic, I., Wonderly, W.R., Kossa, A., McMeeking, R.M., Waite, H., 2022. *Viscoelastic analysis of mussel threads reveals energy dissipative mechanisms*. Journal of the Royal Society Interface 19: 20210828, 1-10.DOI: 10.1098/rsif.2021.0828, IF=4.293.
6. Tomin, M., Kossa, A., Berezvai, Sz., Kmetty, Á., 2022. *Investigating the impact behavior of wrestling mats via finite element simulation and falling weight impact tests*. Polymer Testing Volume 108, April 2022, 107521, 1-10. DOI: 10.1016/j.polymertesting.2022.107521, IF=4.931.
7. Szabo, B., Kossa, A., 2020. *Characterization of impacts of elastic-plastic spheres*. Periodica Polytechnica Mechanical Engineering, 64(2), 165–171. DOI: 10.3311/PPme.15559.
8. Berencsi, B.F., Kossa, A., 2021. *Analyzing the effect of temperature on squash ball impacts using high-speed camera recordings*. Periodica Polytechnica Mechanical Engineering 65(4), pp. 354–362, 2021. DOI: 10.3311/PPme.18381.
9. Kossa, A., 2021. *“Double-Network” hidrogélek mechanikai anyagmodellezése*. Biomechanica Hungarica. XIV. évfolyam, 2. szám, 42-52.

10. Kossa, A., 2020. *Gekkók tapadásának titkáról röviden*. Élet és Tudomány LXXV. évfolyam, 45. szám, 2020.11.06.
11. Kossa, A., Valentine, M.T., McMeeking, R.M., 2022. *Analysis of the compressible, isotropic, neo-Hookean hyperelastic model*. Submitted to a WOS journal. Under Review.

Conferences talks:

12. Horváth, A. L., Kossa, A., 2021. *Efficient parameter fitting of the two-layer viscoplastic constitutive model*. XXVII Conference on Computer Methods in Materials Technology (KomPlasTech), Online Event, Kraków, Poland, March 8-9, 2021.
13. Toth, G., Kossa, A., 2021. *Open-source ready-to-use software for high accuracy motion and deformation tracking*. 37th International Danubia-Adria Symposium on Advances in Experimental Mechanics (DAS), Linz, Austria, September 21-24, 2021.
14. Kossa, A., 2021. *Analysis of the compressible Neo-Hookean isotropic hyperelastic material model*. 33rd Nordic Seminar on Computational Mechanics (NSCM-33), Online Seminar, Jönköping, Sweden, 25-26 November, 2021.
15. Horváth, A. L., Kossa, A., 2021. *Automated stress singularity calculations with Python scripts in Abaqus*. 33rd Nordic Seminar on Computational Mechanics (NSCM-33), Online Seminar, Jönköping, Sweden, 25-26 November, 2021.
16. Berezvai, Sz., Kossa, A., 2021. *Numerical analysis of detachment stability in soft-tip composite fibrils*. 33rd Nordic Seminar on Computational Mechanics (NSCM-33), Online Seminar, Jönköping, Sweden, 25-26 November, 2021.
17. Kossa, A., Hensel, R., McMeeking, R.M., 2022. *Adhesion of a cylindrical punch with elastic properties that vary spatially in a gradual manner*. 11th European Solid Mechanics Conference (ESMC2022), Galway, Ireland, 4-8 July, 2022.
18. Horváth, A. L., Kossa, A., 2022. *Determination of stable center, edge, and ring detachment sizes in the poker chip problem*. 11th European Solid Mechanics Conference (ESMC2022), Galway, Ireland, 4-8 July, 2022.
19. Kossa, A., 2019. *Gekkók tapadását utánzó struktúrák tervezése végeselemes szimulációk segítségével*. XIII. Magyar Mechanikai Konferencia (MAMEK), Miskolc, Hungary, August 27-29, 2019.
20. Horváth A. L., Kossa A., 2020. *Paraméterillesztő szoftver a „Two-Layer Viscoplastic" anyagmodellhez*. XXVIII. Nemzetközi Gépészeti Konferencia (OGÉT), Székelyudvarhely, Románia, April 23-26, 2020

Seminar talks:

21. Kossa, A., 2018. *Mechanics of Gecko-Inspired Dry Adhesives*. University of West Bohemia, Faculty of Applied Sciences, Czech Republic. April 11, 2018.
22. Kossa, A., 2018. *Numerical simulation of adhesion and detachment of composite and funnel shaped fibrils*. Workshop on Modeling Adhesion, Grip and Related Topics, University of California, Santa Barbara, CA, USA, October 30, 2018.
23. Kossa, A., 2021. *Selected topics in computational solid mechanics*. IRG3 Seminar Talk, Materials Research Laboratory, University of California, Santa Barbara, CA, USA, January 12, 2021.
24. Kossa, A., 2022. *Analysis of the compressible, isotropic, neo-Hookean hyperelastic model*. University of West Bohemia, Faculty of Applied Sciences, Czech Republic. April 28, 2022.
25. Kossa, A., 2022. *Analysis of the compressible, isotropic,neo-Hookean hyperelastic model*. BME-KIT seminar talk. Online Talk. May 12, 2022.
26. Kossa, A., 2018. *Gekkók tapadásának mechanikai modellezése és megvalósítása mérnöki alkalmazásokban*. Mechanika Szeminárium, Budapest University of Technology and Economics, Department of Applied Mechanics, Budapest, Hungary, Dec 14, 2018.
27. Kossa, A., 2018. *Gekkók által ihletett száraz ragasztók mechanikája*. Szemináriumi Előadás. Pécsi Tudományegyetem Műszaki és Informatikai Kar, April 27, 2018.

28. Kossa, A., 2018. *Gekkók tapadását utánzó struktúrák tervezése Abaqus szimulációk segítségével*. CAD-Terv Szakmai Konferencia 4.0, Budapest, Hungary, October 10, 2018.
29. Kossa, A., 2021. *Összenyomható anyagokra felírt Neo-Hooke-féle hiperelasztikus konstitutív modell stabilitási kérdései*. Workshop Dr. Béda Gyula professzor 90. születésnapja alkalmából. BME Műszaki Mechanikai Tanszék könyvtára. 2021. november 12.
30. Kossa, A., 2022. *Összenyomható anyagokra felírt neo-Hooke-féle hiperelasztikus konstitutív modell alkalmazásának határai*. MTA Szilárd Testek Mechanikája Bizottság. Online előadás. 2022. február 17.

Budapest, September 30, 2022.

Dr. Attila KOSSA

principal investigator