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Abstracts of PhD theses

Defences - 1 September 2023 to 31 July 2024

PRODEM - Doctoral Program in Mechanical Engineering

DEMec - Department of Mechanical Engineering

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Preface

This booklet contains extended abstracts of PhD theses of the Doctoral Program in Mechanical Engineering (PRODEM), DEMec, Faculty of Engineering, University of Porto, Portugal. These theses were defended between 1 September 2023 and 31 July 2024, corresponding approximately to the academic year 2023–2024.

The booklet contains nineteen extended abstracts covering diverse topics within the broad field of Mechanical Engineering. These include, but are not limited to, innovative methodologies in gear design, varied aspects of composite materials and their applications, simulation-driven product analysis and development, additive and other manufacturing techniques, studies of adhesive joints, fatigue and structural health monitoring, passive vibration control, application of solar energy, and the analysis of viscoelastic fluid flows. The abstracts are organised by the defence date and, when more than one defence occurred on the same day, by the name of the student.

PRODEM is very grateful to the former students for preparing these abstracts and extends its acknowledgment to both the students and their supervisors for the development of the corresponding PhD theses. The abstracts, and the sample publications mentioned in a few of them, illustrate the vibrant intervention of PRODEM students and their supervisors in the scientific community.

The success of PRODEM is built upon an active research environment, the knowledge and conditions accumulated by the host and collaborating institutions, and the dedication and expertise of students, lecturers and supervisors. Various funding sources, alongside FEUP's contribution as host institution, supported the PhD theses. Most extended abstracts include acknowledgments to the respective funding sources, to which PRODEM also expresses its gratitude.

Contents

[1] Original title in Portuguese: “Fiabilidade e manutenção de sistemas de armas”

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Low Computational Cost Gear Mesh Stiffness Modeling: Application to gear dynamics and design optimization

João Duarte Marques Marafona

Supervisors
Supervisor: Pedro M.T. Marques, INEGI
Co-supervisor: Ramiro C. Martins, ISEP

Thesis defence date: 16 October 2023

Abstract

Evolution is inevitable and part of it is overcoming problems by looking at them as opportunities for innovation. This is an era of sustainability where the application of different sources of energy is in development and there are significant energy concerns causing drastic changes in drive technology. Gears, as the main tribological element used to transmit motion and power, will play a prominent role in energy generation and mobility trends. It is up for gear engineers to step up and turn into value all their knowledge in order to find the necessary gear designs. The purpose of this work is to develop a gear mesh stiffness model capable of keeping up with current and forthcoming needs so a low computational cost approach is taken as it allows to easily explore different gear design solutions.

A study on the different types of gear mesh stiffness models in the literature is performed, establishing four types of models: analytical, finite element, hybrid and approximate. Their implementation procedures as well as positive and negative features are analyzed, showing that approximate gear mesh stiffness models have the lowest computational cost. The developed gear mesh stiffness model, which is of the approximate type, comprises two instances, the definition of the single tooth pair slice mesh stiffness and the gear mesh stiffness modeling algorithm for both spur and helical gears. The gear modeling also includes the implementation of a gear-shaft-bearing dynamic model. This results in a set of tools for gear quasi-static and dynamic evaluation that is applied for a parametric study of a modeling stiffness variable, which is mostly neglected in the literature; an analysis of the overlap ratio influence on gear behavior as a preliminary approach to experimental testing on the concept of integer overlap ratio gear design and a research on gear design optimization aiming at improved dynamic behavior without computing the dynamic response.

The developed work gives an approximate definition of the single tooth pair slice mesh stiffness which when applied to approximate analytical models improves the accuracy of their mesh stiffness estimations due to the asymmetrical shape considered and the removal of free/user-defined parameters. The developed approximate gear mesh stiffness model is simple to implement and gives fast mesh stiffness estimations that can consider extension of contact, profile modifications, border weakening effect and any type of manufacturing/assembly error that can be modeled as a change in the separation distance - it is sound and flexible as it can attend current needs and be adapted for future investigations.

Funding
National funds though Fundação para a Ciência e a Tecnologia (FCT) under the PhD grant SFRH/BD/147889/2019.

Sample publications

Marafona, J.D.M., Carneiro, G.N., Marques, P.M.T., Martins, R.C., António, C.C., and Seabra, J.H.O. (2024) 'Gear design optimization: Stiffness versus dynamics', Mechanism and Machine Theory, 191, p. 105503. doi:10.1016/j.mechmachtheory.2023.105503.

Marafona, J.D.M., Marques, P.M.T., Martins, R.C., and Seabra, J.H.O. (2023) 'Effect of overlap ratio on gear dynamic behavior and noise level', in VDI Wissensforum GmbH (ed.) *International Conference on Gears 2023*. Düsseldorf: VDI Verlag, pp. 1239-1256.

Marafona, J.D.M., Marques, P.M.T., Portron, S., Martins, R.C., and Seabra, J.H.O. (2023) 'Gear mesh stiffness and dynamics: Influence of tooth pair structural stiffness asymmetry', Mechanism and Machine Theory, 190, p. 105447. doi:10.1016/j.mechmachtheory.2023.105447.

Marques, P.M.T., Marafona, J.D.M., and Seabra, J.H.O. (2023) 'Crowned spur gears for constant mesh stiffness: A conceptual approach', Mechanism and Machine Theory, 189, p. 105426. doi:10.1016/j.mechmachtheory.2023.105426.

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Marques, P.M.T., Marafona, J.D.M., Martins, R.C., and Seabra, J.H.O. (2021) 'A continuous analytical solution for the load sharing and friction torque of involute spur and helical gears considering a non-uniform line stiffness and line load', Mechanism and Machine Theory, 161, p. 104320. doi:10.1016/j.mechmachtheory.2021.104320.

End-to-end simulation of composite structures: linking composites manufacturing and structural performance in cryogenic tanks

Paulo Reinier Teixeira Goncalves

Supervisors
Supervisor: Albertino Arteiro, FEUP
Co-supervisor: Nuno Rocha, INEGI

Thesis defence date: 31 October 2024

Abstract

End-to-end simulation of composite structures is a methodology that aims at studying the structural performance of a component from the manufacturing step to the operating conditions. This idea seeks to include the most relevant manufacturing features that have a potential impact on the structural response and should be considered to improve the design and to obtain components with lower weight and higher performance. In composite materials, the manufacturing process is particularly critical to the component quality because it involves different thermomechanical processes that produce residual stresses, aside from the inherent manufacturing problems like porosities, fiber misalignments, inclusions, and poor compaction, among others, which directly affect the final performance of the produced component. This process is especially critical in the production of composite overwrapped pressure vessels type V (COPV), where a high-quality component is required to guarantee the structural integrity and tightness to prevent leakage. Improvement of design and manufacturing can have an effect on the final weight, performance, durability and safety of this type of components.

The implementation of end-to-end simulations in composite structures requires considering different phenomenological aspects that take place during manufacturing, like heat transfer, curing, mechanical straining, and posteriorly, the thermomechanical behavior under structural loading. These aspects require the study and development of composite material constitutive models capable of simulating efficiently these phenomenological features, and of simulation models capable of integrating the relevant physics to achieve a proper simulation.

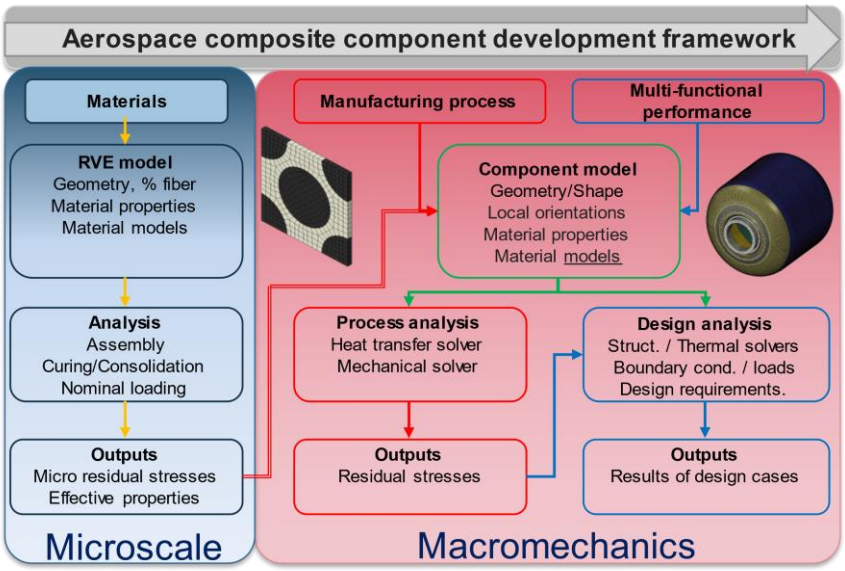

Figure 1. End-to-end simulation framework proposal applied to composite overwrapped pressure vessels.

However, in fiber-reinforced polymer composites, the dissimilar nature of their constituents, namely fibers and polymer matrix, requires additionally to deep down to the micromechanical level to fully understand what happens in the material. The structural performance of the composite component cannot be analyzed at the micromechanical level because the computational cost is prohibitive. This requires considering macroscopic constitutive models capable of capturing the thermomechanical behavior during the manufacturing process and the mechanical response, including plasticity, failure initiation, and propagation. The current state-of-art provides high fidelity constitutive models for the composite materials, but the integration in a unified framework to consider manufacturing features and the coupling with the thermo-mechanical behavior is still lacking, and needs to be addressed to implement reliable end-to-end simulations.

In this work, a review of the simulation models for composite materials at the microscale and macroscale levels was performed to construct a new simulation framework with state-of-art constitutive models that are capable of evaluating the composite effective material properties for thermomechanical analyses using micromechanical simulations (if required) and posteriorly performing end-to-end simulations in a structural component. The curing kinetics model proposed by Kamal was implemented at the micro- and mesoscopic levels and coupled with a pressure-dependent elasto-plastic damage model at the microscale, and a structural invariants-based plasticity and smeared crack model at the mesoscale. This framework is then applied (without loss of generality) to the design of a linerless COPV using the finite element software Abaqus®. Asides from the results obtained for the tested material configurations, this work details the demonstration and validation at application level of a complete set of simulation methods and numerical schemes that can be implemented in commercial finite element codes, like Abaqus®. The application and combination of curing simulation, elasto-plastic deformation and damage initiation and propagation in an implicit, fully 3D setting at different length scales, which are currently not available in the literature, are a step forward in the state-of-art of simulation-driven product development with structural composite materials.

Funding

The current research work has been funded by the project UIDP/50022/2020 New Generation of Cryogenic Propulsion Systems for Future Launchers from LAETA - Laboratório Associado de Energia, Transportes e Aeronáutica, with the support of FCT/MCTES and PIDDAC (Programa de Investimentos e Despesas de Desenvolvimento da Administração Central).

Sample publications

Gonçalves, P. T., Akhavan-Safar, A., Carbas, R.J. and da Silva, L.F.M. (2021) Influence of the Cure State on Mechanical Properties of an Epoxy-based Adhesive: Experimental Characterization and Numerical Simulation. Polym. Adv. Technol. 2021, 33, 1163–1170, https://doi.org/10.1002/pat.5589

Gonçalves, P. T., Arteiro, A., Rocha, N., & Pina, L. (2022) Numerical Analysis of Micro-Residual Stresses in a Carbon/Epoxy Polymer Matrix Composite during Curing Process, *Polymers*, 14(13), 2653. https://doi.org/10.3390/polym14132653

Gonçalves, P. T., Arteiro, A., & Rocha, N. (2023) Micro-mechanical analysis of the effect of ply thickness on curing micro-residual stresses in a carbon / epoxy composite laminate, *Composite Structures*, 319, 117158. https://doi.org/10.1016/j.compstruct.2023.117158

Gonçalves, P. T., Arteiro, A., Rocha, N., & Otero, F. (2024) Modeling 3D transverse elasto-plastic damage of unidirectional fibre-reinforced polymer composites using a smeared crack approach, *Int. J. Solids Struct*, 286–287, 112568. https://doi.org/10.1016/j.ijsolstr.2023.112568.

Gonçalves, P. T., Arteiro, A., & Rocha, N. (2024) 'Experimental characterization and numerical analysis of CFRPs at cryogenic temperatures', *International Journal of Mechanical Sciences*, 265, 108899. https://doi.org/10.1016/j.ijmecsci.2023.108899

Souza, A., Gonçalves, P. T., Afonso, F., Lau, F., Rocha, N., & Suleman, A. (2024) 'On the Multidisciplinary Design of a Hybrid Rocket Launcher with a Composite Overwrapped Pressure Vessel', Journal of Composites Science, 8(3), p. 109. Available at: https://doi.org/10.3390/jcs8030109

High-Speed Rolling Bearings: Torque Loss Measurement and Modelling

Justino Alexandre Oliveira Cruz

Supervisors
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Co-supervisor: David Gonçalves, INEGI
Co-supervisor: Jorge Seabra, FEUP

Thesis defence date: 4 December 2024

Abstract

Nearly 30% of the energy produced worldwide is consumed by transportation vehicles, being approximately one-third still lost due to friction and wear of the several moving parts. Such vehicles are mainly dependent on petroleum, representing a significant contribution to the environment pollution (Holmberga and Erdemirb, 2019 and Boulanger *et al.,* 2011*)*

One of the most popular solutions for this problem is the electrification of vehicles. These vehicles are mainly characterized by their high efficiency and the possibility of being powered by sustainable energy sources.

Nowadays, a global electric car fleet is composed by more than 5.1 million vehicles, where it is estimated that a total of 250 million vehicles will be circulating by 2030 (IEA Paris, 2019).

Vehicle electrification has created new demands to mechanical systems, mainly due to higher operating speeds and the search for more efficient solutions. The new demands require vast research on the matter, including rolling bearings, a component commonly used in mechanical systems. In this way, the focus of this work is the energetic performance of rolling bearings.

Tapered roller bearings (Figure 1. (a)) and angular contact ball bearings (Figure 2. (a)) were selected to perform a vast experimental campaign using different lubricants. These types of rolling bearings were selected due to their frequent use in mechanical systems, as both can support combined loads, although angular contact ball bearings are replacing tapered roller bearings due to their higher efficiency. Such vast experimental campaign allowed a better understanding of the rolling bearings behaviour under different operating conditions.

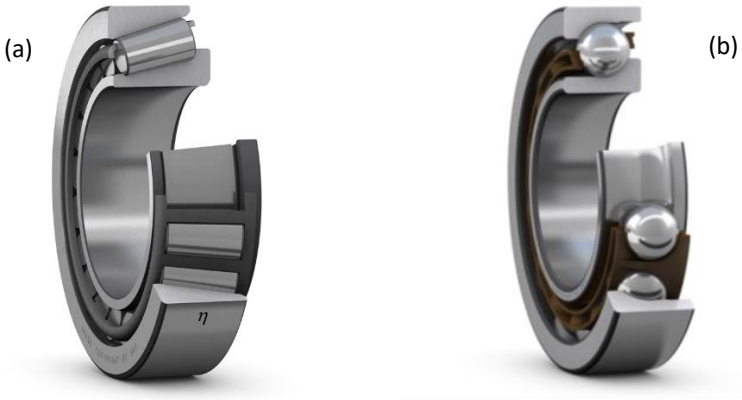

Figure 1. (a) Tapered Roller bearing. (b) Angular Contact Ball Bearing.
Courtesy images from SKF.

To properly estimate the rolling bearings torque loss, a torque loss equation for both types of rolling bearings was developed, based in the theoretical model presented by Houpert (Houpert, 2002). Here, the experimental results were used for both correlation and validation.

To conclude, a test rig capable of reaching high-speeds was developed (see Figure 2) and its detailed presentation was performed. Besides, some preliminary results are also presented.

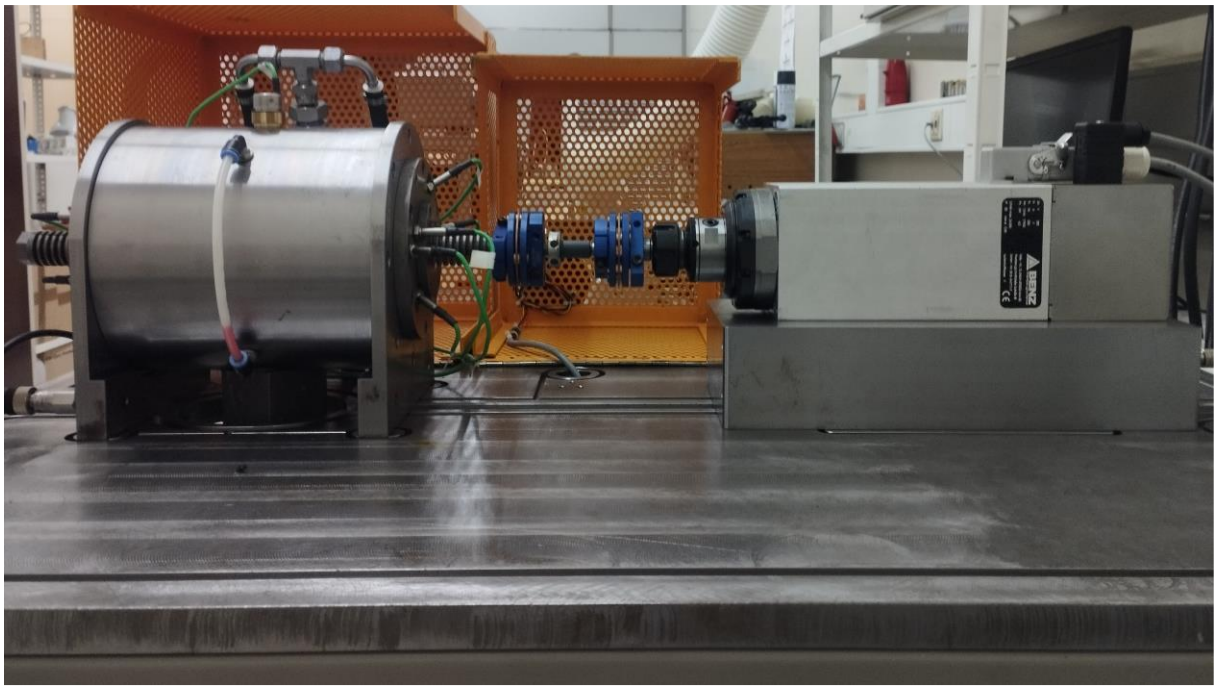

Figure 2. Developed High-Speed Test Rig.

Funding

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- Project Operation NORTE-08-5369-FSE-000027 supported by Norte Portugal Regional Operational Programme (NORTE 2020), under the PORTUGAL 2020 Partnership Agreement, through the European Social Fund (ESF);
- LAETA under project UID/50022/2020.

Sample publications

Cruz, J., Marques, P. and Seabra, J. (2024) 'Vertically assembled tapered roller bearings torque loss: Measurement and Modelling, Under revision

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Holmberga, K. and Erdemirb, A. (2019) ' The impact of tribology on energy use and co2 emission globally and in combustion engine and electric cars.', Tribology International, 135, 389-396. https://doi.org/10.1016/j.triboint.2019.03.024

Boulanger, A., Chu, A., Maxx, S. and Waltz, D. (2011) ' Vehicle electrification: Status and issues.', Proceedings of the IEEE, 99(6), 1116-1138. https://doi.org/10.1109/JPROC.2011.2112750

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Houpert, L. (2002) ' Ball bearing and tapered roller bearing torque: Analytical, numerical and experimental results.', Tribology Transactions, 45(3), 345-353. https://doi.org/10.1080/10402000208982559

A Methodology for Fatigue Performance Analysis of Leaf Springs Suspensions in Freight Wagons

Vítor Manuel Godinho Gomes

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Supervisor: Abílio M. P. de Jesus , FEUP
Co-supervisors: José A. F. O. Correia, FEUP; Roberto S. Barbosa, POLI-USP

Thesis defence date: 4 December 2023

Abstract

Over the years, the rail freight sector has had a major impact on the world economy. This sector, in addition to boosting the world economy, has also proven to be one of the solutions for reducing the carbon footprint and consequently helping to prevent climate change. Despite the enormous advantages associated with this sector, the disinvestment made in technological innovation and scientific development over the last decades has shown its effects nowadays. Problems associated with fatigue failure in critical rolling stock components have been reported such as in leaf springs. The failure of risky components such as leaf springs can cause train derailments and consequently economic and human losses. To prevent the occurrence of these catastrophic events, a methodology for analysing the fatigue performance of leaf spring suspensions in freight wagons was developed.

This research focused on characterising the fatigue performance of spring steel and the structural response of parabolic leaf springs. This steel grade is a high-strength alloy steel that is applied to parabolic leaf springs for wagons standardised by the International Union of Railways (UIC), (DIN 51CrV4). The mechanical characteristics of this steel grade make it suitable for components that operate under severe service and atmospheric conditions. Due to the random service conditions and geometric characteristics of leaf springs, such as notches and high surface roughness, fatigue performance analysis is performed with full-range probabilistic models that allow describing the probability of material failure. Since leaf springs operate under bending loading and high stress ratios, these conditions were analysed using rotating bending and 3-point plane bending tests. Furthermore, as these components are designed to operate for several million cycles, the very-high-cycle (VHCF) fatigue regime was studied in addition to the high-cycle (HFC) regime. The VHCF regime was analysed under ultrasonic fatigue conditions with specimens under uniaxial tension/compression loading, and no significant frequency effect on fatigue resistance was observed. These data also help in analysing the loading effect associated with 51CrV4 spring steel. The fatigue resistance analysis was complemented with tests on notched specimens, tested under rotating bending loads, 3-point flat bending and uniaxial tension ($R > 0$). The combination of different types of loading, loading ratios and notch effect allows the definition of an equivalent fatigue damage parameter based on the Walker and Dowling models and the Theory of Critical Distances. The characterization of spring steel is further complemented by adding to the study an analysis of crack propagation behaviour, a respective analysis of resistance to elasto-plastic fatigue and the development of cyclic plasticity models.

Regarding the structural behaviour of the parabolic leaf spring applied to freight wagons, in a first analysis, the parabolic leaf spring exhibited a characteristic curve with linear stiffness in stage 1 and a non-linear stiffness in stage 2 of operation (see Figure 1 (A)). The cyclic tests carried out showed no effect on the leaf spring response. The numerical model developed to allow new, more detailed analyses made it possible to observe the expected behaviour up to the maximum operating load of the leaf springs (see Figure 1 (B)). Regarding surface stresses, these varied linearly with the applied load, the stress gradient along the thickness of the leaf is essentially constant. From the analysis of the initial stress state due to the assembling process and the surface treatment by stress shot peening on the

leaf springs carried out using techniques of extensometry and X-ray diffraction, respectively, significant compressive stress values were observed, mainly associated with residual stresses.

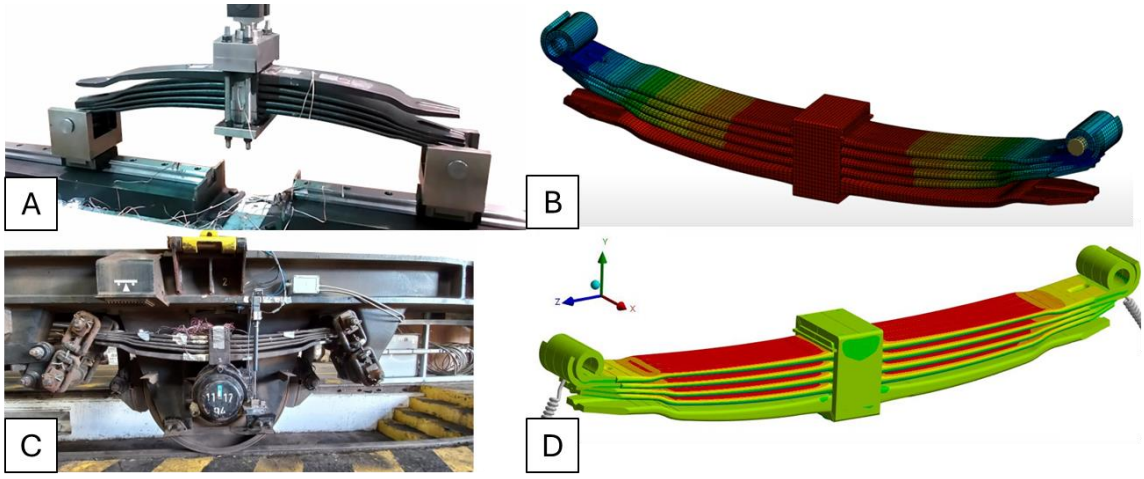

Figure 1. (A) Experimental testing. (B) Computation modelling of the experimental testing. (C) Experimental testing of the leaf spring under real operating conditions. (D) Computation model used to predict the behaviour under real operating conditions.

Finally, an analysis of the fatigue behaviour of the leaf spring in real operating conditions was carried out (see Figure 1 (C)). The numerical model calibrated by laboratory tests with the boundary conditions relating to the suspension of two-axle wagons showed that the horizontal and lateral motions can be neglected compared to the vertical component (see Figure 1 (D)). The numerical model was also used together with data obtained from an experimental monitoring campaign of a freight wagon to predict fatigue damage to leaf springs. The probabilistic fatigue prediction models developed combined with the application of cycle counting and Miner's law methods made it possible to determine the fatigue damage for different failure probabilities. The analysis based on accumulated damage allowed us to demonstrate that the presence and preservation of the compressive residual stress state on the surface is essential to reduce the fatigue damage caused by this component. Furthermore, the methodology implemented to analyse the fatigue performance of leaf spring suspensions for railway wagons proved to be a useful tool to be used in the analysis of this type of components, since the fatigue design standards for rolling stock are very scarce.

Funding

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Sample publications

Gomes, V. M. G., de Figueiredo, M. A., Correia, J. A. F. O., de Jesus, A. M. P., (2024) 'Experimental and Numerical Analysis of the Assembling Stresses in Parabolic Leaf Springs for Railway Freight Wagons. *Preprints*, 2024030986. https://doi.org/10.20944/preprints202403.0986.v1

Gomes, V. M., Lesiuk, G., Correia, J. A., de Jesus, A. M. (2024) 'Fatigue Crack Propagation of 51CrV4 Steels for Leaf Spring Suspensions of Railway Freight Wagons', *Materials*, 17(8), 1831, https://doi.org/10.3390/ma17081831

Gomes, V. M., Souto, C. D., Correia, J. A., de Jesus, A. M. (2024) 'Monotonic and Fatigue Behaviour of the 51CrV4 Steel with Application in Leaf Springs of Railway Rolling Stock' *Metals*, 14(3), 266, https://doi.org/10.1016/10.3390/app13148308

Gomes, V. M. G. Neto, J., Pinto, N., Montenegro, P., Mendes, J. de Jesus, M. P., Calçada, R. (2022) 'Modelo de Previsão em Tempo Real para o Dano por Fadiga em Molas de Lâminas Parabólica de Vagões Ferróviario', proceedings of *10º Congresso Rodoferroviário Português*, 119, https://10crp.crp.pt/wp-content/uploads/2022/07/paper_119.pdf

Gomes, V. M. G., de Jesus, M. P., Correia, J. A. F. O., Calçada, R. (2022) 'Determination of the Highest Potential Spots for Fatigue Failure in Parabolic Leaf Springs using the Maximum Variance Approach', proceedings of ECF23, *Procedia Structural Integrity*, 42, 1552-1559, https://doi.org/10.1016/j.prostr.2022.12.196

Optimization and accuracy of numerical methodologies applied to sheet metal forming with experimental validation

Sara Esmeralda Silva Correia de Miranda

Supervisors
Supervisor: Rui L. Amaral, INEGI
Co-supervisor: Abel D. Santos, FEUP; José César de Sá, FEUP

Thesis defence date: 18 December 2023

Abstract

Sheet metal forming techniques are extensively utilized across numerous manufacturing sectors. The growing complexity of products, the reduction in development times, and the increasing demand for lighter and stronger materials present significant challenges to forming processes. In response to these challenges, virtual try-out evaluations are conducted through finite element numerical simulations. The successful application of numerical simulation in sheet metal forming is heavily reliant on accurate material models that can effectively capture the complex deformation behaviour of metallic materials. Ongoing research efforts are dedicated to refining these models and enhancing their predictive capabilities.

The main objective of this work is to enhance and establish methodologies that will contribute to the advancement of new numerical modelling tools, enabling more accurate and reliable predictions of material behaviour through constitutive models. The materials under investigation include aluminium alloys (AA5182 and AA6016) and advanced high-strength steels (DP500 and DP780). A comprehensive set of experimental tests, corresponding to various strain paths and loading stress states, has been designed and conducted to improve the material behaviour definitions and, in turn, increase the accuracy of the numerical predictions.

Additionally, a series of benchmark tests (Figure 1), representing a range of conditions materials may encounter during the deformation process, were performed. These tests include deep drawing experiments, such as cylindrical cup and cross-die forming tests, as well as a springback analysis based on a split ring for the cylindrical cup.

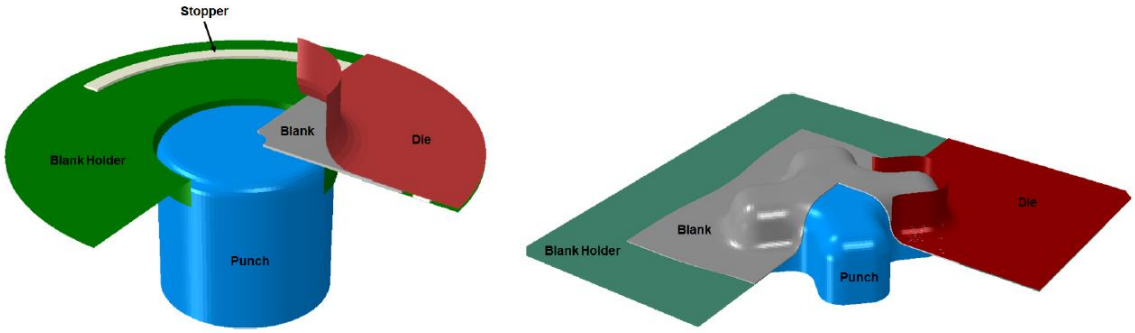

Figure 1. Finite element 3D models: Swift test (a); Cross die forming.

The anisotropic behaviour of materials has been a central focus in the study of sheet metal forming processes. The variation in mechanical properties as a function of the loading direction of sheet materials is a critical factor influencing the accuracy of numerical predictions. To address this, both associated (AFR) and non-associated (NAFR) plastic flow rules have been considered, with the Hill'48

and Yld91 anisotropic yield criteria serving as foundational models to describe the material's anisotropic behaviour, in addition to the Yld2004-18p criterion.

Finite element numerical simulations were performed to evaluate the ability of different constitutive models to predict the anisotropic behaviour of metallic sheets. The numerical results were compared with experimental data to assess their accuracy. The non-associated plastic flow rule approach exhibited a strong correlation with the experimental results, demonstrating improved accuracy in predicting both the anisotropic behaviour and springback effects (Figure 2).

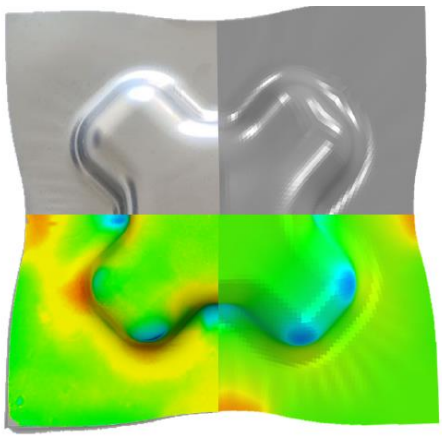

Figure 2. Correlation between experimental data and finite element analysis (FEA) results.

Funding

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Sample publications

Rogério F. F. Lopes, Rui L. Amaral, Sara S. Miranda, Abel D. Santos, Pedro M. G. P. Moreira (2024) Numerical analysis of springback with experimental validation using UCB test. U.Porto Journal of Engineering, 1-10. https://doi.org/10.24840/2183-6493_010-001_001279

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R. L. Amaral, A. D. Santos, D. G. Wagre, S. S. Miranda, D. J. Cruz and J. César de Sá (2021). Numerical Simulation of a Cylindrical Cup Test for Validation of Anisotropic Materials Using Non-Associated Flow Rule. In: da Silva, L.F.M. (eds) Materials Design and Applications III. Advanced Structured Materials, vol 149. Springer, Cham. Online ISBN 978-3-030-68277-4 https://doi.org/10.1007/978-3-030-68277-4_15

Multi-scale Multi-physics FEM-based Modelling Strategies for Metal Additive Manufacturing Processes

Roya Darabi

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Co-supervisor: Ana Rosanete Lourenço Reis, FEUP; Marco Paulo Lages Parente, FEUP

Thesis defence date: 9 February 2024

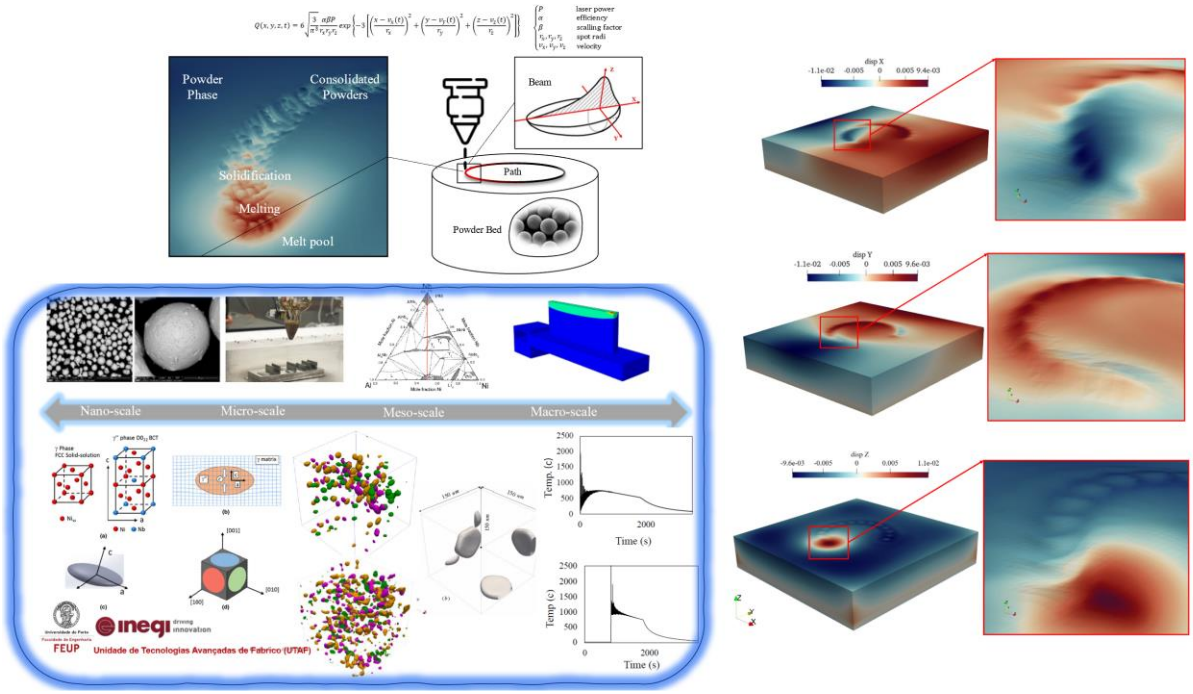
Abstract

This study encompasses various computational aspects of process modeling in additive manufacturing (AM) with a particular focus on dissipative phase field modeling to predict thermal, mechanical, and microstructural responses. The increasing interest in AM stems from its advanced manufacturing possibilities; however, a comprehensive understanding of defect formation and constitutive/structural responses remains elusive due to the complex multi-physics nature of the process. To address these challenges, a reliable computational approach that considers the multi-scale and multi-physics aspects of AM is required. Advanced numerical techniques have recently emerged, enabling the prediction of defects based on process parameters and facilitating the determination of optimal processing windows for desired mechanical properties. Numerical simulations have proven to be robust, cost-effective, and reliable tools for predicting component quality in AM. In this context, this study aims to propose a process model framework that integrates insights from integrated computational materials engineering (ICME) into AM processes. The study employs two approaches. The first approach couples a thermodynamically consistent phase field model with a transient heat transfer model to track material phase states. This approach divides the domain into state regions separated by a diffusive interface. The phase field variable, obtained from explicit solutions of the Wang phase field formulation, accurately captures the degree of consolidation between the powder and molten phases. An enthalpy-based model is incorporated to handle the nonlinearity resulting from coupling the two approaches. The feasibility of studying melt pool behavior is demonstrated through finite element simulations of a material layer processing using the ABAQUS framework. The simulations are then extended to a multi-layer scale, allowing for the modeling of complex geometries and real-world size patterns. By considering phase field-dependent material properties and leveraging thermal responses, the energy dissipative inequality equation enables the prediction of residual stress and deformations. To explore the influence of laser scanning patterns on structural deformations, widely twisting in thin-walled structures, a scenario involving the application of dwell time is devised to mitigate associated issues. In the second approach, the MOOSE platform is employed to model the fully coupled thermo-mechanical phase field formulation, providing insights into the interrelated multi-physics and multi-scale phenomena in Selective Laser Melting (SLM) processes. This approach utilizes massively parallel finite element computations, treating powder particles as a homogenized continuum medium and accounting for heat transfer through conduction. The model aims to capture the nonlinear, non-equilibrium characteristics of the melt pool and various multi-physics phenomena in Powder Bed Fusion (PBF) processes, including powder layer generation, melting-solidification, phase changes, induced distortion, and residual stresses.

Additionally, a computational script is developed to predict secondary phases that emerge during cyclic loading with heating and cooling. This script employs the non-isothermal diffusion concept based on modified JMA model to calculate the phase fractions and couples it with the effect of the changing the temperature. To accurately capture phase transitions and their evolution, a phase field modeling framework is incorporated alongside the mean field computational stage. This

integrated approach provides a comprehensive understanding of phase behavior under cyclic loading conditions. Furthermore, a novel closed-loop controller based on reinforcement learning is introduced to observe and control the evolution of the melt pool in terms of size and temperature. This approach holds great promise for real-world training of controllers, enhancing the capabilities of AM machines, and optimizing process parameters to achieve improved part quality and performance.

Graphical Abstract



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Darabi, R., Azinpour, E., César de Sá, J., Machado, M., Reis, A., R. Hodek, J., Dzugan J. (2021) Fracture Prediction Based on Evaluation of Initial Porosity Induced By Direct Energy Deposition, *European Journal of Computational Mechanics*, 29(3):223-254, https://doi.org/10.13052/ejcm2642-2085.29233

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Reliability and Maintenance of Weapon Systems[1]

Énio Rodrigo Pereira Chambel

Supervisors
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Thesis defence date: 28 February 2024

Abstract

The Maintenance Management strategy for Weapon Systems is the responsibility of each State/Military Operator, which defines the selection of processes and requirements and the necessary human and material resources to its applicability. Due to the increasing intensification of military conflicts worldwide, Military Weapon Systems currently face significant challenges in maintenance management, since sometimes logistical support is complex or non-existent. The logistical difficulties arising from the international missions of these weapon systems are well known due to unexpected failures of their systems and the uncertainty support of the necessary spare parts and the operational context in which they will fulfill their missions. The case study in the scope of this thesis is a weapon system, which has been in service in the Portuguese Army since 2009, the wheeled armored vehicle, PANDUR II 8x8. It is a very recent vehicle and is usually used by the National Forces in international missions with a permanent need, requiring a high level of availability for the missions assigned.

The objective of this study is to improve logistics processes for future missions assigned to the Portuguese Army, in particular maintenance, operability and availability of the weapon system under investigation and to develop a methodology that allows the identification of the need for spares, as early as possible, presenting itself as an excellent decision support tool for the Logistics Command.

The Reliability Centered Maintenance (RCM) methodology is used to identify failure modes. The results of the modeling and simulation methodologies are used as models of Reliability and Maintenance analysis through Generalized Stochastic Petri Nets and Coloured Petri Nets. The results of the modeling and simulation methodologies are compared, namely the Generalized Stochastic Petri Net and the Coloured Petri Net models.

The study results confirm the possibility of using the proposed methodologies to assess the operational reliability of the high-performance weapon system fleet under study. The modeling of the systems and simulations allow the analysis of the failure conditions and the identification of systems, subsystems, and components that frequently fail. Models presented to ensure operational capability and corrective actions to improve maintenance planning and scheduling. They guarantee the availability of systems for future operational situations and improve operability and maintenance logistics. They are also a powerful decision support for the Military Logistics Command, as they allow for predicting the need for spares.

[1] Original title in Portuguese: “Fiabilidade e Manutenção de Sistemas de Armas”

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Adhesive Joint Analysis Using Meshless Methods

Luís Daniel Costa Ramalho

Supervisors
Supervisor: Raul Campilho, ISEP
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Co-supervisor: Renato Natal, FEUP

Thesis defence date: 7 May 2024

Abstract

Adhesive joints are increasingly used in various industrial sectors, including the automotive or the wind turbines industries. This stems from the fact that they possess some advantages when compared to other joining methods, such as more uniform stress distributions and reduced weight. However, adhesive joints also have some disadvantages, such as an impossibility of non-destructive disassembly and required curing times in many cases.

Over the years several analysis techniques for adhesive joints have been developed. The first techniques developed were analytical models. The oldest analytical model still in use is the Volkersen's model. However, these methods require several simplifications, so nowadays it is more common to use numerical methods, usually the Finite Element Method (FEM). Nonetheless, there are alternative numerical methods that can be used. One of them is the eXtendend FEM (XFEM), this is an altered version of the (FEM) used in crack propagation problems. Meshless methods are another important alternative. These methods discretize domains and solve the system of equation using just nodes and integration points, eliminating the need for elements. There are several meshless methods that have been proposed over the years. In this work the Radial Point Interpolation Method (RPIM) and the Natural Neighbours RPIM (NNRPIM) are the ones used. Meshless methods offer some advantages when compared with the standard (FEM), such as showing a lower computational time dealing with problems that require re-meshing and more flexibility in discretizing complex domains since elements are not needed. In turn, one of their disadvantages is that they are usually slower that the FEM, mainly due to the matrices of the global system of equations being more populated.

The strength prediction of adhesive joints is usually performed using one of three different types of criteria: continuum, fracture or damage mechanics criteria. Another alternative is Cohesive Zone Models (CZM), which is the most popular method to predict the strength of adhesive joints. This approach combines continuum and fracture mechanics, and it is able to predict the strength of a wide range of joint designs with minimal errors. However, the cohesive laws that the (CZM) uses to predict the strength of adhesive joints change depending on different geometrical parameters of the joints.

The main goal of this research is use a new tool to study adhesive joints, meshless methods, and assess its advantages and disadvantages over traditional tools, like the FEM, under several different loading conditions, made of different materials and different dimensions, as well as different types of joints. So, in this work joints were studied under static loads, free vibrations and impact loads. Furthermore, two different strength prediction criteria were also tested, one based on continuum mechanics, the Critical Longitudinal Strain (CLS) criterion, and another based on fracture mechanics, the Intensity of Singular Stress Fields (ISSF) criterion. These criteria were chosen aiming at overcoming the limitation of CZM, where the properties can be dependent on the joint's dimensions. In this work two different types of joints were used, Single Lap Joints (SLJ) and Double Lap Joints (DLJ), additionally three different adhesives and three different adherents were also tested. The results showed that the proposed meshless methods can be used in this type of structure, in the three different loading conditions tested, without any numerical issues. The static strength predictions using the CLS criterion were closer to the experimental strength than the strength predictions using the ISSF criterion, but

acceptable predictions were achieved with both criteria. In free vibrations it is shown that the adhesive had no significant influence on the natural frequencies of the joint, for both SLJ and DLJ. In this case the adherents are the most important factor. Under impact loading conditions the ISSF criterion showed an increase in the critical ISSF, when compared to the critical ISSF under static loading conditions.

Funding

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Dionísio, J. M. M. et al. (2021a) 'Fracture mechanics approach to stress singularities in composite adhesive joints', Composite Structures. Elsevier Ltd, 276(August), 114507. https://doi.org/10.1016/j.compstruct.2021.114507

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Ramalho, L. D. C., Campilho, R. D. S. G. and Belinha, J. (2020) 'Single lap joint strength prediction using the radial point interpolation method and the critical longitudinal strain criterion', Engineering Analysis with Boundary Elements. Elsevier Ltd, 113(January), 268–276. https://doi.org/10.1016/j.enganabound.2020.01.010

Theoretical and numerical studies of viscoelastic fluid flows

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Supervisors
Supervisor: Alexandre Afonso, FEUP
Co-supervisor: Fernando Pinho and Manuel Alves, FEUP

Thesis defence date: 10 May 2024

Abstract

Viscoelastic materials, such as polymer melts, polymer solutions and biofluids display complex behaviour described by rheological constitutive models. These models can be classified as differential and/or integral. Differential models are based on partial differential equations and use the local deformation field whereas integral models use direct information from the past history of deformation. Both types have advantages and disadvantages: differential models usually allow a faster numerical solution of the differential equations involved, while integral models are computationally expensive and may lead to error propagation, but otherwise allow a better rheological modelling. A new generation of models that attempts to improve the situation by providing a better description of fluid rheology, while keeping the cost of computations under control, is based on fractional calculus.

One such constitutive equation is the generalised Phan-Thien–Tanner (gPTT) model and one contribution from this thesis is in providing semi-analytical and numerical solutions in canonical flows for the purpose of benchmarking. The gPTT viscoelastic model considers the Mittag–Leffler function instead of the classical linear and exponential functions of the trace of the extra-stress tensor and uses two new fitting parameters. The Mittag–Leffler function allows a wider range of variation in the rates of destruction of network junctions of the polymer network, providing additional fitting flexibility.

In this work, semi-analytical solutions were developed for Couette-Poiseuille flows (with no-slip and with asymmetric slip), for electro-osmotic flow in microchannels of viscoelastic fluids and in annular flows, and a parametric study was also carried out on the influence of the new parameters of model. The derived solutions allow a better understanding of how a fluid described by this model behaves with the considered flows. These solutions are used to validate the numerical methods used in computational fluid dynamics (CFD) codes.

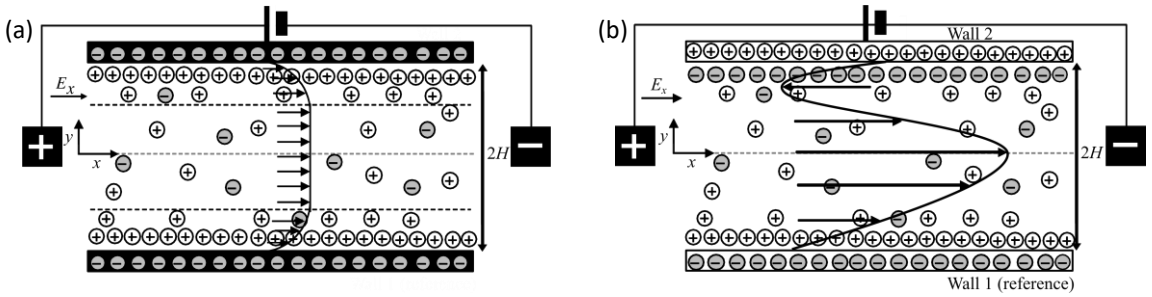

Figure 1. Schematic of the flow in a planar microchannel. (a) Electro-osmotic flow with symmetric zeta potentials at the walls. (b) Electro-osmotic flow with asymmetric zeta potentials at the walls.

CFD investigations can produce vast amounts of data that often overwhelm the user while hiding important information. In particular, it is important to identify and characterise relevant flow structures, and this is especially expensive under transient flow conditions, where the structures are continuously evolving in space and time. To overcome this problem, the entire dataset can be decomposed into smaller sets and important structures present in the main flow and structures with

periodic behaviour, like vortices, can be identified. One way to do it is through model order reduction methods such as the proper orthogonal decomposition (POD) method that is very popular in CFD. POD enables the decomposition of any flow into an infinite set of eigenfunctions or modes, effectively reducing the problem, capturing the essential information using less data and less computational resources.

After the analytical studies presented in the first part of this work, the POD method was applied to the flow around two parallel side-by-side cylinders with different radii, where a Newtonian fluid and two non-Newtonian power-law fluids, with $n = 0.7$ and $n = 1.3$, were considered. In addition, the flow past one cylinder of a fluid described by a gPTT model at very low Reynolds number ($Re = 0.01$) and two different Weissenberg numbers ($Wi = 1.2$ and 1.25) were also investigated through the use of POD method. In both studies a reconstruction of the flows was conducted, followed by a frequency analysis of specific modes. Additionally, for the flow past a cylinder, using the POD analysis made for the flow with $Wi = 1.2$, a prediction of the reconstruction of the flow at $Wi = 1.25$ was obtained and compared with the original simulation at $Wi = 1.25$. The performed analysis showed that the POD method can be used to better identify meaningful flow structures and to obtain new data at different conditions with significantly lower cost.

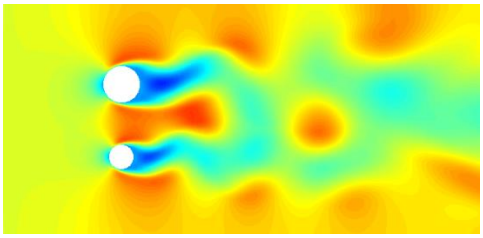

Figure 2. Profile of first component of the velocity, u, for the Newtonian fluid of the flow around two parallel side-by-side cylinders with different radii.

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Ribau, A.M., Ferrás, L.L., Morgado, M.L., Rebelo, M. and Afonso, A.M. (2019) 'Semi-Analytical Solutions for the Poiseuille-Couette Flow of a Generalised Phan-Thien–Tanner Fluid', *Fluids*, 4(3), 129. https://doi.org/10.3390/fluids4030129

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Ribau, A.M., Gonçalves, N.D., Ferrás, L.L., and Afonso, A.M. (2021) 'Flow structures identification through proper orthogonal decomposition: The flow around two distinct cylinders', *Fluids*, 6(11), 384. https://doi.org/10.3390/fluids6110384

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Study of the strain rate dependent behaviour of adhesives undermixed mode loadings

Paulo David Pereira Nunes

Supervisors
Supervisor: Eduardo Marques, FEUP
Co-supervisor Lucas da Silva, FEUP

Thesis defence date: 11 June 2024

Abstract

The study of the behaviour of adhesive joints under impact loading is a very active field of research, driven by significant industrial interest. Many industries, such as the automotive industry, are currently employing adhesive joints extensively, making use of the inherent properties of adhesive joints to improve the mechanical behaviour, reduce weight and simplify manufacturing. Due to high standards in terms of safety required in the automotive industry, namely the occupant's safety during collisions, the behaviour of adhesives under impact loads is becoming a prominent objective of study. Furthermore, the variability of performance of adhesives as function of the loading modes, namely mode I, mode II and all the combinations possible in between, leads to a fundamental requirement of understanding how the impact velocity affects the adhesive behaviour under such different loading conditions. As a result of the fact that the geometric design of a joint may induce a variety of stress distributions along the bonded areas, characterizing an adhesive as function of an impact velocity is not enough as design tool, thus the characterization of the material as function of the strain rate that is an intrinsic property of the material is needed. The possibility of fully characterizing the adhesive behaviour as function of both mode mixity and strain rate in order to feed a simulation tool allows the industry to designing stronger and safer structures. This document aims to enlighten the various steps planned in order to achieve such objective.

Sample publications

Nunes, P. D., Borges, C. S., Marques, E. A., Carbas, R. J., Akhavan-Safar, A., Antunes, D. P., Lopes, A. M., da Silva, L. F. (2020). 'Numerical assessment of strain rate in an adhesive layer throughout double cantilever beam and end notch flexure tests', *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 234(5), 415-425. doi:10.1177/0954408920916007

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Optimization of Fused Filament Fabrication (FFF) Printing Nozzles: Experimental and Numerical Approaches

Tomás Schuller de Almeida e Graça Barbosa

Supervisors:
Supervisor: Francisco Galindo-Rosales, FEUP
Co-supervisor: Paola Fanzio, TU Delft

Thesis defence date: 5 June 2024

Abstract

Fused Filament Fabrication (FFF), a prominent additive manufacturing process, involves the extrusion of molten thermoplastic polymers through a nozzle. This thesis undertakes a comprehensive exploration of FFF printing nozzle optimization, employing a synergistic blend of experimental investigations and numerical simulations. In the initial phase, the focus is on comprehending melt flow patterns within the nozzle. Leveraging a viscoelastic model (Giesekus) and employing numerical simulations through OpenFOAM^{R} and *rheoTool*, the study offers a nuanced understanding of the interplay between rheological properties and melt flow. The research utilizes a nozzle geometry akin to previous work and reveals that while extensional flow is predominant, shear-induced normal stress differences significantly impact pressure drop and equilibrium height in the backflow region.

The subsequent phase introduces an innovative method for monitoring nozzle pressure, addressing both the challenge of obtaining experimental data on melt pressure and the lack of comprehensive numerical models capturing molten polymer rheology. This novel approach involves a pin in direct contact with the molten material, transmitting applied force to an externally mounted load cell. Through steady-state conditions, reliable pressure data is obtained for two nozzle geometries at varying extrusion flows and temperatures. The Giesekus model further facilitates capturing viscoelastic rheometric features, with numerical predictions aligning closely with experimental data. A key revelation is the impact of backflow, the reverse flow of molten polymer between the filament and the liquefier towards the cold end, on non-linearities in total pressure drop measured in the feeders. Moving forward, the exploration extends to the role of polymer rheology in material extrusion applications, particularly FFF. The analysis encompasses a range of polymer melts, modeled through viscoelastic models based on rheological properties experimentally determined under viscometric flows. The distribution of normal stresses around the contraction is linked to fluid rheology, influencing pressure drop differences and instabilities. Elastic instabilities and elastic turbulence at printing speeds are identified as consequences of the elasticity of molten polymer at small length scales, leading to increased excess pressure drop and potential failures during the printing process.

The final phase addresses optimal design considerations for FFF printing nozzles across a spectrum of polymer melts. Employing a dual-pronged approach, numerical optimization through DAKOTA^{C} and OpenFOAM^{R} is coupled with experimental validation through advanced visualization techniques. The optimization process defines variable coordinates for the nozzle's contraction section within manufacturing constraints. Nozzle shape is revealed as a pivotal factor influencing flow patterns, with optimized solutions promoting either shear or extensional flow. Experimental validation demonstrates a significant reduction in backflow-related pressure drop, offering tangible benefits such as increased printing speeds, enhanced productivity, and improved overall print control.

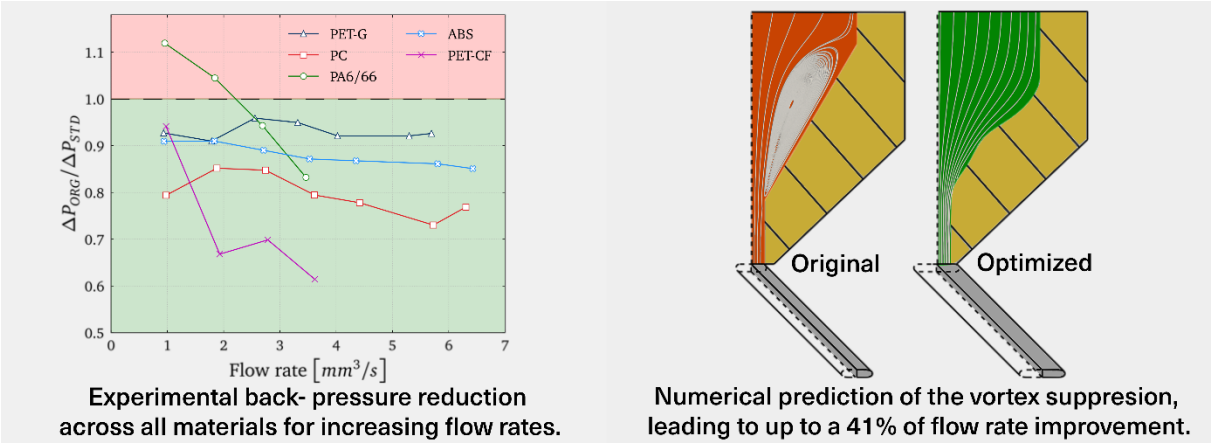

Figure 1. (a) Relative pressure drop between the optimized organic and the standard FFF nozzle geometry. (b) Visual representation of the flow improvement and recirculation reduction, that lead to improved printing.

In summary, this thesis contributes a holistic understanding of FFF printing nozzle dynamics, encompassing melt flow characteristics, the effects of internal stress and pressure, and the profound impact of polymer rheology. The findings not only advance the technological nuances of FFF 3D printing but also hold practical implications for the additive manufacturing industry, providing avenues for heightened efficiency, productivity, and reliability.

Funding

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Development of a small scale triple effect desalination unit driven by solar energy

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Supervisors
Supervisor: Szabolcs Varga, INEGI.

Thesis defence date: 13 June 2024

Abstract

Access to freshwater is a fundamental condition, not only for human life, but life in general. Therefore, water scarcity is a major threat to the existence of actual and future generations. The technological development of sustainable desalination technologies can alleviate this water stress. Several solutions exist; however, most desalination plants are large-scale, complex energy-intensive systems, requiring considerable initial cost and highly skilled personnel. Small communities and businesses (e.g. holiday resorts) could benefit from the use of small-scale clean energy-based desalination systems driven by solar heat, for example. There is a lack of efficient and robust technological solutions for such systems. Thus, the main objective of this thesis is to develop and construct a small-scale triple-effect thermal vapour compression (TVC) desalination unit running on solar thermal energy. An important novelty of this thesis is the first-time integration of a high-performance variable geometry ejector (VGE) into the thermal vapour compression unit, which operates with high efficiency, even under changing operating conditions.

In order to reach the major objective, an extensive numerical effort is performed in the thesis. First, a one-dimensional (1D) mathematical model is developed for the theoretical analysis of the small-scale parallel feed solar multi-effect desalination (MED-TVC) system. A parametric study is carried out by varying the ejector motive steam temperature, the first effect temperature, the between effects temperature difference and the ejector compression ratio. The model predicts the best system performance for the lowest ejector compression ratio. The performance indicators are less sensitive to the temperature between effects. An important output of the parametric study is the identification of the optimal system design conditions. The data indicates that a three-effect MED-TVC unit with a VGE can produce up to 5.8 l/h of freshwater per square meter of solar collector area with a gain output ratio (GOR) of 8.6.

The elaborated prototype concept is made up of two subsystems: the solar field (SF) and the MED-TVC unit. The components of both subsystems are designed in the thesis using a set of mathematical models developed for the purpose. Component selection is carried out considering cost and performance. The final prototype design is made up of compound parabolic collectors (CPC), plate heat exchangers, steam separators, pumps, a small heat storage of 400 l, piping and accessories.

The main innovative component of the system - the VGE - is designed using advanced CFD modelling. The developed model is based on the compressible Navier-Stokes equations. Turbulence is tackled using the realizable k-ε model. The VGE flow path is optimised for a large set of operating conditions, considering a movable spindle in the primary nozzle throat and a movable nozzle exit position into the mixing chamber. The results showed that the use of a VGE can improve ejector performance up to four times under operation conditions, different from the design one (Figure 1a). Finally, the VGE body parts are designed and presented in the thesis, with suitable actuators to control its geometry (Figure 1b).

An adequate control and monitoring system is developed to assess the constructed test rig performance and assure safe operation. For this purpose, a relatively large number of sensors are selected to measure the operating fluid volumetric flow rate, temperature, pressure, level and salinity.

Also, global and beam solar radiation intensity are measured. Safe operation is assured by monitoring the maximum temperature and pressure in the solar collectors, overflow detection of the brine and distillate tanks, and depletion detection of the salty water tank. The control software is developed in LabView and TwinCat to enable start-up, continuous, shut-down and emergency shut-down operations. An uncertainty analysis is performed for the experimentally determined performance indicators, including entrainment ratio, gain output ratio and collector loop efficiency resulting in absolute uncertainty levels of ± 0.0023, ± 0.056 and ± 0.03, respectively.

The major output resulting from the thesis is the construction of the MED-TVC prototype with the integrated innovative variable geometry ejector (Figure 2). This motivates the author to continue the work with the installed prototype, to produce knowledge that contributes to the validation of the developed models and eventually a TRL upgrade of the concept.

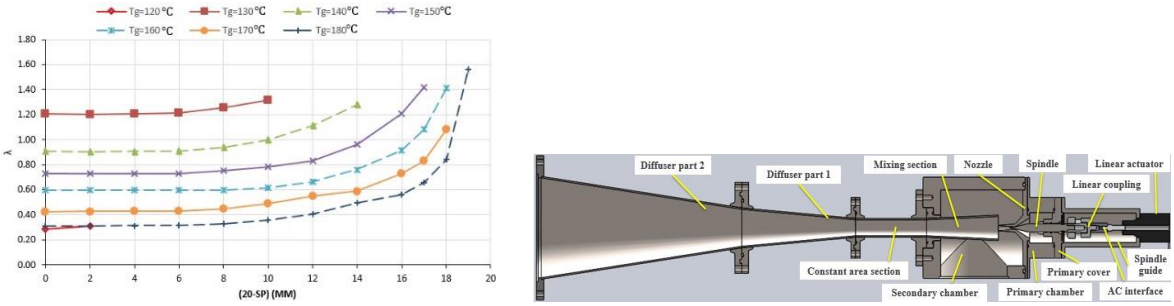

Figure 1. (a) Variable geometry impact on the ejector performance for different operating conditions and (b) cross section of the designed variable geometry ejector.

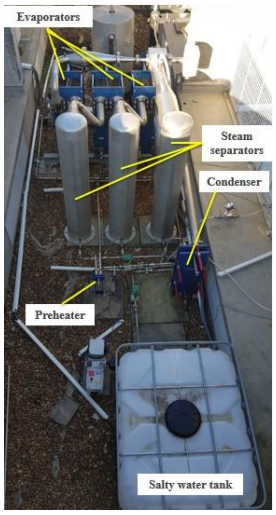

Figure 2. Developed prototype for the Small-SolDes system illustrating the installation of evaporators, steam separators, condenser, preheater and salty water tank.

Funding

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Shahzamanian, B., Varga, S., Soares, J., Palmero-Marrero, A. and Oliveira, A.C. (2021) 'Performance evaluation of a variable geometry ejector applied in a multi-effect thermal vapor compression desalination system', Applied Thermal Engineering, 195, 117177. https://doi.org/10.1016/j.applthermaleng.2021.117177

Topology Optimization of Structures using Non-Linear Algorithms with Stress Constraints

Luís Miguel Moura Frade Vaz Pinto

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Thesis defence date: 13 June 2024

Abstract

Topological optimization has been investigated since the publication of the first article by Bendsoe and Kikuchi in 1988 in which the authors used a homogenization technique applied to composite materials at a macrostructural and microstructural level.

The objective of topological optimization is that for a given structural domain it is possible to obtain a more efficient, lighter, or smaller structure in volumetric terms and that responds with the same stiffness to the applied mechanical stresses, when these are maintained without alteration.

Topology optimization techniques evolved from Bendsoe and Kikuchi 1988's first paper, from gradient or density methods such as the SIMP (Solid Isotropic Material Penalization) method or discrete evolutionary heuristic methods such as the ESO (Evolutionary Structural Optimization) method that later evolved into the BESO (Bidirectional Evolutionary Structural Optimization) method.

Initially, the objective of topological optimization methods was to minimize the deformation energy of a structure, or its compliance, depending on the relative density of the material. These algorithms used, in each iteration, the results obtained from a Finite Element simulation, which applies a geometry discretization technique. The generated finite elements could be considered in two states, with material or voids, thus restricting the volume of the structure. The methods worked correctly with this procedure, however it was found that for practical engineering applications, the value of the stresses installed in the material of the final structure is an important variable to take into account.

In a case where the material is subjected to stresses greater than its yield limit, the structure would collapse. In this way, from a certain point onwards, researchers began to consider the value of the material's yield stress as a restriction or objective, in the optimization process.

In this work, a graphical application was developed to manage the topological optimization process in MATLAB App Designer language and whose development also included a set of linear and non-linear topological optimization algorithms.

In the case of nonlinear algorithms, the stresses present in the structure is an additional variable. Different results filtering schemes were also implemented, in order to avoid the appearance of numerical problems, such as checkerboard patterns in the structure, and also to alleviate the problem of dependence on the mesh used.

The adjoint method was used to obtain the sensitivities of the different variables, in relation to the structural domain variable. The numerical simulation of the structure was carried out in ABAQUS. The algorithm was then applied to three two-dimensional structural problems well known to the academic community, such as the L-beam, the T-bracket and the Portal frame. The objective of the work was to make a comparative study of the results obtained by the linear SIMP, ESO and BESO methods and the non-linear methods that include the restriction or minimization of stress for those three structural examples that typically concentrate high stresses in certain areas of the structure.

The results obtained allowed to conclude on the effectiveness of the implemented algorithms, as well as to give recommendations in relation to the best parameters to be used for the different algorithms.

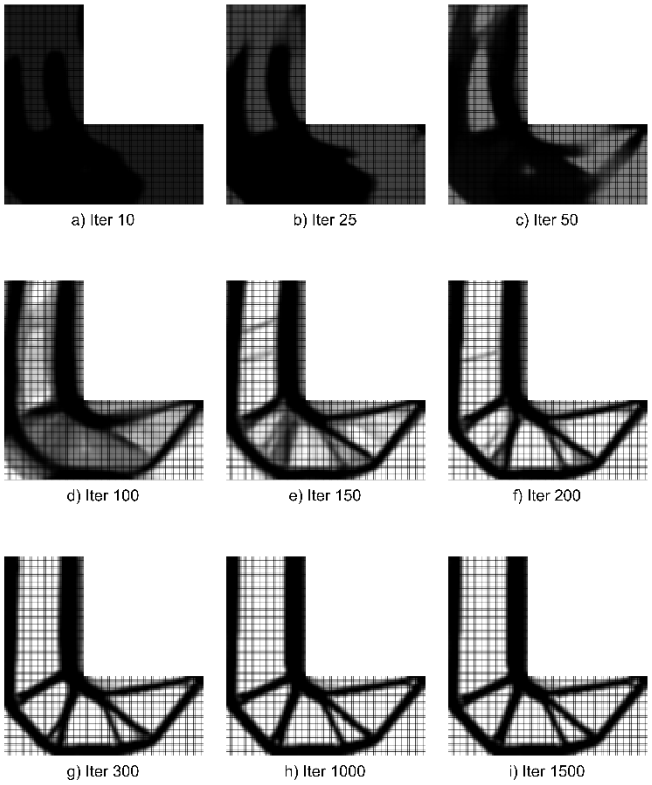

Figure 1. Evolution of the density distribution for non- linear compliance minimization problem, with stress and volume constraint.

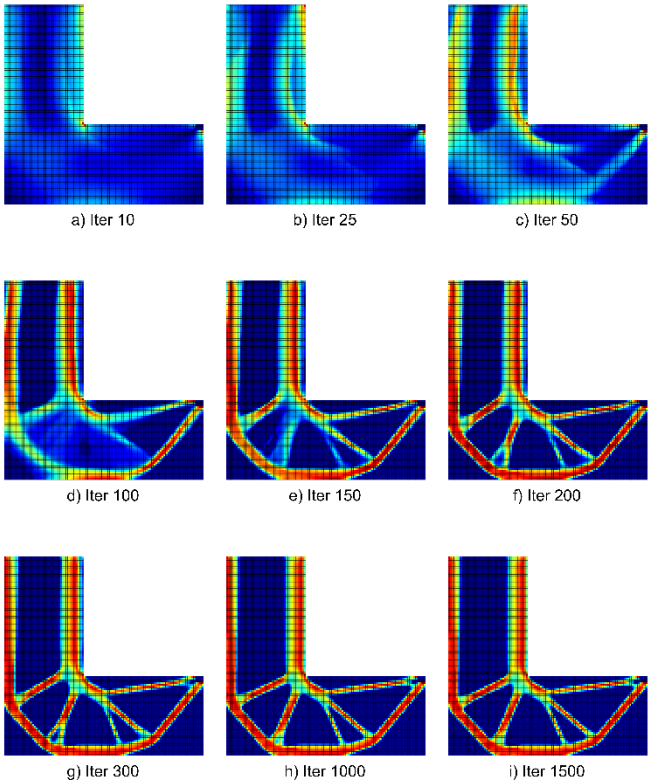

Figure 2. Evolution of the von Mises Stress field for a non-linear compliance minimization problem, with stress and volume constraint.

Structural Health Monitoring of Adhesive Joints Using Lamb Waves and Machine Learning Algorithms

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Thesis defence date: 11 July 2024

Abstract

The search for stronger, lighter, and more efficient structures has led the industry, particularly the aeronautics sector, to use new materials with customized properties and multimaterial structures. Adhesive joints eliminate fastening holes, distribute loads over larger areas than other bonding methods, uniformize stress fields, and allow for thinner substrates, reducing weight. However, adhesive joints are sensitive to substrate surface treatment, cyclic loads, arbitrary load combinations, and environmental conditions, requiring monitoring throughout their lifecycle. Identifying critical damage should precede potential failure, ensuring structural integrity and human safety. Although adhesive joints have advantages over other bonding methods, there are obstacles to their application in aeronautics and other key industries. In fact, current safety regulations require reliable non-destructive testing (NDT) techniques for each bonded part, according to section 23.573(5)- (iii) of the Federal Aviation Regulations (FAR).

Some NDT methods have been explored for monitoring adhesive joints, such as ultrasonic, thermographic, radiographic, holographic, and based on electro-mechanical impedance spectroscopy. However, current NDT methods do not offer good solutions for monitoring the integrity of the bonded surface in primary structures. Structural health monitoring (SHM) utilizes NDT techniques for continuous in-situ monitoring with equipment permanently attached to the structure. SHM involves different technologies, such as instrumentation, signal conditioning, data processing, and damage detection, localization, and quantification. Recently, specific SHM applications have been developed in various areas, with some success, but reliable solutions for general use are not yet available, and applied research on adhesive joints is scarce.

A promising approach for SHM is based on Lamb waves (LW), excited/detected through piezoelectric actuators/sensors. LWs are a particular type of guided waves that propagate through materials and are sensitive to structural damage. LWs are difficult to process due to electromagnetic noise, environmental disturbances, and the complexity of their physical mechanisms, involving dispersive modes that overlap in both the time and frequency domains. Thus, proper processing of LW signals is crucial to extract information on structural integrity. Several data processing techniques have been proposed for LW-based SHM in various areas, but their applicability to bonded structures has still to be proven. Analysis with small-scale structures, simple geometries, and the existence of only one damage focus revealed the potential of LWs to detect damage in adhesive joints. However, LW data processing techniques need to be further developed to extract information on incipient damage, impossible to detect by other methods, as is the case with weak adhesion (a.k.a. kissing bond or zero volume void). This type of damage is characterized by a reduction in the Young's modulus of the adhesive, in the border zone with the substrate, of at least 20%. Currently, there are no NDT methods capable of conveniently detecting weak adhesion, which severely limits the use of adhesives in critical structures in multiple potential application fields. Thus, developing a method for continuous monitoring of adhesive joints throughout their lifespan is essential.

This thesis consists of an extended summary and six papers, detailing the progression of work developed on detecting and characterizing weak adhesion in adhesive joints using LWs and machine learning (ML) algorithms. The work ranges from understanding the problem of weak adhesion and the current limitations in detecting this type of damage, to proposing a method capable of detecting, assessing intensity, and locating weak adhesion in simple lap joints (SLJs).

The first paper reviews equipment, procedures, and NDT and SHM techniques, focusing on applications in adhesive joints. The fundamentals of LWs and their application in damage detection using various signal processing methods, such as statistical indices and ML, are discussed. Issues of modeling, simulation, and manufacturing of SLJs with different values of weak adhesion are addressed. This paper lays the groundwork for subsequent research, highlighting existing research gaps and opportunities.

The second paper describes exploratory work on synthetic LWs data generation and the use of data-driven algorithms for damage detection. It compares the performance of conventional feedforward artificial neural networks (FNNs) and convolutional artificial neural networks (CNNs) for simple damage classification in aluminum plates and proposes a methodology adaptable to various types of damage and structures.

The third paper addresses a specialized feature extraction method on time series representing LWs generated in simulated SLJs subjected to weak adhesion. Followed by feature selection using the Benjamini-Hochberg procedure, supervised ML methods such as Random Forest and Naive Bayes classifiers are employed to achieve classification metrics and isolate relevant features for damage differentiation.

The fourth paper explores different ML algorithms, trained and tested with synthetic data, namely FNN and Gated Recurrent Unit (GRU) networks, showing their performance in terms of accuracy and convergence time.

The fifth paper presents an innovative approach using ML regression and LWs to determine weak adhesion in SLJs. A numerical model of SLJs is validated with real data, and an artificial neural network-based damage detection method is developed, achieving over 95% accuracy.

The sixth paper describes a methodology for detecting and characterizing weak adhesion, using transfer learning, where an extensive synthetic database is used to train CNN-based algorithms, which are then fine-tuned with some experimental data. Tests with SLJs where weak adhesion intensity could vary from 100 MPa to 500 MPa, and damage localization could change up to 125 mm within the adhesive area, showed that the developed pipeline can not only detect weak adhesion in simulated data with over 95.3% accuracy but also identify about 100% of cases with damage in experimental data. Regarding the intensity of weak adhesion, the algorithm achieves an average loss of 45 MPa for the experimental validation dataset, with an average error of 140 MPa and best cases of only 3.6 MPa. As for damage localization, the algorithm exhibits an average loss of 8 mm in the validation synthetic dataset. Importantly, the methodology is flexible enough to deal with other weak adhesion characteristics beyond existence, intensity, and localization, without requiring major alterations.

The developed work demonstrates the potential of properly processed LWs with ML algorithms to improve the quality control of adhesive bonding using NDT and improve the safety and durability of bonded structures throughout their lifespan through SHM.

Development of a unified fatigue life prediction method for adhesive joints

Fernando Manuel Marques de Castro Sousa

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Thesis defence date: 19 June 2024

Abstract

With the numerous benefits offered, and with the increasing demand for more efficient structures, adhesive bonding, is a technology that is rapidly expanding for several engineering applications, by replacing more traditional joining techniques.

During the course of their service life, adhesively bonded structures are commonly subjected to fatigue under different loading and environmental conditions. Even though adhesive joints' fatigue behaviour has been the subject of various investigations, their failure mechanics are not entirely understood. Due to this, the development of fatigue life estimation methodologies remains a major challenge and is of paramount importance to prevent catastrophic failures and increase the level of confidence in this joining method.

Due to the aspects mentioned above, this investigation has two major goals: (i) to study the influence of the parameters that most influence the fatigue life of bonded joints, namely geometrical and material factors and environmental and loading conditions; (ii) to develop a fatigue life prediction methodology able to deal with the parameters that govern the fatigue performance of bonded joints in a efficient and integrated manner.

To achieve this, after a careful literature review, extensive experimental testing was conducted in single lap joints (SLJ) bonded by different adhesives (epoxy and methacrylate) and with different substrate materials (metal and composite) and dimensions. A clear difference on the performance of the joints bonded by the two adhesives was noted, being the methacrylate one less sensitive to load variation. For this adhesive, SLJs with dissimilar substrates were seen to have a higher fatigue strength than similar ones which was associated with the adhesive's large ductility. Experiments were also conducted at high temperature and on hygrothermally aged joints, which were found to degrade the fatigue performance of the joints. The influence of loading history was also analysed by subjecting the specimens to different block loading spectra. A loading sequence effect was observed which was attributed to a combination of load interaction effects and non-linear damage accumulation.

The variable amplitude fatigue life prediction was carried out using existing cumulative rules based on different concepts. A reasonable prediction was obtained by indirectly evaluating the loading sequence. However, a proposed cumulative model further improved the prediction accuracy of the loading sequence effects.

For constant amplitude loading, a fatigue life prediction methodology based on the S-N approach has been developed, for which a schematic overview of the procedure is shown in Figure 1. This model was based on a fatigue parameter combining the hydrostatic and deviatoric components of the strain energy density. To account for the stress concentrations exhibited by adhesive joints, a procedure based on the concepts of critical distance theory was developed. The proposed fatigue life estimation method was validated against the experimental results of several conditions including different adhesive and substrate materials, different joint geometries and environmental conditions. Overall, a good correlation between the estimated and experimental fatigue life was obtained.

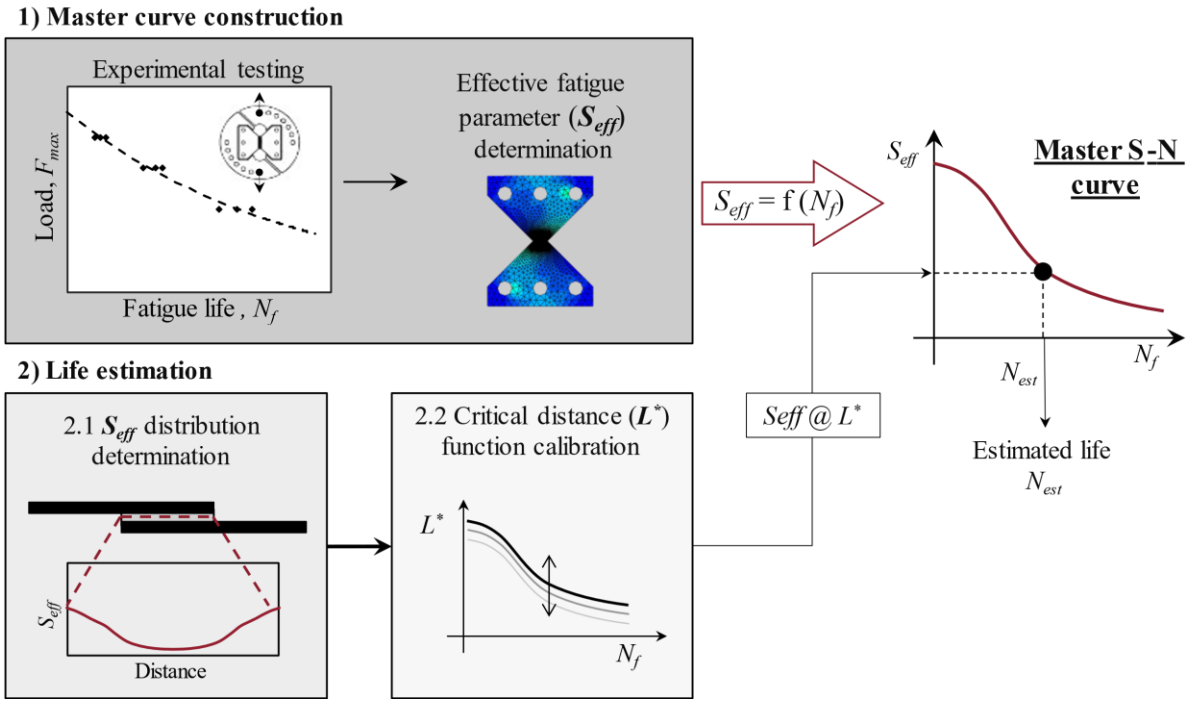

Figure 1. Proposed fatigue life prediction methodology overview.

Funding

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Analysis of the Rolling Contact Fatigue Performance of Direct Laser Deposition Repairs for Wind Turbine Gearbox Applications

Pedro Correia Romio

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Co-supervisor: Jorge H. O. Seabra, FEUP

Thesis defence date: 27 July 2024

Abstract

The wind sector continuously grew in the last decade, with a 236.3% increase in the wind turbines' installed capacity. The increase in the number of turbines brought the inherent problems associated with their maintenance, such as replacing damaged components. The wind turbine gearbox is a critical subsystem subject to different failure modes, but there is no doubt that problems associated with contact fatigue in gears (e.g., micropitting) are persistent. Traditionally, the repair is done through grinding or surface finishing. The processes eliminate surface failures by removing material from the tooth. The problem is that, eventually, it becomes impossible to repair the gear while maintaining the required geometric tolerances and performance.

To extend the useful life of wind turbine gears, a repair strategy driven by advances in Metal Additive Manufacturing, particularly Direct Laser Deposition (DLD), has come to be considered. However, a question remained: Is DLD suitable for repairing wind turbine gear teeth, ensuring the "as good as new" condition of restored gear teeth?

To answer the question, this work investigated the performance of repairs via Direct Laser Deposition in two complementary contexts: discs and gears repaired via DLD. The former characterises the zones deposited at the "Contact Level", while the latter at the "Component Level". Two materials were used for the analysis (AISI 431 and Inconel 625), and the deposition parameters were selected in the initial phases of the GEAR3D Project. On the other hand, this work carried out an extended characterisation focused on contact fatigue resistance (Rolling Contact Fatigue – RCF).

The results showed that at both levels investigated (Contact and Component), the DLD repairs did not meet the conditions for the wind turbine gear application. Either way, the results are promising and show that there was good adhesion between deposits and base material, visible improvements in the contact fatigue resistance concerning previous attempts and, most importantly, the results come from operational tests, which until then did not exist in the literature.

As a complementary activity to this work, a Thermal Plasto-Elastohydrodynamic Lubrication (TPEHL) model capable of simulating rough circular contact in different lubrication regimes was implemented, whose predictions were validated with experimental results. Among its main advantages: (1) the ability to deal with thermal and plastic effects without the need for a prior assessment of whether these are negligible (or not) and (2) the possibility to be used for materials' selection considering contact fatigue resistance.

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G. Lasch, P. Stradolini, G. S. Gehlen, L. Y. Barros, J. C. Poletto, A. Ramalho, C. M. C. G. Fernandes, P. C. Romio, C. L. Petzhold, N. F. Ferreira and P. D. Neis, Comparative tribological investigation of castor oil and its transesterified and aminolized derivatives, Tribology International, 109709, 2024. https://doi.org/10.1016/j.triboint.2024.109709

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Passive Vibration Control of Composite Structures with Viscoelastic Damping Patches

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Thesis defence date: 28 June 2024

Abstract

The ever-increasing interest towards lightweight structures has significantly reshaped the landscape of research and design of mechanical systems over recent decades. This transformative influence is particularly evident in vibration control, where the susceptibility of light structures to higher vibration amplitudes becomes pronounced, particularly when made with composite materials.

Notably, the strategic use of viscoelastic damping materials emerges as a robust and established method for effective vibration damping. This approach has found systematic applications across diverse industries, including automotive, railway, and aerospace, dating back to the early years of the second half of the previous century. The efficacy of viscoelastic damping materials in mitigating vibrations is especially crucial in these sectors, where precision and performance are paramount. As the trend towards lightweight structures continues to shape engineering, its influence extends beyond the structural components and permeates the methodologies employed for viscoelastic damping treatments. The emphasis has shifted towards the localised application of viscoelastic damping treatments, ensuring a notable damping capacity without unwarranted mass increases. This strategic placement might enhance the overall efficiency of the damping process but also align with the overarching goal of maintaining structural integrity while achieving optimal vibration control in the face of evolving engineering demands.

The present work proposes a numerical framework to investigate viscoelastic damping patches, adopting the appropriate mechanical models to build a reliable and efficient numerical tool based on the Finite Element Method to handle inhomogeneous complex composite structures, including viscoelastic materials. Based on a complete set of parametric analyses, one develops a groundwork for a comprehensive understanding of the damping mechanisms involving viscoelastic damping materials in general and damping patches in particular.

Consistently with the ever-increasing demand for ultra-efficient and lightweight structures, one proposes some guidelines for structural vibration control covering the design, analysis and application of emerging passive damping technologies for composite laminates, including interleaved damping layers and patches, extending the numerical tools developed for a comprehensive understanding of the damping mechanisms involving viscoelastic damping materials.

This work also addresses a thorough experimental campaign of testing and analysis of composite laminates with interleaved damping materials with a detailed comparison with numerical results to investigate the proposed approach of embedding viscoelastic damping patches.

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Simulation of fracture of ultra-thin ply polymer composite structures

Anatoli Mitrou

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Co-supervisor: Albertino José Castanho Arteiro, FEUP, José Antonio Reinoso Cuevas, U. Sevilla

Thesis defence date: 30 July 2024

Abstract

Objectives of improving efficiency and reducing costs in aerospace design are often translated to needs of developing new materials and their subsequent inclusion in design. This requires of course the understanding of the material behavior and the development of accurate tools to model them. Such a material is carbon fiber reinforced polymers (CFRPs) that, for a few decades already, have been of interest and are vastly used. Recently a new variant, thin-ply CFRPs, has been introduced and is acting as gamechanger. This because, early studies in the direction of understanding thin ply CFRP behavior demonstrated that, contrary to observations on standard grade (standard ply) composites, thin-ply CFRP laminates fail in a through thickness single crack, net-section type pattern, without presenting delaminations and other subcritical failure events.

Along those lines and to aid in creating more efficient modeling tools for this novel type of CFRPs this study is carried out. The idea is to apply models relying on assumptions of quasi-brittle crack like failure, relying on plate level analysis that stems from an equivalent single layer representation of the laminate. This comes as a follow up to some initial studies done in that direction. The methods under question are the phase field (PF) method and finite fracture mechanics (FFM). The effort revolves around the specific problem of notched strength, mainly open hole tension (OHT) that was selected to be studied as it is a problem very pertinent to aerospace design since structures commonly contain cutouts and holes.

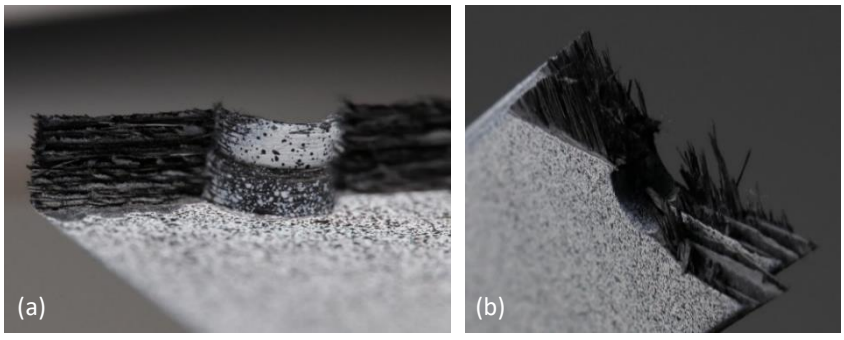

Figure 1. (a) Failure form typical of the laminates with weaker anisotropy, an example of the net-section type failure surface (the specific specimen is from the CP30 loaded on-axis), (b) Failure forms observed in the laminates with stronger anisotropy that alongside fiber failure also presented more complex failure events (the specific specimen is from the CP1575 60^o off-axis loading featuring extensive fiber pull out and some delaminations)

To achieve a basis of validation for the developed models thin-ply CFRP laminates of standard and non-standard lay-ups were subjected to on-axis and off-axis OHT loading. Off-axis OHT especially holds small representativity in the related literature and can easily provide complexity to the problem of OHT so as to challenge the developed methods. The laminates behavior was evaluated and categorized in

terms of their *level of anisotropy* defined from an elastic point of view. The laminates were categorized either as weakly anisotropic or strongly anisotropic. As expected, all laminates failed in a crack like through thickness failure form when loaded on-axis. This was also the case for the off-axis failure of the weakly anisotropic laminates. Interestingly though, contrarily, for off-axis loading, the strongly anisotropic thin-ply laminates failed more like standard grade CFRPs presenting premature failure events and subcritical damage.

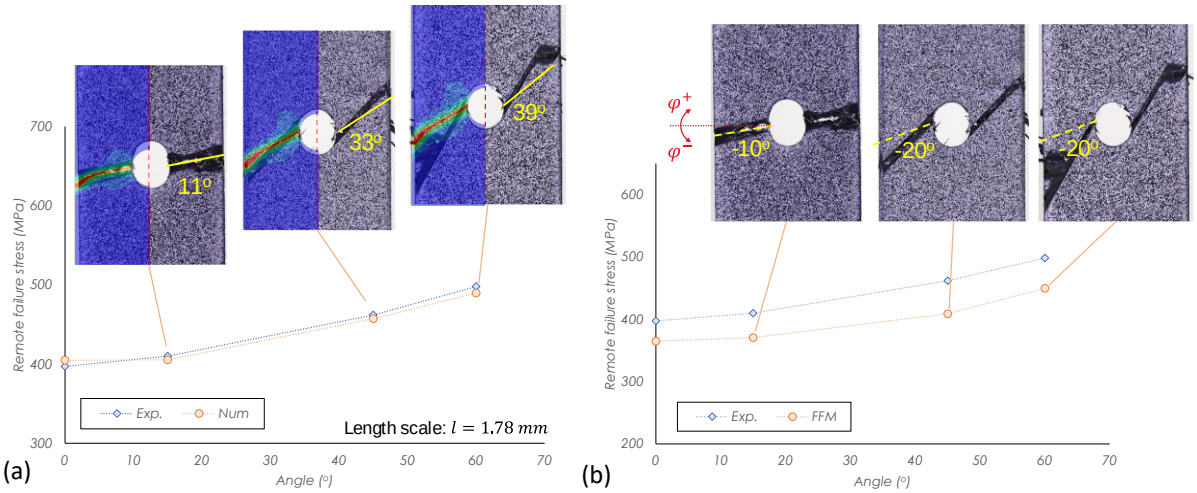

Figure 2. Strength and crack path predictions compared to the experimental evidence for the SOFT laminate, of the tested laminates in the study, via (a) PF (b) FFM, serving as an example for the overall results presented in the present thesis.

These results were then used to validate, verify and propose for this problem the use of the PF method and FFM on the basis of their ability to accurately predict the experimental results, always restricted to the weakly anisotropic laminates. It is shown that the former was rather adequate and able to produce close enough strength predictions with strengths lying under 5% of error. Additionally, crack path predictions were also very close to the experimental crack paths. The latter, FFM, did not achieve the same with errors in strength ranging around 10% and for some cases bad crack path predictions. Nonetheless, the development aids in comparing the two methods and furthermore understanding the challenges such ESL representations of CFRP laminates entail. Figure 2 (a) and (b) show for the purpose of serving as an example the predictions for one specific laminate studied for PF and FFM. These results were a novel effort to expand both FFM and PF for their application in composite laminate failure alongside expanding the knowledge on thin-ply CFRP failure and hopefully serves as the first step in answering the multiple more open questions that this work led to.

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Sample publications

Mitrou, A., Arteiro, A., Reinoso, J. and Camanho, P.P., 2024. Effect of the level of anisotropy on the macroscopic failure of notched thin-ply laminates. *Composite Structures*, *348*, p.118407. https://doi.org/10.1016/j.compstruct.2024.118407

Mitrou, A., Arteiro, A., Reinoso, J. and Camanho, P.P., 2023. Modeling fracture of multidirectional thin-ply laminates using an anisotropic phase field formulation at the macro-scale. *International Journal of Solids and Structures*, *273*, p.112221. https://doi.org/10.1016/j.ijsolstr.2023.112221

Sangaletti, S., Mitrou, A., García, I.G. and Arteiro, A., 2023. Effect of tailored fiber deposition in 3D printed composites: application of an anisotropic phase field model. *Theoretical and Applied Fracture Mechanics*, *127*, p.104030. https://doi.org/10.1016/j.tafmec.2023.104030

Health monitoring of bonded joints using Electromechanical Impedance Spectroscopy (EMIS)

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Supervisors
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Abstract

Adhesive bonding of structural components is being progressively adopted in applications, such as aircraft and automobiles, reducing weight and carbon emissions, while guaranteeing mechanical performance. In this manner, one must guarantee the integrity of structural adhesives and consider the appearance of damage foci, either during the manufacturing stage, or the operation of said structure. As per industrial standards and international legislation, a necessary step in integrity evaluation is to perform periodic Non-Destructive Tests (NDT) throughout the useful life. However, these tests are costly, time-consuming and do not guarantee complete adhesive damage detectability. Structural Health Monitoring (SHM) has emerged as an alternative, where sensors continuously monitor a structure by per- forming physical measurements. A central processing unit stores the measurements and feeds them to algorithms, which will try to tackle damage detection, characterization and estimation of severity to the structure. One such SHM method is the Electromechanical Impedance Spectroscopy (EMIS), which makes use of the coupled electromechanical coupled behaviour of Piezoelectric Wafer Active Sensors (PWAS). Therefore, by measuring the PWAS impedance spectra over a range of frequencies, one is measuring the integrity of the interrogated structure.

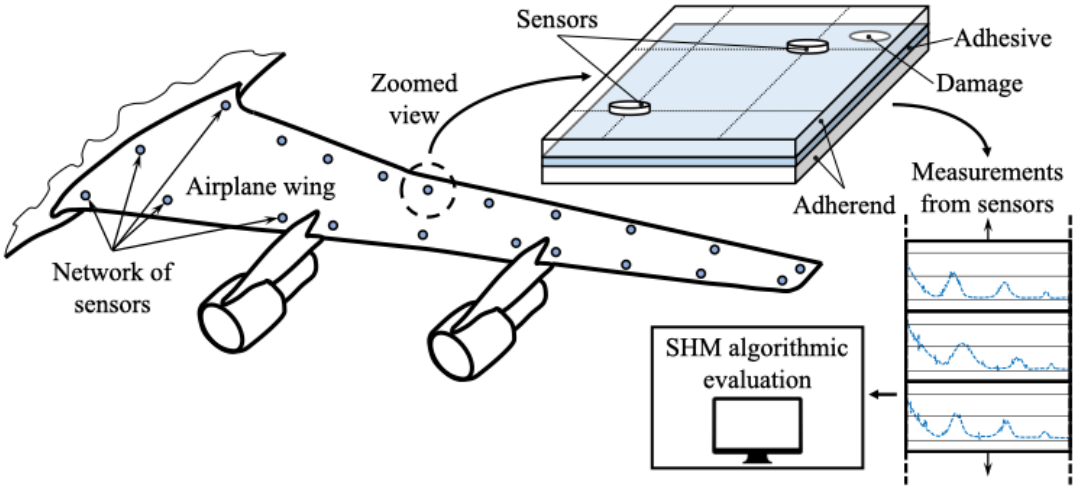

Figure 1. Schematic representation of the SHM methodology applied on an airplane wing.

Given the potential of SHM in sectors such as the automobile or aeronautic industry, the following work studied the performance of EMIS on Single Lap Joint (SLJ) specimens, where 6000 series aluminium alloy adherends, used in vehicular structures, are connected thanks to a crash-resistant modified epoxy adhesive. This adhesive is specifically formulated for aeronautic applications. Furthermore, preliminary work was also done with SLJ specimens with a silicone adhesive and a Pressure Sensitive Adhesive (PSA). These joints were instrumented with PWAS, and their electrical impedance was measured between 1 kHz and 1 MHz.

Quasi-static tensile tests and Vibrating Cantilever Beam Tests (VCBT) were performed to determine the elastic and dynamic behaviour of both modified epoxy and silicone adhesives. These tests allowed one to estimate average elastic and damping properties over the wide range of frequencies, which were relevant input on direct-steady state linear perturbation analysis numerical models that can replicate the electrical impedance measurements obtained experimentally. Furthermore, for the case of undamaged adhesive joints, the mechanical impedance was computed with stress and particle velocity results from these simulations. In this manner, the mechanical impedance of the SLJ and electrical impedance of the sensor were correlated.

With this, conventional damage metrics and newly proposed damage metrics were used to ascertain, in a numerically quantifiable manner, damage detectability from the obtained impedance spectra of instrumented modified epoxy SLJ specimens. While conventional damage metrics make use of the real component of the measured impedance, most of the proposed metrics use the active electrical impedance, which is the part of the measured impedance that is sensitive to damage, and enables the use of both real and imaginary components. Likewise, two Machine Learning (ML) approaches were followed. Firstly, Multidimensional Scalling (MDS) ML model performed a dimensionality reduction of the real component of the measured impedance, obtaining a three-dimensional *map*. A second approach made use of the *k*-Nearest Neighbours (*k*NN) ML model for classification.

Experimental and numerical results revealed that adhesive elastic and damping dynamic properties contribute to the obtained electrical impedance measurements. Furthermore, artificially created voids influence the measured impedance spectra, given the complex correlation with the mechanical impedance of the adhesive joints. However, no clear trend is observed regarding the void placement and void size, while numerical results show that the adhesive, bonding the PWAS to the SLJ, may also affect the obtained spectra.

The damage metrics results reveal that damage detection is possible, and that the active electrical impedance, which is sensitive to structural parameters, further improves damage detectability. Conversely, the MDS reduced dimensionality *maps* enable not only damage detection, but also damage differentiation between large voids, small voids in the middle of the overlap, and small voids in the corner of the overlap. The *k*NN approach, used with a defined number of extracted resistive peaks from the measurements, also enable good damage detection and classification.

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Sample publications

Tenreiro, A. F. G., Lopes, A. M. and da Silva, L. F. M. (2022), A review of structural health monitoring of bonded structures using electromechanical impedance spectroscopy. *Structural Health Monitoring*, 21(2), 228-249. doi.org/10.1177/1475921721993419.

Tenreiro, A. F. G., Lopes, A. M., da Silva, L. F. M. and Amorim, J. D. P. (2023), Effect of mechanical properties and geometric dimensions on electromechanical impedance signatures for adhesive joint integrity monitoring. *Mechanics of Advanced Materials and Structures*, 30(7), 1437–1452. doi.org/10.1080/15376494.2022.2033891.

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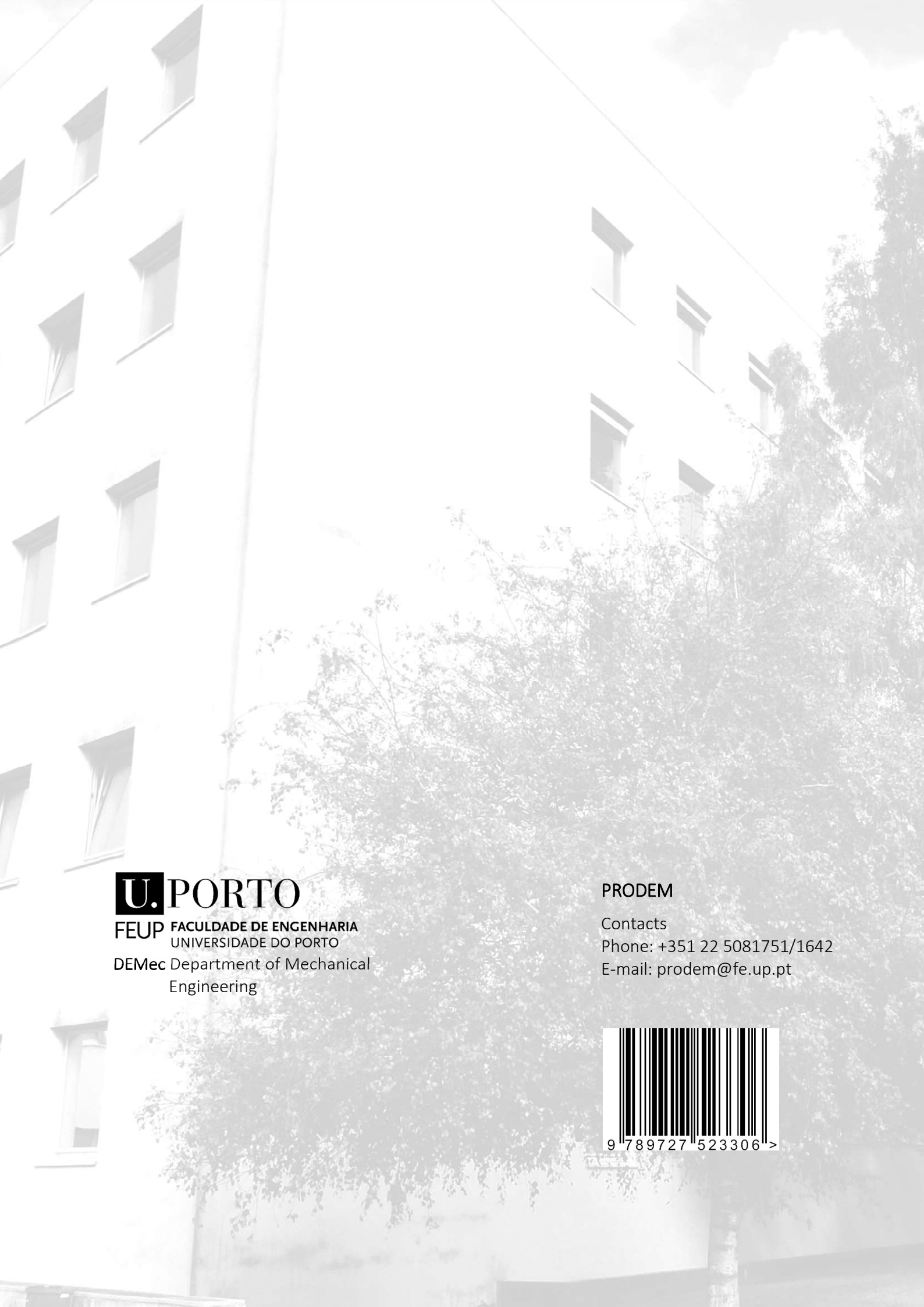

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