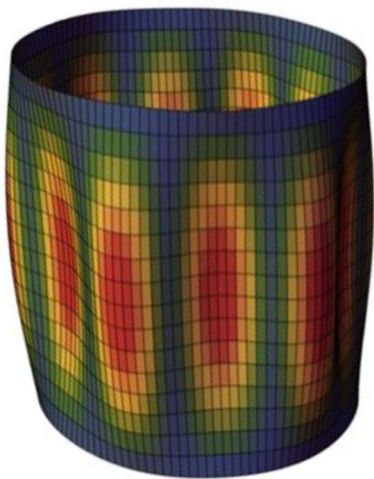


XVI Finnish Mechanics Days

30 September – 2 October 2026

Book of Abstracts



$$\frac{Et^3}{12(1-\nu^2)}\Delta^4 w + \frac{Et}{R}\frac{\partial^4 w}{\partial x^4} + Q\Delta^2\left(\frac{\partial^2 w}{\partial x^2}\right) = 0 \Rightarrow Q = \frac{1}{\sqrt{3(1-\nu^2)}}\frac{Et^2}{R}$$

PREFACE

The first Finnish Mechanics Days were held in Oulu in 1982. The event was established to bring together researchers, engineers, and educators working in mechanics and strength of materials to discuss current topics in the field. Since then, every fifth Finnish Mechanics Days has brought the Finnish mechanics community back to Oulu. This tradition continues in 2026, as the XVI Finnish Mechanics Days are held in Oulu in the same year that the city serves as a European Capital of Culture.

The fundamental task of mechanics remains unchanged: to understand, model, and predict the behaviour of physical systems. Its methods and fields of application, however, have evolved considerably. Experimental methods and computational mechanics have advanced alongside increasingly complex multiphysics models, while measurement data, machine learning, and artificial intelligence are becoming increasingly important. At the same time, new materials, technologies, and applications continue to pose new questions for mechanics research.

The programme of the XVI Finnish Mechanics Days reflects the breadth of the field. The presentations cover topics including computational and experimental mechanics, material behaviour, fatigue and fracture, fluid mechanics and coupled problems, structural engineering, measurement methods, and data-driven and machine-learning approaches. The plenary lectures are given by Professor Manfred Bischoff of the University of Stuttgart and Professor Flyura Djurabekova of the University of Helsinki.

The central purpose of the Finnish Mechanics Days, however, has not changed since the first meeting. The event provides an opportunity for the Finnish mechanics community to meet, present new research, exchange ideas, and establish new collaborations. Of particular importance is bringing together researchers from different areas of mechanics, early-career researchers and experienced experts, and those working in both fundamental research and practical applications.

These proceedings collect the contributions presented at the XVI Finnish Mechanics Days in Oulu, 30 September–2 October 2026. The abstracts have been included essentially in the form submitted by the authors. We hope that they will not only document the scientific content of the meeting but also contribute to the continuing tradition of the Finnish mechanics community that began in Oulu in 1982.

We thank all authors, speakers, session organisers and chairs, and everyone who has contributed to organising the event. We warmly welcome all participants to Oulu and to the XVI Finnish Mechanics Days.

Oulu, September 2026

Antti H. Niemi
Chair of the Organising Committee

ESIPUHE

Vuonna 1982 järjestettiin Oulussa ensimmäiset Suomen Mekaniikkapäivät. Tapahtuman lähtökohtana oli saattaa yhteen mekaniikan ja lujuusopin parissa työskenteleviä tutkijoita, suunnittelijoita ja opettajia keskustelemaan alan ajankohtaisista kysymyksistä. Sittemmin joka viidennet Mekaniikkapäivät ovat tuoneet suomalaisen mekaniikan yhteisön takaisin Ouluun. Tämä perinne jatkuu vuonna 2026, kun XVI Suomen Mekaniikkapäivät järjestetään Oulussa samana vuonna, jolloin kaupunki toimii Euroopan kulttuuripääkaupunkina.

Mekaniikan perustehtävä on säilynyt ennallaan: pyrkimys ymmärtää, mallintaa ja ennustaa fysikaalisten järjestelmien käyttäytymistä. Sen menetelmät ja sovelluskohteet ovat kuitenkin kehittyneet huomattavasti. Kokeelliset menetelmät ja laskennallinen mekaniikka ovat edenneet rinnakkain yhä laajempien monifysikaalisten mallien kanssa, ja mittausdatan, koneoppimisen ja tekoälyn merkitys kasvaa nopeasti. Samalla uudet materiaalit, teknologiat ja sovelluskohteet asettavat mekaniikan tutkimukselle uusia kysymyksiä.

XVI Suomen Mekaniikkapäivien ohjelma kuvastaa alan laajuutta. Esitelmät käsittelevät muun muassa laskennallista ja kokeellista mekaniikkaa, materiaalien käyttäytymistä, väsymistä ja murtumista, virtausmekaniikkaa ja kytkettyjä ongelmia, rakenteiden suunnittelua, mittausmenetelmiä sekä dataan ja koneoppimiseen perustuvia lähestymistapoja. Päivien plenaariesitelmät pitävät professori Manfred Bischoff Stuttgartin yliopistosta ja professori Flyura Djurabekova Helsingin yliopistosta.

Mekaniikkapäivien keskeinen tehtävä ei kuitenkaan ole muuttunut ensimmäisistä päivistä. Ne tarjoavat suomalaiselle mekaniikan yhteisölle mahdollisuuden tavata, esitellä uutta tutkimusta, vaihtaa ajatuksia ja rakentaa uutta yhteistyötä. Erityisen tärkeää on tuoda samaan keskusteluun mekaniikan eri alojen tutkijat, nuoret tutkijat ja kokeneet asiantuntijat sekä tieteen ja käytännön sovellusten parissa työskentelevät.

Tämä julkaisu kokoaa XVI Suomen Mekaniikkapäivillä Oulussa 30.9.–2.10.2026 esiteltävien töiden abstraktit. Abstraktit on sisällytetty julkaisuun pääosin kirjoittajien toimittamassa muodossa. Toivomme julkaisun paitsi dokumentoivan päivien tieteellistä sisältöä myös osaltaan jatkavan vuonna 1982 alkanutta suomalaisen mekaniikan yhteistä perinnettä.

Kiitämme kaikkia kirjoittajia, esitelmöitsijöitä, sessioiden järjestäjiä ja puheenjohtajia sekä muita tapahtuman järjestämiseen osallistuneita. Toivotamme kaikki osallistujat lämpimästi tervetulleiksi Ouluun ja XVI Suomen Mekaniikkapäiville.

Oulussa, syyskuussa 2026

Antti H. Niemi

järjestelytoimikunnan puheenjohtaja

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Recent Advances in Explicit Dynamics

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Key Words: *Structural Dynamics, Explicit Time Integration, Critical Time Step Estimation, Mass Scaling*

A key feature of explicit time integration schemes is that stability depends on a critical time step size. In this context, two innovative concepts are presented.

First, a data-based method for assessing the quality of time step estimators is introduced [3]. It can also be used to develop *time step estimators based on neural networks* that outperform state-of-the-art estimators. It is a quickly accessible and generally applicable technology that can be immediately applied in scientific and industrial contexts with minimal implementation effort.

Second, a novel framework for selective mass scaling to increase the critical time step size for shell elements is presented [1], [2]. It is based on hierarchic shell formulations, previously developed in Stuttgart, that are also intrinsically free from locking. This *intrinsically selective mass scaling* method has the potential to dramatically reduce computational effort in explicit dynamics. Benchmark computations indicate a potential speedup of factor 10 and more compared to the state-of-the-art.

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Mechanical Response of Metals Under Extreme Conditions in CERN Particle Accelerators

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Key Words: *Vacuum breakdown, high electric fields, conditioning, dislocation dynamics, multiscale modeling, particle accelerators.*

Vacuum arcing remains a major limitation for the operation of high-gradient accelerating structures, where intense electric fields can trigger surface damage and ultimately lead to electrical breakdown. Within the framework of the Compact Linear Collider (CLIC) project at CERN, extensive experimental and theoretical investigations have been conducted to elucidate the mechanisms governing vacuum arc initiation. This work presents a unified multiscale theoretical framework that integrates processes spanning atomic to macroscopic scales and explains the evolution from a pristine metal surface to the onset of a breakdown plasma. The model combines experimental observations from radio-frequency and pulsed direct-current conditioning studies with atomistic simulations of dislocation activity, field-induced surface diffusion, nanotip formation, electron field emission, thermal runaway, material evaporation, and plasma initiation [1]. The findings indicate that intrinsic material processes, particularly electric-field-driven dislocation dynamics and biased surface diffusion, play a central role in conditioning behavior and the progressive development of field-enhancing surface features that create the conditions necessary for plasma formation. The resulting framework provides a comprehensive physical picture of vacuum arc initiation and offers guidance for improving the performance and reliability of future high-gradient accelerator technologies.

We further explain the blister formation on Cu surfaces of radio-frequency quadrupole structures that are exposed to high fluences of negatively charge H ions in the proton beam sources used in Hadron Colliders at CERN [2].

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Experimental Hydrogen TDS of Steels containing Deep Traps and ML-based Prediction of Desorption Energies

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Key Words: *Thermal desorption spectroscopy, hydrogen embrittlement, martensitic steels, ferritic steels, machine learning*

Hydrogen plays a key role as a clean energy carrier in achieving global decarbonization. Its utilization is expanding across various industries, including transportation, energy storage, and even fossil-free steelmaking. Meanwhile, there is a growing need for advanced high-strength steels to reduce the weight of structures, including vehicle components. Lighter structures contribute to lower fuel consumption and reduced CO₂ emissions, which are critical for achieving net-zero goals. However, hydrogen interaction with metals, especially high-strength steels, can cause hydrogen embrittlement, a failure mechanism that weakens materials. Understanding how hydrogen diffuses and becomes trapped in metal microstructures is therefore essential. Thermal desorption spectroscopy (TDS) is a key technique for studying these interactions by identifying hydrogen trapping sites and measuring desorption behaviour. This study investigates steels containing deep hydrogen traps, particularly carbides, with emphasis on the influence of carbide coherency on hydrogen desorption energies. Additionally, a unified framework, SimuTDS, is validated, combining numerical TDS simulation with machine learning regression to analyse and predict hydrogen desorption energies in titanium carbide-containing steels. A MATLAB-based model generates TDS spectra through peak convolution and estimates desorption energies from a single heating rate experiment. Machine learning models trained on structured experimental data achieve high accuracy, with tree-based ensembles reaching R² up to 0.97. Results show that carbide type, size, and coherency strongly influence hydrogen trapping, with coherent carbides acting as shallow traps and incoherent carbides forming deep traps. The framework effectively reproduces experimental TDS spectra, accurately estimates desorption energies, and captures complex nonlinear relationships between microstructure and hydrogen trapping.

Hydrogen Uptake During Electrochemical Charging in Welded X70 Pipelines, and a Novel Fatigue Life Prediction Model

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The mitigation of hydrogen-assisted failure in steel pipelines is a key focus of many studies, particularly in the context of long-term durability and safety. Hydrogen embrittlement is observed in most metals, especially in stressed and weakened regions, where hydrogen diffusion and accumulation can significantly degrade mechanical properties. Welds are among the most critical areas, as they experience high residual stresses, microstructural inhomogeneities, and potential defects that act as preferential sites for hydrogen uptake and embrittlement. Therefore, understanding the behaviour of different regions in and around welds in hydrogen-rich environments is of great importance for improving pipeline integrity and reliability.

Due to the safety concerns associated with handling pressurized hydrogen gas, electrochemical charging is often employed as an alternative method for hydrogen exposure in laboratory studies. This technique allows controlled hydrogen introduction into the material, enabling precise assessment of hydrogen embrittlement susceptibility under various conditions. Thermal desorption spectroscopy (TDS) is a widely used analytical technique for studying hydrogen absorption, trapping sites, and distribution in metals, all of which contribute to hydrogen embrittlement. TDS enables the quantification of different hydrogen states, such as diffusible and trapped hydrogen, providing insights into hydrogen transport mechanisms within the material.

While multiple models have been developed to predict fatigue life in hydrogen, these models are often material-specific, rely on empirical factors or are too convoluted for practical use. With recent advances, we are developing a model that relies on hydrogen concentration, grain size and hydrogen diffusion. The main advantage of our model is that each variable can be acquired through simple measurements, making it applicable to welds. Furthermore, the gradient of hydrogen concentration can also be considered in simulations.

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Fatigue and material modelling of solution-strengthened nodular cast irons

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Key Words: *Thermal fatigue, Nodular cast iron, Unified viscoplastic material model, ONERA*

The fatigue, creep and mechanical behavior of solution-strengthened cast iron grade GJS-500-14, as defined in EN 1563, and SiMo grades, with focus on SiMo-40-10, as defined in EN 16124, were investigated in temperature range from room temperature to 650 °C for applications in high temperature components of marine and power plant engines [1]. The objective was to fit ONERA fatigue model [2, 3] and Chaboche style unified viscoplastic material model for these materials for use in transient thermal stress analysis, as described by Kreivi et al. [4]. Because ONERA model is relatively complex, particularly when creep and creep-fatigue interaction are considered, it was also compared with the more conventional SWT model in a case study to assess its suitability for this application.

This study was started as part of a master's thesis [5], which included a literature review of fatigue and mechanical properties of before-mentioned materials. For SiMo cast irons substantial research on mechanical and fatigue behavior and ready-made viscoplastic material models [6, 7] are available. For GJS500-14 publicly available information on mechanical behavior is more limited and very little data is available about fatigue and especially creep properties.

With publicly available data it is possible to fit viscoplastic material model for SiMo40-10 with a broad temperature range or use a ready-made model and verify its behavior against test data. Material model by Thiele et al. [6] was found to work satisfactorily as it successfully replicated tests it was verified against under most test conditions. ONERA model was fitted for this grade. Model covers conditions required by the use case. Next step in the future is verifying the model against real world components.

A preliminary fit for a viscoplastic material model for grade GJS-500-14 was made. More data is needed to verify this preliminary fit, and it is used for a future test plan. Due to lack of available test data, fitting an ONERA model for this grade was not

considered feasible at this stage for temperatures above room temperature and test plan for future tests was made.

Acknowledgement

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Fatigue resistance of cell terminal laser weld joints in high voltage traction batteries.

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Key Words: *Laser welding, High voltage connections, Aluminium, Fatigue strength*

High voltage traction battery systems are assembled by tens or even hundreds of individual battery cells. Cells are typically connected at their terminals by aluminum or copper alloy busbars to constitute the system voltage by series and parallel electrical grouping. For these connections, laser beam welding has become an established joining method due to modest heat input, high speed and spatial precision. [1,2,3]

Throughout the lifetime of the battery the busbars will be subject to electrical and temperature loads induced by charging/discharging of the battery: low-cycle loads are mainly the consequence of displacement constraints combined with cyclic strains caused temperature differences within the battery system and/or cell swelling. High cycle loads are typically caused by environmental conditions, e.g. vehicle-induced vibrations. Hence, due to the spectral nature of the weld joint load, the fatigue life reserve must be calculated stress-number (S-N) data associated with the detail category of the weld joint. [4]

The authors have performed load controlled axial fatigue testing for extraction of S-N data in the high-cycle regime. Overlap fatigue test specimens were manufactured by welding 1000-series aluminum thin sheets across the full width of slightly thicker 3000-series aluminum base [4,5]. Fatigue testing revealed two failure modes: at higher loads failure occurred through the weld by shear, and at lower loads failure occurred transverse to the bulk stress direction through the higher strength 3000-series base material [4]. Statistical evaluation was done by reduction of the S-N curve to 2.5% failure probability using log-normal probability distribution and 90% confidence interval [6,7,8,9]. Finally, results were compared against detail categories available in international publications [6,7].

Finite element analysis (FEA) of the fatigue specimen was performed using elastic-plastic material models obtained from tensile testing of the base materials. Simulated stress-strain response for tested load ranges shows local yield of the thinner 1000-series aluminum section in front of the weld line. The point of highest stress range is located at the 3000-series sheet, which matches the observed failure location. [4]

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Tailored precipitates from additive manufacturing improve hydrogen trapping in aluminum alloys for high-pressure vessels

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Key Words: *Aluminum alloys, Wire arc additive manufacturing (WAAM), Hydrogen trapping, Al₃Sc precipitates, Hydrogen embrittlement*

Abstract

Hybrid and wire arc additive manufacturing improve hydrogen trapping in aluminum alloys for high-pressure vessels by enabling control over microstructure and chemistry. In this work, as-built WAAM, thermally post-processed WAAM, and WAAM combined with in-process deformation are used to tailor precipitates and their interfaces. The formation of Al₃Sc precipitates strongly depends on the processing route. No Al₃Sc particles are observed in the as-built condition, while post-processed samples show conventional precipitates with semi-coherent interfaces. In contrast, WAAM combined with in-process deformation produces a unique elongated ellipsoidal shape with fully coherent interfaces, a morphology not previously reported. This transition is driven by excess vacancies introduced during non-equilibrium processing, which influence precipitate growth and interface structure. Coherent interfaces between Al₃Sc precipitates and the aluminum matrix act as strong trapping sites for hydrogen, while semi-coherent interfaces are much less effective. Atom probe tomography reveals that WAAM modifies the nanochemistry of nanoprecipitates (Mg₂Zn) and grain boundaries in high-strength Al–Zn–Mg–Cu alloys through repeated thermal cycles acting as an in-situ heat treatment, altering the composition and distribution of strengthening phases. Mechanical testing in humid air confirms enhanced resistance to hydrogen embrittlement without reducing strength. The engineered precipitates and their interfaces reduce hydrogen accumulation at grain boundaries and suppress hydrogen-induced intergranular fracture. This work shows that WAAM and hybrid manufacturing routes provide powerful tools to design precipitates, interfaces, and nanochemistry in aluminum alloys for high-pressure vessel applications [1].

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Stress-State-Dependent Fracture Anisotropy in LPBF Metals

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Key Words: Additive manufacturing, LPBF, anisotropy, fracture, stress triaxiality

The layer wise architecture of laser powder bed fusion (LPBF) creates directional microstructures, textures, residual stresses, and defects. Consequently, the response of an LPBF component depends on the relation between loading and build directions. Although tensile anisotropy is well documented [1], [2], its interaction with the local stress state at fracture remains insufficiently understood.

This study compares ductile 316L stainless steel with AlSi10Mg aluminium alloy. Specimens were manufactured at orientations from 0° to 90° relative to the build direction. Smooth tensile, shear, central-hole, and notched geometries covered loading conditions from shear-dominated deformation to constrained plane-strain tension. Digital image correlation quantified strain localization and evolving R-values, and scanning electron microscopy identified the fracture mechanisms.

Both alloys showed orientation-dependent plastic flow. The experimental results indicate that the evolution of plastic deformation and strain localization varies with build orientation and loading condition, highlighting the fact that microstructural features and the applied stress state influence each other in a non-simple, interdependent way in LPBF materials. More importantly, fracture anisotropy changed non-monotonically with stress state: under highly constrained loading conditions, the fracture behaviour of 316L became more similar across different build orientations, meaning the directional differences were less pronounced. In contrast, under lower stress triaxiality conditions, the influence of build orientation became stronger, leading to larger differences in how much deformation each orientation could sustain before failure. Fractography revealed ductile micro void coalescence in 316L and more cleavage-like features in AlSi10Mg.

Build orientation and stress state must therefore be treated as coupled variables. Smooth uniaxial tensile data alone are insufficient for fracture assessment and structural qualification of additively manufactured components.

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Algorithmic generation of patterns for lower and more uniform measurement uncertainty in DIC

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Key Words: *DIC, pattern, uncertainty quantification*

DIC performs optimally when it is provided with a high-contrast sensor pattern that has a narrow range of feature sizes and sufficient randomness to make each subset of the pattern unique. Featureless areas and large variations in feature size should be avoided, as they are detrimental to DIC performance. Furthermore, any subset where the pattern resembles a set of parallel lines will result in poor DIC performance locally for the displacement component parallel to those lines. A Fourier synthesis has been used previously to generate good quality black and white DIC patterns with tightly regulated frequency band and, subsequently uniform feature size [1]. This earlier version of the method relied on having a wider spatial frequency band to avoid parallel features in the pattern and computationally expensive iterative morphological operations to detect featureless areas or large features. The wide spatial frequency band results in larger than ideal variation in the feature size. Furthermore, some parallel lines remain, and fixing those manually is laborious. In this work further development of the Fourier synthesis method is presented. It uses properties of the underlying grayscale pattern as a proxy for morphological features of the pattern and replaces morphological operations by solving a linear sparse matrix system to achieve a pattern with tightly regulated feature sizes. A Lucas-Kanade based optical flow estimation [2] is used to benchmark the local displacement sensitivity of the pattern and to make localized pattern adjustments to eliminate any subsets that resemble parallel lines or cause similar issues.

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3D In-Situ Characterization of Microstructural Evolution in Metastable Austenitic Stainless Steels

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Key Words: *Three-dimensional x-ray diffraction, Dark field X-ray microscopy, local orientation, local strain, strain-induced phase transformation*

Understanding deformation mechanisms in metastable austenitic containing steel requires bridging conventional experimental mechanics with advanced three-dimensional microstructural characterization for designing new steels and translating their development into practical applications. In this work, we highlight how three-dimensional X-ray diffraction (3DXRD) methods, particularly Dark Field X-ray microscopy (DFXM) can significantly enhance the interpretation of strain-driven phenomena during tensile loading. These advanced 3D X-ray microscopy techniques offer non-destructive, in situ, and high-resolution three-dimensional characterization of microstructural evolution.

This study aims to provide a fundamental understanding of the local microstructural factors influencing strain induced austenite to martensite. While traditional experimental mechanics provides macroscopic quantities such as stress strain response, phase fraction etc., it lacks direct access to the evolving internal local microstructure that governs these responses. By integrating 3DXRD techniques and DFXM, it becomes possible to probe individual grains within bulk materials and track their 3D in-situ evolution during deformation. 3DXRD enables the identification of individual grain within the bulk and DFXM offers high-resolution imaging of intragranular features, providing unique insight of crystallographic orientation, local strain accumulation, and phase transformation in three dimensions. Such capabilities facilitate direct correlation between local orientation, local strain fields, and local transformation behavior, revealing why certain grains undergo plastic deformation while others transform to martensite. The data obtained from these advanced techniques can be directly used to improve and validate crystal plasticity and phase transformation models, thereby enhancing predictive capabilities.

Advanced synchrotron-based 3D X-ray techniques such as 3DXRD and DFXM provide 3D in-situ characterization and unique opportunities to probe the internal microstructure of metastable austenitic stainless steel in a non-destructive and spatially resolved manner. In this study, these techniques are applied to investigate the 3D microstructural evolution of EN 1.4318 (AISI 301LN) stainless steel under tensile loading. These advanced techniques provide three-dimensional mapping of crystallographic orientation, local misorientations, local phase fractions, and local strain heterogeneities of interested grain with good resolution. The presentation focuses on the use of advanced 3D X-ray microscopy techniques to investigate local deformation mechanisms and phase transformations, highlighting their ability to enable non-destructive, in situ 3D characterization of microstructural evolution, and to link local deformation mechanisms with macroscopic response.

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Advances in fatigue assessment of complex welded connections with root side failure

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Key Words: *Fatigue, Weld root, Local nominal weld stress*

This paper summarizes some of the recent developments in fatigue analysis of complex welded connections with root side fatigue failure. Recent fatigue test data have shown that local nominal weld stress approach was well suitable for predicting fatigue life for complex connections. On other hand, the commonly used effective notch stress approach and structural weld stress approach resulted in high scatter being less accurate for fatigue life prediction in such connections. Despite the local nominal weld stress analysis requiring the least modelling and computational effort, the stress value can be tedious to define from a connection including multiple parts and complex force concentrations along the weld seam. To make it easier, a new traction force approach is recently proposed using a solid 3D FE model that simplifies the connection between the weld and the base plate by merging the nodes only along selected lines at weld leg section. This modelling strategy simplifies the reading of forces along weld seam to capture the local transversal peak forces acting on the weld. As the simplified connection approximates the correct stiffness of the joint, it was further shown that the weld stiffness error correlates the error that is induced on the peak weld force value along the weld seam.

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Fatigue strength of ultra-high strength steels – the role of microstructural barriers

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Key Words: *Fatigue limit, Microstructural barriers, Ultra-high strength steels*

Schönbauer et al. [1] showcase anomalous fatigue behaviour of ultra-high strength steels. Namely, the so-called large-defect threshold is found systematically and significantly higher than the long crack threshold. In the fracture mechanical interpretation of the fatigue limit of metals [2,3], this should not be possible. The most straight-forward explanation would be that the fatigue limit is not, for this class of materials, explained by crack non-propagation but rather increased crack initiation resistance [4]. While non-propagating cracks have typically been difficult to be observed for such high strength steels, Chiba et al. [5], in their experimental campaign, convincingly demonstrate non-propagating cracks found at the fatigue limit for a similar hardness material – so the anomaly remains to be explained.

Here, we show how our recent probabilistic extension to cyclic R-curve approaches [6] can plausibly explain these findings with the hypothesis of Weakest Link of microstructural barriers describing the crack arrest of microstructurally short cracks – closely aligned with the hypothesis of K.J. Miller [7] and the work of Prof. M.D. Chapetti [8].

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Computational Mechanics Framework for Coupled Analysis of Hydrogen Transport and Fatigue in Welded and Unwelded Steels

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Abstract

Fatigue failure in stainless steels is strongly affected by both the material condition and the surrounding environment, especially when hydrogen is present. Attention is given to how welding alters the microstructure, introduces residual stresses, and creates geometric discontinuities, and how these factors influence fatigue life as well as crack initiation and growth.

Hydrogen interaction with stainless steel is known to cause degradation mechanisms such as hydrogen embrittlement, which can promote crack initiation and growth under cyclic loading. In welded specimens, the presence of heat-affected zones (HAZ), variations in grain structure, and residual stresses further enhance the tendency for fatigue damage. Comparative experiments are conducted to evaluate the fatigue life, crack growth rates, and failure modes of specimens under different environmental and material conditions.

In this study, real-time diffusion and trapping of hydrogen are simulated simultaneously with fatigue loading in the welded region. This phenomenon is described with the help of two user subroutines (UMAT and UMATHT) developed in ABAQUS for finite element analysis. The developed subroutines include accumulated plastic strain and the gradient of hydrostatic stress, which drives hydrogen diffusion and trapping. The results of this study will demonstrate the fatigue crack growth rate and its influence in welded specimens compared to unwelded specimens. In addition, the study will investigate hydrogen transport mechanisms, including diffusion and trapping behavior, during cyclic fatigue loading. The interaction between fatigue loading and hydrogen transport will be analyzed to understand their combined effect on crack propagation and material degradation in welded structures.

These findings contribute to a better understanding of hydrogen-assisted fatigue mechanisms in stainless steels and provide valuable insights for the design and safe operation of structural components in hydrogen-based applications.

Keyword: Hydrogen Embrittlement, Fatigue, Finite element analysis, UMAT, UMATHT, Crack initiation and growth, Trapping, Diffusion.

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Comparative visualisation of results obtained for the same images by different DIC implementations

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Key Words: *DIC, stereo DIC challenge, stereo calibration, visualization*

Having been involved in the stereo DIC challenges [1,2] organised by the International Digital Image Correlation Society, as the group that collates and analyses the results from all the participants, we make some observations about the process by which we arrive at comparable data sets:

1. It is non-trivial to get full-field data into a common format and coordinate system so that the data can be directly compared. This is especially difficult when there is no ground truth to which all the data can be compared fairly.
2. Data is often resubmitted a few times, to resolve discrepancies in the initial submissions due to varying interpretations of the instructions or errors in the code.
3. It is challenging to clearly visualize what is interesting in the comparisons, even more so for exploration than for presentation. This is especially challenging because it is not always the differences that are most interesting. It is important to highlight when the results are in good agreement! The visualizations most useful for exploration —by people who have seen similar visualizations before and are interested in details— are different from the visualizations most useful for presenting the highlights of the results to people new to the results.
4. Automating much of the analysis and visualization with modular scripts can help a lot. There are "sweet spots" for scripts that execute quickly enough to use interactively, and for "fire and forget" scripts that will dump a full set of graphics in a few hours.

While the iDICs challenges demonstrate that the results of various DIC implementations are in excellent agreement, the community does not yet understand some aspects —e.g., spatial resolution— well enough to directly compare those between codes.

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Facile and inexpensive microfabrication methods to apply small-scale patterns for DIC

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Key Words: *DIC, Microcontact printing, Pattern applications, Fluorescent pattern*

Major limitation of using optimized patterns for DIC is the applications of these prefabricated patterns in the small 3-5 pixels per feature length scale. For typical tensile specimens and smaller specimens, application accuracy in the range of few to tens of micrometers is required. To use the full potential of DIC equipment, reliable and inexpensive pattern application methods are needed for prefabricated patterns. Previously a contact photolithography has been used to oxidise a small scale pattern on copper specimens [1]. However, contact photolithography is problematic for specimens that have small fluctuations in the flatness, and require multiple steps, which can go wrong. Microcontact printing is simple and relatively inexpensive method used for printing small features with sub-micrometer accuracy. A form of microcontact printing, channel stamping, using UV-transparent PDMS stamps and photopolymer can be used to apply DIC patterns on variety of surfaces [2]. Furthermore, fluorescent dye can be added to the photopolymer. Fluorescence is useful for many DIC applications due to the high contrast it provides with the ability to get rid of any specular reflections with a simple application of filters in front of the cameras. The method works by filling gaps of PDMS stamp with a photopolymer and placing it on the surface to be patterned. UV light is then applied through the stamp to cure the photopolymer on the surface. The stamp is then removed leaving only the photopolymer features on the specimen surface.

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An Inverse Modeling Framework for Identification of Taylor–Quinney Coefficient and Latent Heat in Metastable Austenitic Steels

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Key Words: *Strain-induced phase transformation, Adiabatic heating, Inverse method*

Steels containing metastable austenite (e.g., Stainless Steels, TRIP, Q&P and medium-Mn steels) have attracted significant attention due to their superior mechanical performance. These properties are primarily attributed to the transformation-induced plasticity (TRIP) effect, where the softer retained austenite transforms into hard and strong martensite during plastic deformation, increasing both strength and ductility at the same time. During this coupled plastic deformation and phase transformation, the heat balance in the material is governed by three thermodynamic processes: heat conduction, plastic work converted to heat, and the latent heat released by the phase transformation. The Taylor–Quinney coefficient (TQC) describes the fraction of the plastic work which is converted to heat while the remaining part of the plastic work is stored in the microstructure as dislocations and other defects. In contrast, the latent heat of martensite formation describes the amount of heat that is released by the exothermic phase transformation. However, it is very difficult to distinguish between the two heat sources experimentally, and therefore only an apparent TQC combining both heat sources has been determined so far. In this study, an inverse parameter identification framework is developed to determine both the TQC and the latent heat simultaneously based on multiphysical experimental data. The approach is applied to multiphase steels DH800 and TRIP700 at a strain rate of 1 s^{-1} , where adiabatic conditions allow neglecting heat diffusion. The results indicate that the TQC varies with strain and temperature, while for each steel, the latent heat is treated as a single effective scalar parameter within the proposed framework. These findings show that the TQC cannot be assumed constant during deformation and highlight the non-uniform partitioning of plastic work into heat and microstructural transformations. The proposed framework is applicable to both stable and unstable steels, enabling consistent comparison of material behavior independent of the identification method.

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Weld joint fatigue analysis with a parametrized residual stresses and comparison to conventional methods

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Abstract The welding is a cost efficient method in manufacturing components such as frames, supports and piping, which are common structures in engines [1]. However, the welds affects on fatigue durability and behavior of the structures. The welding process results in discontinuities in geometry, imperfections and uneven stress equilibrium; i.e. residual stresses, which have effect on component performance. [2, 3, 4]

The welding joint lifetime analysis relies a preparation in the FE model for fatigue assessment: the notch stress & strain method needs the modeled notch, and the hot-spot method needs in practice a dividing line in certain distances of the weld joint. A sufficient element mesh in the notch stress method easily leads to unreasonably big model. The model size can be reduced if the studied weld can be pre-selected, but with new designs and with a dynamic loadings the highest loaded welds cannot be known in advance. [5, 6]

The residual stresses from the welding process affects in the stress equilibrium and material behaviour. The welding results in a local yield strength limit exceeding and a residual stress state in magnitude of the initial yield strength [7]: these have a deteriorating effect on the fatigue strength. The simulated residual stress field can be included in the FEA model to have an effective impact on fatigue with base material fatigue model. [8, 9]. The welding simulation is challenging and computationally expensive and therefore hard to implement in normal simulation workflow. This study is focused on using the parametrized welding residual stresses from welding simulation in usage of a weld fatigue analysis.

The implemented residual stress effect on the base material fatigue was accessed with Smith-Watson-Topper damage model. The fatigue results were compared to results of conventional methods with the hot-spot, notch stress and the 4R method. In the 4R method the material cyclic behavior and residual stress assumptions are taken into account [10]. The results of the previous studies [5, 4] are produced with a similar principle, therefore they form a suitable ground for the comparison.

Key words: Weld fatigue, Residual stress, FEM

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On the viscous regularization of a tensorial damage model

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Key Words: *Continuum Damage Model, Strain Softening, Strain Localization, Viscous Regularization*

Abstract Kachanov presented in 1958 [1] a formulation to model continuous degradation of a material. Since then the continuum damage mechanics has developed into an important and active field of continuum mechanics, see e.g. [2, 3]. Continuing degradation of elastic properties will eventually lead to strain softening behaviour, which results to ill-posedness of the underlying partial differential equation system. In numerical solution the ill-posedness caused by strain softening produces severe mesh size dependency. Several remedies have been proposed to alleviate or remove this deficiency: non-local integral constitutive models, adding spatial gradients, rate-dependency, etc. In this presentation viscous regularization applied to the tensorial continuum damage model [4] is applied. Both consistency visco-damage [5] and Perzyna type overstress [6] models are implemented and compared. Research on gradient regularization of elastic damaging models has mostly concentrated on scalar damage approach, and only few papers have been published where tensorial damage models are considered [7]. Some comments on gradient regularization will be given.

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Material sink approach for modelling failure in brittle materials

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Key Words: *Material failure, Material sink, Brittle materials, Finite element method*

A recent method to model material failure proposes that crack can be viewed as a material sink [1]. The basic idea of this approach is the physical observation that broken bonds in fracture are diffused on a finite band width, called internal length scale, rather than confined to two neighboring atomic layers. In the fracture process zone, multiple micro-cracks lead to localized loss of mass, implying that the conservation of mass should be replaced by the mass balance presenting the mass density as the damage variable that approaches zero in the cracked areas [2]. In other words, the mass density itself becomes a damage variable. This means that, in contrast to other approaches, the fracturing material loses inertia (in addition to stiffness) in the material sink approach.

The method has been successfully implemented in Abaqus software for numerical analyses of mode I fracture in soft materials [2]. In the present study, we give an alternative formulation of the theory similar to the phase field approach for fracture. For quasi-static analyses, we implement the model in Abaqus as a user element subroutine (UEL). Moreover, we also implement the material sink theory in Matlab for explicit dynamic analyses. We demonstrate the method with several numerical examples.

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Fatigue crack initiation of nodular cast iron under pressurized hydrogen environment

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Key Words: *Fatigue Strength, Hydrogen, Crack Initiation, Bayesian Inference*

The fatigue strength of machine components may require re-evaluation in the presence of emerging green fuel environments, such as hydrogen. Hydrogen is known to degrade the mechanical properties of metallic materials [1], and its influence on fatigue strength remains an active area of research. In particular, elevated stress ratios R have shown potential hydrogen-related effects on fatigue behaviour [2].

This study focuses on the crack initiation phase in nodular cast iron, recognized as a critical stage in fatigue life of material [3]. A probabilistic framework based on Bayesian inference is employed to analyse the experimental results, enabling the incorporation of uncertainty in the evaluation.

Fatigue experiments were conducted both in air and in a hydrogen environment at 0.7 MPa, allowing direct comparison between the two differing environments. Artificial defects were introduced into the specimens to enable controlled crack initiation at predefined locations.

The results are influenced by the multiphase microstructure of nodular cast iron, where graphite nodules act as preferential sites for crack initiation and reduce the initiation threshold. The influence of these microstructural features is investigated through a controlled test series with introduced secondary imperfections. The effect of hydrogen on the crack initiation limit is evaluated using probabilistic analysis, providing insight into whether the initiation behaviour observed in air and hydrogen follows the same underlying distribution.

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Impact of Water Contamination from Green Fuels on Cavitation Behavior of Marine Engine Lubricant

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Key Words: *Cavitation, Water contamination, Journal bearings, Marine lubricants*

The increasing use of green fuels in internal combustion engines, such as hydrogen, ammonia, and methane, introduces new lubricant contamination pathways, particularly water ingress from hydrogen combustion. This contamination may alter cavitation behavior in lubricated journal bearings and promote a shift from relatively benign gaseous cavitation to more aggressive vapor cavitation, increasing the risk of erosion and material degradation.

This study experimentally investigates the cavitation tendency of a representative marine engine lubricant under controlled water contamination. Shell Gadinia S3 40 oil is tested in its pure state and with systematically varied water content. Cavitation is evaluated using an ASTM G32 ultrasonic vibratory cavitation-erosion apparatus with stationary specimens, enabling isolation of fluid-driven cavitation effects.

Before cavitation testing, the contaminated oils are characterized by water-content measurement and basic physicochemical property analysis. After testing, cavitation damage is evaluated using mass loss, optical microscopy, SEM, and surface profilometry, complemented by post-test oil analyses including water content re-check, viscosity change, and wear particle/debris assessment.

The results provide comparative insight into cavitation aggressiveness as a function of water contamination and support lubricant formulation, monitoring and contamination management strategies for sustainable ICE operation.

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Bayesian approach to inclusion sizing in phased array ultrasound – implications for fatigue design

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Keywords: *Nondestructive evaluation, Bayesian methods, Defect characterization*

Reliable prediction of fatigue strength necessitates accurate estimation of defect size [1]. Furthermore, the need to limit material waste and consequently reduce excessive conservatism while still ensuring the safety and robustness of machine components defines a need for probabilistic defect size estimation and uncertainty quantification.

Advances in ultrasonic nondestructive testing and phased array techniques have improved detection and enabled increasingly representative imaging of material defects [3]. However, the comparative, amplitude-based defect sizing methods currently in use provide only point estimates and tend to underestimate the defect size [2]. To address these deficiencies, this work considers a probabilistic and physically founded defect sizing approach combining approximate Bayesian computation and an analytical, approximate model for phased array ultrasound.

The Bayesian defect sizing method is applied to phased array ultrasound data to infer the square root area of an inclusion. The resulting size distribution is then applied to fatigue limit prediction and further compared to a size estimate obtained through conventional defect sizing. The Bayesian approach is shown to improve upon the limitations of the conventional sizing methods. The findings emphasize the importance of uncertainty quantification and probabilistic approaches in both nondestructive testing and fatigue strength prediction.

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Design of test setup for experimental evaluation of fretting-induced damage in high-pressure hydrogen environment

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Key Words: *Fretting-induced damage, High pressure hydrogen, Test setup design*

In nominally stationary machine contacts, small amplitude relative motion, known as fretting, can occur, for example, due to vibration. Fretting can promote the nucleation of fatigue cracks, which is called fretting fatigue [1]. It can reduce the operating life of machine components, such as engine parts. Modern engines can use green fuels, such as hydrogen, but its effect on fretting damage behavior is not well understood.

In this study, the aim is to design and validate a fretting test setup for a high-pressure hydrogen environment. A servohydraulic fatigue testing system is equipped with an autoclave capable of withstanding gas pressure of hundreds of bars such as hydrogen. The small internal dimensions of the autoclave limit the size of the setup. A bolted-joint-type fretting test setup is designed to fit into the autoclave and emulate practical contacts. The setup is simulated using FEA to determine contact conditions such as stresses and slip amplitudes and then validated under air atmosphere with varying loads and in-situ measurements prior to high pressure hydrogen testing.

In the future, fretting experiments will first be carried out in high-pressure nitrogen as a reference condition, followed by tests in a high-pressure hydrogen environment. Results are utilized to understand the effect of hydrogen on fretting behaviour and to support design choices with the aim of extending the operating life of machine elements exposed to hydrogen.

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Integrating Multiphysics Data to Characterize Metastable Austenitic Stainless Steels

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Key Words: *TRIP phenomenon, synchrotron X-Ray, Phase volume fractions, optical and infrared imaging*

Metastable austenitic stainless steels demonstrate excellent strength and ductility because of transformation-induced plasticity (TRIP) effect. This phenomenon happens when soft austenite gradually transforms into hard α' -martensite. However, the phase transformation is a very complex phenomenon and is highly sensitive to the local thermomechanical state of the material such as strain rate, temperature (adiabatic heating), stress/strain state, and the microstructural response. Due to this complexity, reliable characterization of metastable steels requires sophisticated measurement techniques that allow simultaneous measurement of stress, strain, temperature, phase fractions, dislocation density, texture, lattice strains, as well as stress and strain load partition among phases.

In this work, we show how complex multiphysics data from a single test can be used to characterize the deformation and transformation behavior of metastable steels. Our new multiphysical experiment uses the high-energy synchrotron X-Ray combined with optical and infrared imaging of the deforming specimen. Mechanical tests are performed under different loading paths such as uniaxial tension, simple shear, and plane strain tension, and at different strain rates of 10^{-3} s^{-1} and 1 s^{-1} .

The results show that the α' -martensite transformation rate is significantly dependent on strain rate and stress/strain states. For example, at the strain rate of 10^{-3} s^{-1} , the transformation rate was higher under plane strain state compared to that in other stress states. Similarly, at uniaxial and plane strain states, the transformation was slower at the higher strain rate due to adiabatic heating that occurred at this strain rate. However, the transformation kinetics at simple shear were totally different from those of other stress states because lower number of nucleation points were formed in the microstructure.

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Simulation and multi-objective optimisation for multifunctional fibre-enriched composites

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Key Words: *Fibre-enriched composite, Uncertainty, Multifunction, Homogenisation, Surrogate model, AI-assisted design*

Fibre-enriched composites have attracted increasing attention due to their lightweight characteristics, cost-effectiveness, and multifunctional potential^[1]. However, manufacturing-induced uncertainties introduce considerable variability in their performance^[2], posing significant challenges for reliable multifunctional design. To address this issue, this study presents an integrated computational workflow that combines stochastic geometric and material modelling, homogenisation, surrogate modelling, and multi-objective optimisation. The effects of key geometric and material parameters on the mechanical, thermal, and acoustic properties are systematically investigated. High-fidelity simulation data are then used to construct surrogate models, enabling rapid property prediction and inverse design. Finally, the surrogate models are integrated with a multi-objective optimisation framework^[3] to efficiently identify Pareto-optimal designs that balance multiple performance objectives.

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Influence of Imperfections and Residual Stress on Fatigue Assessment of 316L Stainless Steels Manufactured by Laser Powder Bed Fusion

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Key Words: *Laser powder bed fusion, SS316L, Fatigue-life prediction, Residual Stress, Imperfection*

Laser powder bed fusion (LPBF) is an additive manufacturing process that uses a laser to fuse powder layers, enabling the production of complex, high-precision parts. 316L stainless steel (SS316L), also produced via LPBF, is considerably valued in industries such as aerospace and biomedical for its ability to achieve intricate geometries and fine properties. However, the fatigue behavior of LPBF-built SS316L parts is influenced by local microstructure, defects, residual stresses, surface roughness, and porosity, all of which can affect early crack initiation.

Previous research on austenitic stainless steels [1] and additively manufactured aluminium alloys [2] indicates that fatigue sensitivity is linked to defect size, morphology, and distribution, with certain defect populations enhancing fatigue resistance. To better understand these relationships in LPBF-built SS316L [3], this study employed X-ray microcomputed tomography (μ -CT) and Electron Backscatter Diffraction (EBSD) to map defects and microstructures. These analyses highlighted the role of imperfections, identified the microstructural features and defects most associated with fatigue crack initiation. The main goal of the study is to develop a practical method and model for predicting the fatigue life of LPBF-built SS316L by correlating material features with mechanical performance. The results help lay the groundwork for standardizing the qualification of LPBF-built SS316L parts for demanding applications.

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Probabilistic modelling of the mechanical properties of glued laminated timber beams

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Keywords: *Glued laminated timber beams, Finger joints, Probabilistic modelling, Experimental validation*

Glued laminated timber (GLT) beams are a type of engineered wood product. GLT beams are widely used in structural applications because of their versatility, high strength-to-weight ratio, and ability to mitigate climate change by reducing the construction industry's carbon footprint. The GLT beams are fabricated by finger-jointing graded timber boards and gluing them together [1].

The mechanical properties of GLT beams depend significantly on the mechanical, morphological, and geometrical properties of their constituent timber boards and finger joints (FJs) [2]. The properties of timber boards and FJs vary considerably due to natural variation in timber and production quality. This results in variation in the mechanical properties of GLT beams, making it less competitive than other common construction materials (steel and concrete). Thus, it is of great importance to develop and validate a model to predict the mechanical properties of GLT beams, thereby enabling more efficient use of the material and the exploitation of its full potential.

A probabilistic numerical model for predicting the mechanical properties of GLT beams is developed [3] and validated against full-scale experimental investigations (5-6 m beams) [4]. The model includes local material variation of timber boards and FJs in a probabilistic scheme. The results demonstrate reasonable accuracy in predicting bending strength ($R^2=0.60$) and high accuracy for predicting bending stiffness ($R^2=0.97$). The model can be used to optimize the mechanical properties of GLT beams, leading to more efficient use of materials and making the beam more competitive in the construction industry, thereby contributing to sustainable development [5].

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Reconstructing Structural Dynamics from Sparse Strain Gauge Measurements using SLIDE Networks

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Keywords: Robot manipulators, Structural dynamics, Reduced-order models (ROMs), Flexible multibody system dynamics, SLIDE Networks, Machine Learning (ML).

The precision and stability of flexible structures in heavy machines—such as robotic manipulators, cranes, and excavator and telescopic booms—are affected by their highly nonlinear structural dynamics (i.e., stress, strain and deflection). In such machines, conventional strain gauges can interpret structural dynamics at specific locations. However, these sensors offer several disadvantages, such as high cost, limited measuring points, insufficient reliability and poor real-time capability. Motivated by these challenges, the Physics-Inspired network SLIDE (SLiding-window Initially Truncated Dynamic-response Estimator) estimates structural dynamics efficiently and accurately [1]. However, it still requires various sensors to approximate structural dynamics at all nodes in a finite element-discretized body. To this end, this work reports the reconstruction of structural dynamics at an arbitrary node on a hydraulically actuated flexible boom from the sparse strain gauge measurements using SLIDE networks. Training data is generated from the system dynamic simulations from random initial configurations. For each configuration, the strain data are mapped onto the respective modal coefficients using an appropriate number of modes and a modal basis from linearly projected ROMs. The estimated mode coefficients reconstruct stress, strain and local deflection at arbitrary node on the boom. These findings provide a basis for designing ML-based controllers and real-time fatigue estimation.

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Numerical Reconstruction of Vibration Responses in Electric Motor Structures

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Key Words: *Electric motor; Electromagnetic vibration; Finite element method; Inverse dynamics identification; Virtual sensing*

A limited number of measurement points can prevent a detailed assessment of vibration propagation throughout an electric motor. Increasing the number of physical sensors is not always feasible, particularly when the locations of interest are inaccessible or unsuitable for sensor installation. To obtain vibration information beyond the available measurement points, this study develops a virtual sensing approach based on finite element (FE) modeling and inverse dynamics identification. Experimental vibration responses from selected locations are used together with the FE model to establish a numerical representation of the measured dynamic behavior. The identified dynamic state is subsequently used to predict vibration responses at other locations without requiring additional physical sensors. In this manner, the proposed approach extends the spatial coverage of experimental vibration measurements and enables the response of inaccessible locations to be evaluated. The method offers a practical framework for combining experimental measurements and numerical modeling to improve vibration assessment of electric motors under limited sensor availability.

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CFD-based sensitivity analysis of beer fermentation in refrigerated cellars: impact of the tank aspect ratio on thermal performance

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Key Words: *Brewing, Fermentation tanks, Computational fluid dynamics, Temperature distribution,*

Fermentation is one of the main steps in the beer brewing, during which the fermentable sugars in the wort are converted to ethanol, CO₂, and other compounds by yeasts through exothermic reactions, with continuous generation of heat and, consequently, increase in temperature. Temperature is a critical parameter, strongly influencing the process yield and quality of the product, as it affects yeast growth and survival, the kinetics of sugar conversion, and the formation of desired and undesired products. In this study, Computational Fluid Dynamics (CFD) was used to generate a space-dependent model of a fermentation tank, initially based on the specifics given in [1], accounting for the flow generated inside the domain due to temperature and density differences. Fermentation reaction kinetics were also included in the simulation [2]. A simulation campaign was run to compare tank configurations with the same inner volume and different aspect ratios, installed in a refrigerated cellar maintained at a constant temperature. The results of this sensitivity analysis were used to derive KPIs related to (i) maximum temperature in the domain, (ii) temperature uniformity, (iii) spatial temperature distribution, (iv) heat released into the environment and (v) fermentation dynamics

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A User Interface for Simulation-Based Data Extraction and Neural-Network Training

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Key Words: Data extraction, Flexible multibody simulation, Mevea, Neural networks, User interface

Neural networks (NNs) can be used to estimate selected states of mechanical systems, but their practical use requires representative data and an organised process for data extraction, training, evaluation, and deployment. This contribution presents a user interface (UI) and workflow demonstrated on a simple hydraulically actuated, real-time-capable flexible multibody simulation model implemented in Mevea. The interface shows how the Mevea model can be configured to output data required for training a SLIDE neural network, where SLIDE refers to a neural-network-based approach for estimating selected flexible-body response quantities [1]. The UI supports configuration of simulation scenarios, checking of selected input and output signals, and organisation of generated datasets. The tool also includes settings for NN training, evaluation of trained models, comparison of different trained NN models, and integration of a selected trained model into the simulation model for testing purposes.

The demonstrated interface helps organise simulation data, trained NN models, and their comparison in one process, with the aim of reducing manual work and speeding up NN training and deployment. Future work should focus on making the interface more general, so that it can be adapted to different Mevea-based simulation models.

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Fatigue life prediction of cast steels

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Key Words: *High cycle fatigue, cast steel, stress intensity factor, defects, shrinkage porosity*

The fatigue life of a cast component depends on the size of the component, the microstructure of the material and especially the defects such as shrinkage porosity. The number of defects in a component is closely related to the physical size of the component (size effect) especially in cast steels because the size of the component affects the cooling time during casting and thus the resulting microstructure and defects. This can become a problem when fatigue life of a large component is estimated based on small laboratory sized specimens.

Murakami's equation for stress intensity factor (SIF) assumes that defects act as cracks and this has been proven to work for small and symmetrical defects like inclusions. However, shrinkage porosity usually has very arbitrary shape and the size of a single defect can be large compared to the stressed volume. Because Murakami's equation is very efficient, its applicability is studied further for large and arbitrary defects.

The rotating beam fatigue machine (RBFM) at Tampere University allows testing of larger samples in four point bending configuration. Several series of specimens are studied with this device to study the effects of surface finish and defects on the high cycle fatigue life of large cast samples. Fracture surfaces are investigated with microscopy to identify the source of fatigue cracks. The SIFs of selected defects are investigated with finite element method (FEM) analysis in Abaqus software by modeling the shrinkage porosity as an elliptical crack and calculating the SIF using the software's built-in calculation function. In this presentation we will compare SIF values of large, arbitrary shaped shrinkage porosity calculated with FEM, analytical solution and Murakami's solution and explore the effects of the shape of the selected area on SIF.

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Fracture Behaviour of Saline Ice: DIC-Measured Crack Growth and J-Integral Analysis

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Key Words: *Saline Ice, fracture toughness, DIC, J integral*

Displacement-controlled Mode I in-situ fracture experiments were conducted on laboratory-grown columnar saline ice. Edge-cracked rectangular plates with dimensions $1.5 \text{ m} \times 0.75 \text{ m} \times 0.29 \text{ m}$ were used. Digital Image Correlation (DIC) was employed to capture full-field displacement contours and to monitor crack propagation. Values for fracture toughness and J-integral were calculated for the initiation of crack growth. The J-integral was calculated by using both an analytical expression and a numerical method. The numerical (Finite Element) method employed DIC displacement fields as full-field boundary conditions with a viscoelastic material model. The analytical and experimental-numerical models gave similar results demonstrating the validity of the combined experimental–numerical approach.

Consideration of global and local weld geometry in fatigue assessment of high-strength steel joints

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Key Words: *Fatigue, Local approaches, TCD, Welded joints, High-strength steel*

In joining engineering steel assemblies, manual welding is still principally utilized, resulting in varying local weld geometry and global joint imperfections. These may be additionally governed by weld start and stop positions at fatigue-critical locations in addition to other imperfections such as gusset offsets and angular misalignment. As fatigue strength is highly influenced by both local weld geometry [1] and secondary stresses, it is essential that welded details are accurately assessed incorporating these effects in the analyses. The aim of this study is to investigate how 3D laser and profilometer scan data can be incorporated into finite element (FE) models used to obtain the fatigue notch factors for evaluating experimentally fatigue-tested specimens. The geometry modeling approach applies non-uniform rational basis splines [2] in reconstructing a solid geometry from point clouds. For the computation of effective stresses from the numerical FE models, the critical distance approach [3] is applied. Manually flux-cored arc-welded high-strength steel joints are selected for the assessment including longitudinal stiffener joints with start and stop locations at the gusset end. The results show clear differences between the idealized and real weld geometry-based fatigue notch factors leading to a decrease in scattering of the fatigue test data. Furthermore, the framework was found especially suitable for irregular, complex weld shapes providing feasibility in fatigue assessment.

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Effect of oxide-induced crack closure on crack growth resistance and crack front geometry

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Keywords: *Fracture mechanics, Crack growth resistance, Oxidation, Near-threshold*

Fatigue crack fronts in engineering components evolve toward shapes governed by the balance between local crack driving force and crack growth resistance, providing valuable yet largely underutilized information on the mechanisms governing fatigue crack growth. While conventional approaches predict crack front geometry by assuming homogenization of the nominal stress intensity factor [1, 2], they do not account for spatially varying crack closure mechanisms. This work presents a framework that couples crack front geometry with the generally inhomogeneous, nominal crack driving force, enabling backwards inference of local crack growth resistance from experimentally observed fracture surfaces under the assumption of a uniform effective crack driving force.

The approach is demonstrated using fatigue threshold experiments on ferritic nodular cast iron conducted in laboratory air and an oxygen-free environment. The results show that oxide-induced crack closure substantially redistributes crack growth resistance, producing convex crack fronts with increased closure near the specimen midplane, whereas suppression of oxidation results in conventional concave crack fronts. These findings demonstrate that crack front geometry provides valuable information on the spatial distribution of crack closure, offering new opportunities for physics-based fatigue prediction and more realistic three-dimensional assessment of fatigue crack growth.

Acknowledgements

The authors would like to acknowledge the financial support of Business Finland in the form of the research project Fadefuel 7818/31/2024.

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OPTIMIZATION OF DIMPLE DIMENSIONS AND SHAPES FOR JOURNAL BEARING USING CFD SIMULATION

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Key Words: *Tribological performance; Hydrodynamic journal bearing; CFD; Load-carrying capacity, Coefficient of friction.*

In this study, the effect of different types of texture shapes, i.e., square, triangular and chevron were studied to improve the tribological performance of hydrodynamic journal bearings made of bronze alloy against cast iron. A three-dimensional numerical model was developed using the Navier-Stokes equations to predict hydrodynamic pressure generation, solved via the finite volume method in ANSYS Fluent. Numerous CFD simulations were conducted under the operating conditions of 10 MPa bearing pressure and 5-10 m/s sliding speeds with SAE 40 lubricant. It was found that tribological characteristics such as static pressure distribution, load-carrying capacity (LCC) and coefficient of friction (CoF) were significantly improved when the texture distribution was in the upstream, just beyond the minimum film thickness location. Conversely, there was a detrimental effect on performance when the texture distribution overlapped with the minimum film thickness location. The optimal dimple depth was found to be 22.5-micron corresponding with 0.01125 aspect ratio. At this depth, square dimple bearing with a surface texture density of 5.301% raised the LCC by 1.91% and lowered the CoF by 1.79% in comparison with the untextured bearing. Also, when textures were distributed over the central part of the bearing, it provided better results than fully axial textured bearings. The best overall performance was obtained for square dimples distributed from -100 to 110 degrees, with texture density of 26.51% where the LCC increased by 12.25% and the CoF decreased by 12.09% compared with the untextured bearing. Furthermore, tribological performance depends on the texture shape, texture density, texture sizes and operating conditions. In addition, the optimization of different types of texture shapes will be also studied to improve the tribological performance of hydrodynamic journal bearings under green fuel conditions. This numerical investigation provides a detailed evaluation

of the effects of surface texture in journal bearings and optimization of surface texture parameters to enhance tribological performance.

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Effects of Hydrogen Ageing on Lubricant Properties and Film Regimes in Journal Bearings and MTM Contacts

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Key Words: *hydrogen ageing; engine oil; lubricant properties; journal bearings; MTM; lubrication regimes*

Hydrogen-fueled internal combustion engines pose lubrication challenges because hydrogen exposure can alter lubricant chemistry, viscosity-related behavior, additive stability, and film-forming ability. Recent studies show that hydrogen and other green-fuel environments can modify lubricant composition and change friction and load-carrying behavior [1]. Work on lubrication-regime identification has also demonstrated the value of combining measurements, simulation, and data analysis to distinguish hydrodynamic, mixed, and boundary lubrication in journal bearings [2]. Correlating application-level lubrication testing and simulations with laboratory Mini Traction Machine (MTM) tests can accelerate lubricant development by enabling efficient pre-screening of regime-dependent behavior [2]. In addition, tribological studies in hydrogen indicate that lubricant–surface interactions and protective films can change under hydrogen exposure [3,4].

Therefore, with the need to link hydrogen-induced ageing of engine oils with lubrication-regime changes, to assess changes in viscosity-related response, friction, and film-forming capability across hydrodynamic, mixed, and boundary lubrication. This work studies the fresh and hydrogen-aged commercial engine oils, evaluating the hydrogen ageing affects lubricant properties and lubrication regimes in journal bearings and MTM contacts. The results will improve the understanding of how hydrogen exposure influences the contact-regime transitions and supports the evaluation of lubricants for future hydrogen-compatible engine systems.

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Quantitative acoustic emission-based characterization of fretting damage in flat-on-flat contacts under different sliding amplitudes using machine learning

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Key Words: *Fretting damage, Acoustic emission, Machine learning*

Acoustic emission (AE) enables the detection of elastic waves generated by fretting-induced micro-events; however, the resulting high-volume data require reliable processing techniques for meaningful interpretation of fretting damage mechanisms.

Building on our previous unsupervised machine learning (ML)-based AE analysis framework, which linked AE feature patterns to fretting damage mechanisms under fretting tests with identical operating conditions [1], this study extends the methodology to fretting tests conducted under different sliding amplitudes in a flat-on-flat contact configuration. The capability of the developed ML model is evaluated to provide insight into the influence of sliding amplitude on AE feature distributions and unsupervised pattern recognition performance. In addition, the quantitative relationship between AE features and fretting damage severity is investigated.

The study is expected to provide further insight into the reliability of the developed ML model for AE-based assessment of fretting-induced damage.

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Characterization of fretting induced fatigue damage through cross-sectional analysis of quenched and tempered steel samples

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Key Words: *fretting fatigue, materials characterization, crack formation*

Fretting fatigue causes damage via formation of cracks, which can lead to significant reduction in fatigue life of mechanical parts. This investigation concerns materials characterization results from 112 cross section images of specimens from fretting experiments done with self-mated quenched and tempered steel in a dry annular flat-on-flat contact with a nominal contact area of 314 mm². The running conditions of the tests include sliding amplitudes up to 50 µm, contact pressures up to 30 MPa and test durations up to 3*10⁶ load cycles (at 40 Hz). The data was used to analyze the relationships between crack dimensions and quantities such as frictional energy (figure 1). This study provides important information about which running conditions cause the formation of cracks with significant sizes.

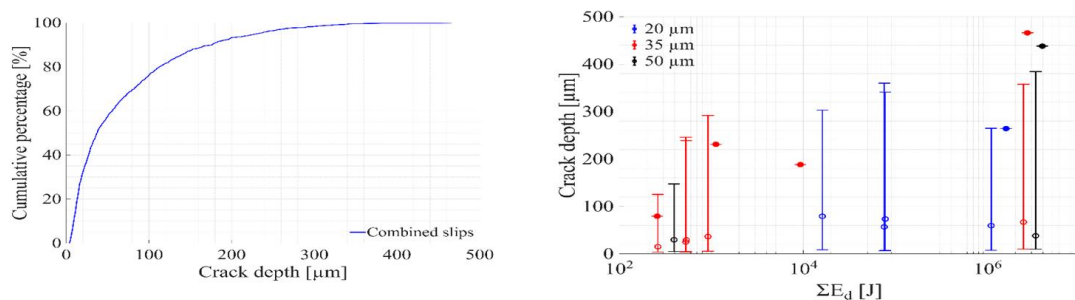


Figure 1. Examples of crack depth increasing according to the contact conditions. Distribution of all measured crack depths from tests with 30 MPa contact pressure and crack depth vs cumulative frictional energy.

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In-situ and post-mortem characterization of concrete mortar failure with application to AAM

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Key Words: *Mortar testing, Digital image correlation (DIC), X-ray computer tomography (XCT), Portland cement (OPC), Alkali-activated materials (AAM)*

The testing standard SFS-EN 196-1-2016-en is designed to determine the mechanical resistance of concrete mortar with uniaxial compressive flexural tensile strength. For other parameters, such as elastic properties and fracture energy, the standard test setup must be modified, and strain measurements are needed. DIC strain field measurements on the specimen surface are well adapted to small scale mortar specimens as virtual strain gauges are used to compute stress-strain plots. Elastic properties inferred from the stress-strain plots are compared to the ones computed from ultrasound wave front velocity measurement. To characterize the failure mode, specimen surface cracking is inferred from the principal strain field. Post-mortem XCT scans provide a three-dimensional model of the crack geometry, which is post-processed for crack surface normal determination to quantify damage anisotropy.

These measurement methods are used to understand the differences in mechanical behavior between OPC and AAM, as studies have shown more brittle behavior in AAM, [1]. Preliminary results show that the original RILEM mix, [2], with sand-to-binder ratio 1 is brittle, despite enhanced strength properties. However, a modified RILEM mix, with sand-to-binder ratio 3 has better ductility properties, comparable to OPC. The work is funded by the Research Council of Finland, Decision number 356502.

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Fast fatigue life prediction of ductile glassy materials through combined constitutive mathematical and AI-based modeling

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Key Words: *Very-high cycle fatigue, Low-cycle fatigue, Modeling, Machine learning, Microstructure-based damage, Digital twins*

Fatigue life is of great importance in design, while advanced modeling nowadays offers a worthwhile alternative to expensive and time-consuming physical experimentation. The proposed microstructural-based constitutive model used for low-cycle (plastic) and high-cycle (elastic) fatigue for specific, ductile glassy materials (polymers and metals) is based on the evolution of the fatigue damage which encompasses a moving endurance surface within the stress space, without the need for indistinct cycle-counting approaches [1]. For the first time, all fatigue model parameters for specific glassy materials were derived using the widely-known Basquin-Coffin–Manson model parameters. Nevertheless, this mathematical constitutive modeling is, in addition to experimentation, computationally expensive, when used to predict very high-cycle fatigue. Therefore, the constitutive–fatigue modeling was used exclusively to produce accurate data for training and teaching machine learning methods which can enable significantly improved computational efficiency [2]. The fatigue prediction of ductile glassy materials, traditionally ensured by costly and time-consuming experiments, is now accelerated through the proposed modeling approach that integrates mathematical constitutive modeling with AI-based.

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Capabilities and recent advances on understanding environmentally assisted fracture from the University of Oulu

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Keywords: Fracture toughness, Fatigue, Hydrogen embrittlement, Hydrogen infrastructure, In situ testing and characterisation.

The ongoing transition to a hydrogen economy places new demands on the structural integrity assessment of steels used in production, transport, and storage infrastructure. Hydrogen uptake within load-bearing materials can severely degrade fracture toughness and fatigue resistance, and these effects are further complicated in the Nordic and Arctic conditions by wintry sub-zero service temperatures. The research activities and recently developed infrastructure at the University of Oulu addresses these challenges through thorough investigation of the interactions between hydrogen and metal, e.g., diffusion, uptake and local concentrations of hydrogen, and how hydrogen affects the mechanical behaviour of metals. The study methods cover electrochemical characterisation methods like hydrogen permeation experiments, thermal desorption spectroscopy (TDS), and mechanical testing with *in situ* hydrogen-charging for fracture toughness and fatigue testing, and high-pressure gaseous charging for uniaxially loaded specimens.

Recent advances demonstrated cover current projects that address hydrogen storage and transport, and novel materials development for future high-performance materials. These studies illustrate a coherent, multi-scale testing capabilities developed. The results confirm that microstructural design, particularly control of retained austenite stability and morphology, offers a practical route to improving hydrogen compatibility in high-strength steels, while the Nordic-relevant fracture toughness data provide direct input for the safety assessment of hydrogen transportation infrastructure in cold climates. This mini-symposium contribution aims to make these experimental capabilities more widely known to the Finnish structural integrity community and to invite further academia-industry collaboration on hydrogen-related material qualification.

Subsurface fatigue cracks in large size bevel gears

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Key Words: *Gears, Fatigue, Testing, Modelling, Fracture mechanics, Fatigue*

Large-size bevel gears are a power transfer component used in heavy industry and marine applications. The limiting factor of usage life of gears is often fatigue-based failure modes. In marine industries, gears are inspected periodically. In recent years, Classification Societies have started to inspect gears with ultrasonic inspection during usual maintenance of ships. After these tests, a significant number of gears have been replaced in a schedule far shorter than expected by historic experiences.

The phenomenon of subsurface initiated fatigue cracks was studied to better understand how subsurface fatigue cracks initiate and propagate during the usage life of the gears. Large-size bevel gears were tested using a unique test rig, using large-size case-hardened bevel gears. Significant number of subsurface fatigue failures were observed during testing. In higher loaded gears, gear teeth failed without prior indication. In lower loaded gears, many of the gear teeth developed subsurface fatigue cracks, before one gear tooth was observed to fail suddenly. The tooth that contained the oldest indications was not the one that ultimately failed, rather it would be a tooth that had no prior indications or a tooth that had multiple indications. Numerical modeling was conducted to better understand the cracks propagation behavior. When the cracks were parallel to the flank of the tooth, the crack tip energy release rates were below critical threshold. When the crack was at 45-degree angle to the surface, the contact load was observed be a significant factor in driving crack propagation.

The results suggest that presence of subsurface cracks is not indication of imminent failure. Reducing the power throughput of gears reduces chance of ultimate failure. The work is described in full detail in a doctoral thesis [1].

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Elastic-plastic solution-dependent three-dimensional fatigue crack growth model

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Keywords: *Fracture mechanics, Fatigue strength, Numerical modeling, Plasticity*

Due to oversimplification, linear elastic fracture mechanics fails to predict fatigue crack growth. Aspects such as plasticity, crack closure, and microstructure play a decisive role. Traditionally, advanced predictive crack growth simulation is carried out using either remeshing [1] or nonconforming mesh [2] strategies. In such formulations, the crack can extend based on a local growth criterion, predicting not only the global crack growth but also the crack front shape. However, these strategies are not only cumbersome to implement, but often also inaccurate and overly restricted.

A flexible, robust, and accurate alternative for natural fatigue crack growth simulation is needed in order to extend the capabilities of physics-based fatigue prediction framework. We introduce a new, versatile method for this purpose, with plug-and-play compatibility with commercial finite element software. The method uses the actual state at the crack tip to successfully predict the natural crack front shape, among other aspects. An overview of the model's algorithm is shown in Fig. 1.

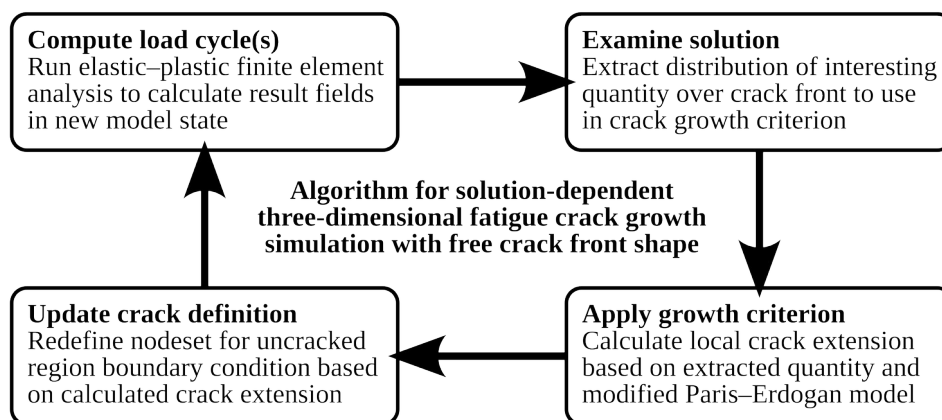


Figure. 1. Overview of the finite element analysis workflow.

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Influence of groove parameters on the frictional performance of journal bearings: A combined CFD and experimental study

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Key Words: *Tribology; Marco-Grooves; Journal bearing; Numerical Simulation.*

Journal bearings are essential components in rotating systems, but their performance is often limited by friction, wear, and lubrication challenges. Although surface coatings are commonly used to improve performance, they can increase manufacturing costs and complexity. This study focuses on the numerical investigation of macro-grooved journal bearings as a cost-effective alternative to traditional coated bearing solutions. The objective of this work is to examine how different groove design parameters influence friction, load-carrying capacity, and lubrication behavior under hydrodynamic conditions.

Journal bearings manufactured from bronze alloys (JM-3 and LF-3) and paired with 42CrMo steel sleeves were numerically investigated by computational fluid dynamics (CFD) after being modified with precision-planned macro-grooves. In the numerical model, groove depths (25, 50, 100, and 200 μm), three insert tip radii (50 μm , 400 μm , and 800 μm), the position of the groove and the length of the groove were considered. The groove nose angle was 55° for all configurations. Furthermore, the number and density of the grooves were optimized. Hydrodynamic pressure generation was governed by the Navier-Stokes Equation, which was solved using the finite-volume method in ANSYS solver. The model was used to predict pressure distribution, load-carrying capacity, wall shear stress, and coefficient of friction under hydrodynamic lubrication conditions using SAE-40 lubricant. Simulations were performed at a sliding speed of 10 m/s and an applied pressure of 10 MPa for the assessment of the effects of macro-groove geometry on load capacity, friction behavior, and lubricant film stability.

Experimental tests were carried out under matching operating conditions. Measured frictional behavior, temperature, and other operating characteristics were compared with numerical predictions to validate the model and assess the practical performance of the proposed modified bearing designs.

Both the simulations and experiments indicate that the optimized macro-groove pattern positively affect lubrication starvation while having a minimal effect on the friction and the load-carrying capacity. The results suggest that groove depth of and edge radius, the position of the grove along with the density and the number of grooves play an important role. The smallest increase in the coefficient of friction and the smallest decrease in load-carrying capacity was achieved with a groove depth of 50 μm , a radius of 0.5 mm, and a length of 5 mm, positioned between $0-140^\circ$ and $200-360^\circ$. For industry-oriented optimization, the best overall balance between minimizing COF increase and maintaining load capacity was obtained with a groove depth of 100 μm , a radius of 0.5 mm, a width of 15 mm, and four grooves placed between 100° and 140° . The close agreement between numerical and experimental results supports the reliability of the model. Overall, the study shows that macro-grooving can be an effective and practical way to enhance journal bearing performance without relying on expensive surface treatments.

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A systematic approach to the development of a high-frequency multiaxial fatigue testing device

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Key Words: *Product development, MBSE, System-level problem definition*

Multiaxial fatigue in metallic materials is an industrially significant phenomenon due to complex stress states, which can lead to substantial damage in components and structures. However, its experimental investigation remains challenging, as existing test devices typically operate at low frequencies [1]. The development of high-frequency multiaxial fatigue testing devices is constrained by their technical complexity and the need to integrate multiple subsystems. The operation of such a device relies on the synergistic interaction among mechanical, electrical, and control systems, making its design a multidisciplinary machine-design challenge [2].

Building on this multidisciplinary challenge, a key aspect in the development of such a device is systematic problem definition and the management of the design process in a manner that supports the integration of different architectures. Model-Based Systems Engineering (MBSE) provides a structured approach for this purpose, enabling requirements, concept development, analysis, verification, and validation to be linked into a unified design framework [3].

In addition to technological solutions and design requirements, the development of a functional and robust testing device also requires creative technical innovation. This includes, for example, the integration of piezoelectric elements into the mechanical structure to form a resonance-based system [4], as well as the generation and optimization of a combined loading path consisting of longitudinal tension–compression and torsional loading [5]. This study examines the integration of machine design perspectives as part of the development of a novel and innovative multiaxial fatigue testing device. The objective of the research is to achieve an optimal device concept that meets stakeholder needs.

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Fretting fatigue in hydrogen gas: Insights from advanced microstructural characterization

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Key Words: *Fretting fatigue, Hydrogen, Martensitic Steel, Materials characterization*

Fretting fatigue occurs in the contact interfaces subjected to contact pressure and small-amplitude cyclic relative motion. Its relevance is increasing in hydrogen-related applications, where contact interfaces may operate under hydrogen gas exposure. Under such conditions, fatigue damage is governed by coupled mechanical, tribological, and environmental processes. The work investigates the fretting fatigue behavior of self-mated quenched and tempered steel in air and hydrogen gas using a bridge-type bending fretting fatigue configuration. The aim is to clarify how hydrogen alters the relationship between fatigue life, frictional force, and fretting damage. Hence, various microscopy techniques, including 3D optical surface profilometry, scanning electron microscopy, energy dispersive spectroscopy, and electron backscatter diffraction are used to examine fretting scar morphology, adhesion, debris formation, degradation layers, cracking, and microstructural changes. The importance of the detailed characterization for interpreting fretting-induced damage was demonstrated previously for quenched and tempered steel in air [1]. This work provides insight into the mechanisms governing fretting fatigue of high-strength martensitic steel in hydrogen gas and highlights the vital role of advanced characterization in understanding contact fatigue in future hydrogen energy systems.

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Gas path dimensioning and pressure pulsation study in a Closed-Loop Hydrogen-Argon Power Cycle

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Key Words: Argon Power Cycle, Hydrogen, Internal Combustion Engine, Pressure pulsation, Gas dynamics

Argon Power Cycle has been shown to potentially reach exceptionally high thermal efficiencies, exceeding 60% thermal efficiency by leveraging the high specific heat ratio of argon ($\gamma \approx 1.67$) [1], [2], [3]. While previous research has mainly focused on combustion behavior [4], [5], limited attention has been drawn to the gas-path dynamics, especially in a closed-loop configuration. In such an architecture, pressure pulsations and flow oscillations influence the system's stability and performance [6].

The present study investigates the influence of the piping diameter on pressure pulsations and flow dynamics. Different pipe diameters, ranging from DN 80 to DN 150, were evaluated under identical operating conditions. Parameters such as argon ratio, compression ratio and engine power output were maintained, while the system pressure was adjusted to match the desired power output. Pressure and mass flow oscillations were analyzed at several key locations of the closed-loop.

The results indicate that a smaller pipe diameter may, counterintuitively, improve engine performance by reducing pressure and flow pulsations due to higher acoustic impedance and stronger viscous damping. Although larger diameters would theoretically reduce pressure losses in the loop, thereby lowering pumping work and improving thermal efficiency, the present findings suggest that gas-dynamic stability and pulsation attenuation play a significant role in overall closed-loop operation.

The findings provide additional design insight for future experimental facilities. In particular, the analysis emphasizes the need to view the piping design of APC systems not only in terms of pressure losses under steady-state conditions but rather in a combined thermo-fluid and acoustics approach.

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Numerical framework for fatigue crack monitoring using optical methods and strain drop measurement

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Key Words: *Fatigue, Welded joints, Crack monitoring, Camera imaging, Strain drop*

Fatigue cracks in welded joints are commonly observed during experimental testing through strain drop measurements using strain gauges [1]. In recent years, various camera-based imaging systems, such as digital image correlation (DIC) [2], have been widely applied for crack monitoring in both fatigue testing and industrial contexts.

In this study, the objective is to develop a numerical framework that combines strain gauge measurement data with surface crack size measurements obtained from a camera imaging system in order to estimate the depth of the crack through reverse engineering. This approach provides a more comprehensive insight into fatigue crack growth behavior, enabling more accurate monitoring of crack development, size, and growth rate during testing.

To integrate the information from both strain gauges and the camera system, three-dimensional finite element (FE) modeling is employed. To simplify the problem, a deterministic surrogate model is developed based on multiple FE simulations with varying crack sizes and semi-elliptic aspect ratios ($a/2c$) in all cases assuming a semi-elliptical crack shape. The developed model is first verified using FE simulations outside the training dataset, after which a global sensitivity analysis is conducted to evaluate the robustness and sensitivity of the model to its input parameters. Finally, the approach is validated against experimentally with welded aluminum transverse attachment joints, in which beach-marking was conducted to enable post-mortem crack size analysis.

The preliminary verification indicates that the developed framework is able to reproduce the relationship between strain measurements and crack geometry with consistent accuracy across the investigated parameter space. The surrogate model exhibits stable behavior for varying crack sizes and aspect ratios, indicating adequate robustness for practical application. Overall, the methodology provides a promising basis for improved real-time monitoring of fatigue crack growth in welded joints, with potential applicability to a wider range of structural components.

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EDE3: Early Detection of Extreme Engine Events Using Measurements and Digital Twins

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Key Words: Diesel Engine, Measurements, Predictive Maintenance, State Estimation

This talk introduces the EDE3 project, developed in collaboration with Wärtsilä, which aims to support early detection of severe mechanical failures in diesel engines before irreversible damage occurs. The approach combines engine measurements, physics-based models, and state estimation to identify changes in engine behavior. The presentation outlines the industrial motivation, main failure cases considered, and the connection between the following presentations on experiments, model validation, acoustics, reduced-order modeling, and state estimation.

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Mapping Real-Time and Online Fatigue Assessment Approaches for Working Mobile Machinery Applications

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Key Words: Real-time and online fatigue assessment, Metallic structures, Working mobile machinery, Transferability

Fatigue is a major degradation mechanism limiting the reliability and service life of metallic structures used across many engineering fields [1], including working mobile machinery. During engineering system operation, timely information on the fatigue state, including damage accumulation, crack growth, or remaining useful life, can support monitoring, preventive maintenance, operational decision-making, and, in some cases, fatigue-aware control strategies. However, obtaining and utilizing this information under challenging real-world conditions remains an open problem.

This review systematically maps where online and real-time fatigue assessment solutions have been investigated, which components and operational conditions they address, and how the resulting fatigue information is utilized. Using an LLM-assisted workflow, the collected studies are classified according to technical and application-related characteristics. This classification is used to identify existing approaches in working mobile machinery, as well as approaches from other engineering domains that may face comparable challenges, particularly regarding component type, loading conditions, sensor instrumentation, environmental robustness, and integration with operational decision-making. The review identifies typical assumptions, deployment challenges, and future research directions in broader literature, while the transferability discussion examines studies and application domains facing challenges comparable to those encountered in working mobile machinery.

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A mixed formulation of the Cahn-Hilliard phase-field model coupled with strain gradient elasticity

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Key Words: *Cahn-Hilliard, Phase-field, Strain gradient elasticity, Mixed finite elements*

The Cahn-Hilliard framework is widely used to describe phase separation and coarsening phenomena in diffusive systems. In the present contribution, we consider a coupled mechano-diffusion problem that combines Cahn-Hilliard diffusion with Mindlin's strain gradient elasticity [1]. The governing partial differential equations (PDEs) are of 4th order resulting in higher continuity requirements on the finite element discretization. One way to address these requirements is using NURBS basis functions to achieve higher order continuity on the whole domain [2]. A second common approach is to split the higher order PDEs into a set of lower order ones [3, 4]. In this work we propose a mixed formulation of the coupled problem. Although both problems alone have been successfully studied using mixed formulations, the coupling gives rise to additional higher order terms that need to be treated. We first demonstrate the effectiveness of the mixed formulation by comparing it with a NURBS-based isogeometric analysis formulation, before showing the effects of the coupling on the phase separation process and the mechanical response.

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Modeling of phase transformations in duplex stainless steel in the cooling zones of a continuous annealing line

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Key Words: *Duplex stainless steel, Continuous annealing, Phase transformations, Finite element modeling, Process optimization*

Duplex stainless steels exhibit a dual-phase microstructure consisting of approximately equal fractions of ferrite and austenite. The desired phase balance is achieved by annealing the material at 1050–1150 °C. The annealing is followed by controlled cooling to room temperature. The cooling cycle must be meticulously controlled to prevent the formation of detrimental secondary phases, which can impair both corrosion resistance and mechanical properties.

For strip material, the final heat treatment is conventionally done in a continuous annealing line. In a continuous annealing line, strips welded together are continuously passed through several horizontal annealing furnaces and cooled back to room temperature by high-velocity air jets. The heat cycle is controlled by line speed, furnace zone temperatures, and airflow to the cooling-zone jets. Parameter optimization based on production trials is associated with a risk of producing significant quantities of defective material. For this reason, computational modeling is a more attractive approach for identifying optimal process conditions without interrupting industrial operations.

In the present work, an economical finite element model is developed using the Elmer FEM software to simulate microstructural evolution of duplex stainless steel in the cooling section of a continuous annealing line. The model captures the essential thermal and metallurgical phenomena while remaining computationally efficient, enabling optimization of the line speed and cooling parameters on a standard desktop computer.

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Resolving scalability bottlenecks in finite element modeling of radiation heat transfer

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Key Words: Radiation Heat Transfer, Radiosity, Emissivity, Finite element method

Radiative heat transfer plays a pivotal role in high-temperature industrial processes, such as crystal growth and metal manufacturing. Radiation heat transfer models were implemented in Elmer finite element software [1] already in its early days and applied mainly to axially symmetric crystal growth. True 3D radiation heat transfer was usually deemed too slow. Recently, we have continued the work on this topic for the heat treatment of metals with complex 3D geometries.

Computing internal radiation boundary conditions where bodies see themselves relied initially on the Gebhart factor method. While the method provides robust nonlinear convergence, it suffers from a massive computational bottleneck: constructing the dense Gebhart matrix requires solving an independent linear system for every single radiating boundary element. To overcome this scalability bottleneck the radiation heat transfer was rewritten in terms of radiosity, which describes the total radiative power leaving a surface [2]. The radiosity vector is solved once for each nonlinear iteration, and it completely decouples the dense radiative interactions from the underlying sparse matrix topology of the heat equation. This preserves global matrix sparsity, enabling efficient iterative linear solvers with modest memory consumption. The chosen method also extends naturally to spectral / non-gray boundaries, where materials exhibit temperature-dependent emissivity and absorptivity.

The nonlinear convergence rate of the radiosity model is considerably slower than that utilizing fully implicit Gebhart factors. To boost the convergence, a partial Newton linearization is also applied to the radiosity model. With an optimal choice of relaxation parameters, the number of nonlinear iterations needed stays reasonable while each linear solution is much faster than before.

The computational efficiency of calculating the geometric view factors in 3D has also been heavily optimized. A recursive geometric Element Combination algorithm traverses adjacent boundary elements, matching their surface normals to merge fine meshes into coarse polygonal loops [3]. This drastically reduces the total element count while fully preserving geometric fidelity. The computation is also sped up by the use of symmetry, when available. View factor computation has also been multithreaded with good scalability.

We will demonstrate the usefulness of the implementations with numerical experiments. With these improvements, the solution of realistic industrial use cases involving radiation heat transfer becomes feasible.

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Finite Element Methods for Elastic Contact: Augmented Lagrangian and Nitsche

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Key Words: *Elastic contact, FEM, Augmented Lagrangian, Nitsche*

We consider three alternatives for solving elastic contact problems, a stable mixed method, a mixed method based on the augmented Lagrangian and Nitsche's method.

The first method derives directly from the theory of mixed FEMs; the Lagrange multiplier, i.e. the contact traction, is approximated with discontinuous piecewise polynomials and the stability is obtained by adding bubble degrees of freedom for field variable at the contact boundary. The saddle point linear system thus obtained is very efficiently solved by the Augmented Lagrangian method. With this method, the stability of the discrete system and the linear algebra (i.e. AL) to solve it are clearly separated. It will work for any value of the penalty parameter, the bigger the value is, the faster is the convergence. There is however a trade-off with the conditioning of the system to be solved at each iteration. The requirement that this conditioning should be that of second order elliptic equations, leads to the choice $O(h^{-1})$ for the penalty parameter.

In the engineering literature the choice for the Lagrange multiplier is often that of the trace space of the field value. This mixed method thus obtained is stable, cf., e.g., a recent [paper](#) by Råback, Gustafsson and Videman. The use of the AL iteration is, however, detrimental since the continuity of the Lagrange multiplier leads to a less sparse stiffness matrix, the bandwidth is doubled. This method is hardly used in practice.

The method that seems to be mostly used in practice is based on the AL formulation of the continuous system with the trace space as Lagrange multiplier. A consequence of this is that the analysis couples the stability and the AL formulation. It seems that this

point has not been addressed in the literature. The outcome of our analysis is that the method is optimally convergent as long as the penalty parameter is bounded by above the $O(h^{-1})$ limit, i.e. we have a wide range of valid choices for the it. The extreme lower limit zero gives the Uzawa iteration. Again, the optimal conditioning for the stiffness matrix yields the choice $O(h^{-1})$. We remark that the existing literature is quite vague on how the parameter should be chosen.

At the previous Finnish Mechanics Days, we [analysed](#) the penalty method and showed, that the lack of consistency is the dominating part of the error. In this respect, the AL is a true improvement, it is always consistent. However, when the penalty exceeds the limit $O(h^{-1})$, the accuracy decreases due to an unbalance in the stability, for the displacement it is too strong, and too weak for the Lagrange multiplier.

The third method to be consider is Nitsche's method. A way of arriving at that, is to look at the AL method with the $O(h^{-1})$ choice for the penalty. In each iteration, we solve for the displacement with the last approximation for the traction as an input on the right-hand side. The better this approximation is, the better the solution is. An unsymmetric Nitsche would amount to move this term to the left-hand side and replace the approximation for the traction with the traction obtained from the unknown. It is easy to prove, that this now gives a solution with optimal accuracy. No iteration needed! The final Nitsche is now obtained by adding a consistent symmetrising term.

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F-barES-FEM T4: A locking-free tetrahedral element implementation in CalculiX

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Key Words: *locking-free element, tetrahedral FEM, ES-FEM, F-bar method*

Volumetric locking restricts linear tetrahedral elements in incompressible and nearly incompressible solids, where the constant-volume constraint leaves too few deformation modes and makes the response artificially stiff. Tetrahedra mesh complex geometries automatically but are prone to locking. We implement F-barES-FEM-T4 [1], a locking-free tetrahedral element combining edge-based strain smoothing (ES-FEM) with the F-bar method.

The deviatoric response is carried by an edge-smoothed deformation gradient from the four-node geometry, while the volumetric response is taken from a Jacobian smoothed cyclically between elements and nodes and to the edges. We use the single-smoothing setting $c = 1$ to remove locking. We apply the element at bulk-to-shear ratios of 500 and 5000, beyond the validated range.

Because the stress comes from the modified gradient but the virtual work from the unmodified one, the tangent is non-symmetric, a Petrov-Galerkin structure required by the F-bar construction, assembled through an asymmetric sparse-solver path. The element is delivered as user elements in CalculiX, while a generator script rewrites existing C3D4 decks into the smoothing domains, requiring no mesh change. The element passes the patch test to round-off, extends to finite strain, and reproduces $C_{1111} = K + 4G/3$. On a layered near-incompressible cell it converges with two elements through the soft layer, whereas plain C3D4 locks without convergence. Its macroscopic modulus agrees with Abaqus's C3D4H element to 0.23%, and its pressure field is oscillation-free.

The method provides a ready-to-use, locking-free tetrahedral element, lowering mesh-generation effort and expanding the reach of low-order finite elements.

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Thermal Modeling and Insulation Design of Sensible Heat Storage

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Key Words: *Thermal energy storage, Heat transfer, Insulation design, Scale-up analysis, Differential-algebraic equations*

Sensible thermal energy storage is a promising approach for improving the flexibility of low-temperature heat systems when heat availability and demand are temporally misaligned. In early design stages, detailed CFD simulations are often impractical for comparing multiple storage configurations and insulation options because of their high computational cost. This work develops a computationally efficient thermal model for an insulated packed-bed sensible heat storage system, building on the lightweight dynamical modeling approach of [1].

The storage is represented using a radial resistance-capacitance (RC) thermal network, in which appropriate thermal resistances for the core and insulation layers are derived and the system is discretized into multiple thermal nodes. The model describes heat exchange between the working fluid and the storage core, radial conduction through the storage and insulation, and convective heat loss from the outer surface, covering the charging, storage, and discharging phases. It is validated against reference CFD data for spherical storage geometry.

The model is applied to parametric and scale-up studies examining the influence of insulation material, insulation thickness, and storage size on thermal performance. The proposed tool is well suited for preliminary insulation sizing and material screening before more detailed simulations or experiments are conducted.

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Numerical modelling of river-derived PFOS transport and dispersion in the Archipelago Sea

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Key Words: *PFOS, Archipelago Sea, Shallow-water flow, Water quality, Passive scalar*

Perfluorooctane sulfonate (PFOS) is a persistent pollutant that can be transported over long distances in aquatic environments and may accumulate in receiving water bodies. In coastal areas, its dispersion is affected by river inflow, bathymetry, complex shoreline geometry, and hydrodynamic connectivity between open and sheltered water regions. This work aims to model the transport pathways and dispersion of PFOS from the Aura River into the Archipelago Sea and to support the interpretation of sparse monitoring data.

A two-dimensional depth-averaged hydrodynamic model [1] is coupled with a passive-scalar transport equation for PFOS. The computational domain covers approximately $24 \text{ km} \times 19 \text{ km}$ of the Archipelago Sea, with a horizontal resolution of 4 m, allowing the main coastal channels, islands, sheltered water regions, and bathymetric variations to be represented. Flow and PFOS enter the model domain through the Aura River in Turku.

Results show that PFOS transport is controlled by flow pathways, bathymetry, and coastal geometry. Higher depth-integrated concentrations occur along the main river-driven route, with local maxima about 2.3 times the inlet value, suggesting localized retention and possible accumulation. The plume therefore does not simply dilute downstream, but can be intensified by bathymetry, shoreline geometry, and coastal circulation. Time series at monitoring locations show different arrival times and concentration levels, indicating variable exposure to the PFOS plume. The results can, therefore, support the identification of PFOS pathways, potential accumulation zones, and suitable locations for targeted monitoring in complex coastal waters.

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Experimental Investigation of Various Effective Bulk Modulus Models Under Low Pressure and Aerated Fluid Conditions

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Keywords: Pressure-compensated valves, Hydraulic actuators, Aerated fluid, Effective bulk modulus, Fluid power systems.

Most working machines are predominantly hydraulically actuated, owing to the favorable power density, robustness, and ability to produce large forces at low speeds. In such systems, hydraulic circuits pose some persistent modelling challenges. Examples of such challenges include transient aeration, cavitation and low-pressure operation [1]: where the effective bulk modulus, β_e , drastically drops due to air-release. The nominal β_e model in hydraulics fails to capture such low bulk modulus, thereby introducing errors in pressure computation and digital hydraulics. In fluid mechanics, several low-fidelity models were proposed to compute β_e at the low pressure, aerated and iso-thermal conditions, such as Wylie, Nykänen, Ruan, and pressure-based models. Performance of these models were investigated using numerical examples, and experimental measurements were also reported. However, these models did not account for the coupling of hydraulics with the mechanical systems. Consequently, the practical applications of these models in hydraulic machinery remain unclear. Motivated by these gaps, this work introduces a systematic comparison of state-of-the-art effective bulk modulus models — Nominal, Wylie, Nykänen, Pressure-based and Ruan—under low-pressure, iso-thermal and aerated fluid conditions in an experimental setup. The parameters for each model are identified using empirical tuning. These findings provide practical guidance for selecting appropriate β_e models and parameters for the digital twin of hydraulically actuated working machines.

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Numerical Validation of Non-Reactive Sonic Hydrogen Jet Injection and Mixing Characteristics under Different Nozzle Pressure Ratios and Ambient Compositions

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Key Words: *Hydrogen injection; Sonic jet; Underexpanded jet; Non-reactive validation; Nozzle pressure ratio; Compressible flow; Turbulent mixing; Hydrogen-oxidizer mixing; Direct injection; OpenFOAM*

Abstract

The present study investigates the transient behavior and mixing characteristics of non-reactive sonic hydrogen jet injection under engine-relevant conditions using combined numerical and validation approaches. A compressible high-speed injection framework is developed to capture underexpanded hydrogen jet dynamics, including shock structures, jet penetration, and turbulent mixing evolution. The numerical model is first validated against available experimental data for sonic hydrogen injection in quiescent environments, focusing on jet morphology, penetration length, and transient development. Following validation, the study extends toward a systematic investigation of hydrogen-air mixing under different nozzle pressure ratios (NPRs) and ambient gas compositions representative of combustion and exhaust gas dilution environments. The effects of NPR variation on jet core structure, entrainment rate, scalar dissipation, and mixture formation are analyzed in detail. In addition, the influence of ambient composition, including Ar/O₂ and N₂/O₂, environments, on jet spreading and mixing

efficiency is examined. Results demonstrate that increasing NPR enhances jet penetration and compressibility effects while modifying turbulent entrainment and local mixing rates. Ambient composition significantly affects jet density gradients, shock-cell structure, and hydrogen dispersion behavior. The study provides fundamental insight into high-pressure hydrogen injection physics and establishes a validated framework for future reactive and engine-scale investigations involving direct hydrogen injection, thermal management, and advanced combustion strategies.

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Catchment-scale CFD analysis of future extreme rain events in a peri-urban catchment area

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Key Words: *Climate change, Rain intensity, Flood, CFD, NBS*

Climate change is expected to increase the frequency and intensity of short-duration extreme rainfall events and prolong drought periods globally. Intense rainfall events create major challenges for urban stormwater systems and increase the risk of localized flooding in coastal catchments. This work focuses on identifying flood-prone areas in the Kuninkoja catchment area in the city of Turku under future extreme rainfall scenarios using high-resolution catchment-scale CFD modelling.

In this study, an in-house OpenFOAM-based shallow-water flow solver, with infiltration and drainage sink terms, is utilized to simulate surface-runoff dynamics [1]. The model integrates high-resolution topography, land-cover-dependent Manning roughness coefficients, and simplified infiltration and drainage representations. Three rainfall-intensity scenarios of 50 mm/h, 200 mm/h, and 500 mm/h, representing severe future storm events, are investigated to evaluate their influence on water depth, flow velocity, and flood propagation within the catchment area.

Numerical results for the 200 mm/h rainfall scenario indicate substantial spatial variations in runoff behaviour, with several low-lying urban regions showing significantly increased flood susceptibility and flow accumulation under high-intensity rainfall conditions. The results further highlight the influence of drainage capacity and land-cover characteristics on localized flooding and surface-flow pathways. Local water depths exceeded 0.5 m, while flow velocities reached up to 3 m/s in confined flow regions. The results can support climate-adaptation planning by identifying critical flood-prone areas and guiding the implementation of nature-based stormwater mitigation solutions to improve urban resilience and coastal water quality.

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Finite Element Model Validation using Acoustic Measurements

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Key Words: *Acoustic Measurements, Vibration, FEM, Frequency Domain*

This study develops a finite element model (FEM) of an instrumented four-cylinder diesel engine to predict vibration- and noise-relevant responses under operating conditions. The workflow includes building the engine assembly model, defining appropriate damping and boundary condition assumptions, extracting modal properties, and evaluating the system's frequency-domain response. The model predictions are compared with NOME's acoustic measurements to relate the FEM response to operating and acoustic signatures.

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Forward Model Aspects of the Engine Failure Detection

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Key Words: *ROM, Simulation, Engine Failure, Dataset*

We present the implementation details of our engine fault classifier. To generate the training data, we use reduced-order models (ROMs) to create an ensemble of simulations that produce feature vectors for the engine. A key challenge in constructing the training dataset is ensuring sufficient coverage of fault scenarios, which can occur in many forms. These challenges are explored in the talk, with particular emphasis on visualization.

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Engine Setup and Measurements Pre- and Postprocessing

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Key Words: *Diesel Engine, Measurements, Test Bench, Validation*

An AGCO Power diesel experimental engine is installed and commissioned on a dynamometer test bench, and the full measurement chain is verified end-to-end, from instrumentation and synchronization to high-speed data acquisition, storage, and post-processing. The test-stand automation and core instrumentation are operational, and NOME's measurement system is integrated and commissioned, enabling crank-angle-resolved rotational speed measurements and complementary acoustic recordings. The measurements support model validation and subsequent fault modeling and analysis.

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Engine Model Validation using Test-Bench Measurements

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Key Words: *Cylinder Pressure, Dynamometer, Model Validation*

This study presents a practical workflow for validating a numerical model of a four-cylinder diesel engine using laboratory measurements from a dynamometer test bench. The validation inputs include cylinder pressure from a single cylinder and available sensor data from the test setup. The measurements are processed and compared with model predictions to tune key parameters and assess the consistency between simulated and experimental responses.

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A Robust Diagnosis Method for Early Detection of Engine Failures

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Key Words: *Rigid-Body, FEM, Digital Twin, Engine Failure*

We introduce statistically robust methods for detecting and identifying the most common engine failure scenarios. We use rigid-body modeling and the Finite Element Method (FEM) to create a digital twin of the engine. We employ state and parameter estimation in fault detection. Also, we use an offline dataset and a classifier trained on simulated engine models and failure scenarios to detect engine faults.

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MODSIM + AI: Enabling Concurrent Engineering Through an Integrated 3D Data Model

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Key Words: MODSIM, Concurrent Engineering, Integrated 3D Data Model, Parametric Design Space Exploration, Simulation Automation, AI-Enhanced Design Optimizations

Modern product development demands rapid iteration and data-driven optimization; however, traditional workflows remain bottlenecked by sequential, disconnected modeling and analysis stages. In this showcase, we present an AI-enhanced MODSIM framework built on science-backed Industry World Models that unify CAD and CAE into a single, traceable 3DEXPERIENCE data model. By embedding the entire simulation pipeline alongside native CAD features and physics-grounded constraints, we eliminate tedious data translation and enable instantaneous simulation updates that collapse design-iteration loops from weeks to days.

Leveraging this AI-native, agentic architecture, we establish a collaborative workspace where engineers and researchers interact directly with autonomous Virtual Companions. We demonstrate how the orchestration of Aura, Leo, and Marie empowers human teams to guide complex multi-physics parametric explorations and structural validations. Rather than managing raw data, researchers instruct these agentic AI systems to autonomously optimize design spaces against critical performance targets. Ultimately, this framework shifts engineering from manual software operation to high-level, intent-driven co-creation, offering a scalable foundation for next-generation intelligent product development.

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Generative AI-Augmented Multidisciplinary Design Optimization for Sustainable Design-to-Manufacturing Workflows

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Key Words: *Multidisciplinary Design Optimization (MDO), Generative AI (GenAI), sustainability-by-design*

Engineering design is increasingly shaped by decisions made in the earliest stages of product development, where geometry, material selection, manufacturing routes, structural performance, and environmental impacts are still flexible but highly interdependent. Traditional design optimization approaches have provided powerful tools for improving discipline-specific objectives, such as mass reduction, stiffness, manufacturability, or process efficiency [1]. However, next-generation engineering workflows require a broader multidisciplinary perspective in which structural mechanics, manufacturing constraints, material behavior, and sustainability indicators are evaluated concurrently.

Through three connected case-study demonstrators in additive manufacturing and engineering design, including a digital-twin-driven redesign framework for lightweight drone structures, an MDO-driven design-to-manufacturing workflow for a large-area additively manufactured mold, and a generative-AI-assisted CAD-to-manufacturing workflow, this work proposes and evaluates a research direction toward GenAI-augmented design-to-manufacturing systems that support early-stage decision-making. The proposed perspective integrates computational mechanics, surrogate modeling, digital twins, generative design, and large language model-based engineering agents to promote more automated workflows for generating designs that are structurally feasible, manufacturable, and environmentally sound.

The digital-twin case study demonstrates how experimental data, model-driven finite element simulations, surrogate models, and multi-objective optimization can be combined to support structural redesign. In this case, the digital twin enables the exploration of trade-offs between mass, deformation, and safety factor, highlighting its role as a design-support tool for lightweight mechanical structures [2]. The large-area additive manufacturing case study shows how multidisciplinary design optimization can connect material selection, design and simulation, manufacturing time, and

sustainability indicators within a unified workflow. The results demonstrate that early-stage choices in geometry and material selection can strongly affect both structural performance and environmental impact, including carbon and water footprints [1]. The GenAI-assisted workflow further shows how large language models can support CAD generation, feedback-based refinement, and design-to-manufacturing integration, lowering the barrier to entry for design automation while exposing remaining limitations in geometric accuracy, manufacturability reasoning, and model reliability [3].

The contribution of this work is a unifying view of how mechanics-based design optimization can evolve from isolated disciplinary optimization toward intelligent, sustainability-aware, and human-interactive design-to-manufacturing systems. By connecting these examples under a common methodological perspective, the work shows how model-driven simulations, data-driven surrogate models, digital twins, and GenAI-assisted reasoning can support the early-stage exploration of trade-offs between structural performance, manufacturability, and sustainability.

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Methodology for designing asymmetric constant-stress tied-arch bridges

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Key Words: *Tied arch, Constant-stress, Hanger inclination, Span-to rise-ratio, Costs*

Asymmetry in arch geometry typically arises from differences in abutment elevations, yet recent bridge projects have increasingly employed intentionally asymmetric arches to create distinctive architectural expression. While visually compelling, such geometries introduce questions regarding structural efficiency, internal force distribution, and potential cost implications. These considerations motivate a deeper examination of the asymmetric, moment-free, constant-stress form of the arch in tied-arch bridges.

The paper presents a systematic methodology for designing an asymmetric tied-arch whose geometry follows a constant-stress, moment-free idealization. The approach builds on the classical theory of funicular and tied-arch forms and extends it by introducing a rational procedure for employing inclined parallel hangers. This hanger configuration enables the formation of a stable and aesthetically coherent arch profile while preserving the desired moment-free behaviour throughout the structure.

The proposed shape-finding procedure is implemented through an iterative computational scheme and subsequently verified using analytical results and finite element analysis. The comparison confirms that the derived arch geometry closely reproduces the intended constant-stress behaviour under dead load and provides a structurally robust basis for further design stages. Parametric study results illustrate how variations in hanger inclination and span-to-rise ratio influence the resulting arch form as well as the costs associated with the tie, hangers, and arch.

The primary objective of the paper is to demonstrate that asymmetric tied-arches can be designed to satisfy both structural and architectural requirements without incurring significant additional costs. The results show that, when the arch geometry is optimized

according to constant-stress principles, asymmetry does not inherently reduce structural efficiency. Instead, it offers a viable design alternative that broadens the aesthetic and functional possibilities available for tied-arch bridges.

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Folding paper to origami core sandwich structures

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Key Words: *Miura-ori, Folding, Compression, Bending, Crushing, Finite Element Analysis, Experimental Validation*

Fold-projects [1], funded by Business Finland, have developed machinery, techniques, designs, models and methods to create and analyze sustainable products for packaging and other applications of light-weight structures by relying on the classical idea of folding paper to origami structures [2]. During the projects, it has turned out that both the process of folding and the performance of folded structures such as sandwich structures appear as interesting and critical areas of basic and applied research, at least from the point of view of mechanics [3].

Miura-ori pattern which has been in the center of the projects has turned out to be a machine-foldable origami pattern. Miura-ori structures, in turn, can be used for applications either as such alone or as a core of flat sandwich plates or curved sandwich shells. For these types of structures, the typical applications require high-level mechanical performance in different loading scenarios: e.g., compression and bending in different directions [4, 5].

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Integrating DEM Simulations and Machine Learning for Mixing Analysis of Polydisperse Granular Materials

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Key Words: Granular Mixing, Discrete Element Method (DEM), Machine Learning, Polydisperse Materials, Subdomain Mixing Index (SMI)

Achieving homogeneous mixing in polydisperse granular materials remains a critical challenge across numerous industrial sectors, including pharmaceutical manufacturing, food processing, chemical processing, powder metallurgy, and battery material production, where product quality and process efficiency are strongly influenced by mixture uniformity. Owing to the complex interactions among particles with different sizes and compositions, accurately predicting and optimizing mixing performance remains difficult. This study presents an integrated Discrete Element Method (DEM) and Machine Learning (ML) framework for the analysis and prediction of mixing behavior in vibrated polydisperse granular systems.

To quantitatively evaluate the degree of mixing, the Subdomain Mixing Index (SMI) is employed as a robust measure of mixture homogeneity [1]. The effect of vibration intensity, which serves as the primary energy input to the vibrating bed system and drives particle flow, is systematically examined. The results demonstrate that increasing vibration intensity enhances particle motion and mixing, resulting in an increase in the SMI. Beyond a critical threshold, however, the mixing behavior exhibits a distinct transition, reflecting changes in the mechanisms controlling particle rearrangement and mixture evolution.

Subsequently, the influence of key particle-scale parameters, including the sizes of coarse, intermediate, and fine particles, is systematically investigated. Particular emphasis is placed on understanding the coupled effects of these particle classes and their contribution to the evolution of mixing quality. The study further examines the impact of particle size distribution and the relative proportions of each size fraction through an extensive DEM simulation campaign. Furthermore, ternary composition diagrams are constructed using SMI-based mixing outcomes to visualize the mixing landscape and identify compositional regions that promote or inhibit homogeneous mixing.

The simulation data are subsequently used to develop machine learning models capable of capturing the complex nonlinear relationships between particle characteristics and the resulting mixing performance. The ML framework is inspired by recent advances in combining DEM simulations with data-driven predictive models for granular systems [2]. The resulting models

enable rapid estimation of mixing quality across a broad parameter space while significantly reducing computational requirements compared with DEM simulations alone.

The proposed DEM–ML framework provides fundamental insights into the mechanisms governing granular mixing in polydisperse systems and offers a powerful tool for the prediction, optimization, and design of industrial mixing processes involving complex particle size distributions.

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Geometry-driven design of programmable 3D chiral metamaterials with tunable mechanical response

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Key Words: *Chiral programmable metamaterials, Compression-Twist coupling, Finite element analysis, Bistability, Additive manufacturing, Physics-informed machine learning*

Chiral mechanical metamaterials are architected structures that couple axial compression and rotational deformation through their non-centrosymmetric geometry. However, their mechanical response is highly sensitive to unit-cell geometry, making systematic design challenging [1, 2, 3]. Building upon our previous work [4], we present a programmable 3D chiral metamaterial unit cell that enables transitions between bending, rotation, and instability dominated deformation without changing topology. Finite element simulations in COMSOL Multiphysics generate a large dataset of physically consistent unit-cell configurations, with numerical predictions validated by experiments on additively manufactured specimens. Preliminary results reveal bistability and snap-through instabilities, highlighting potential applications in energy absorption and adaptive structures. Finally, a physics-informed machine learning surrogate model is employed to accelerate design-space exploration and inverse design of unit cells with targeted mechanical performance.

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Tension-compression asymmetric mechanical metamaterials: Design and analysis

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Key Words: *Tension-compression asymmetry, Bi-modulus behaviour, Multi-material design, Lattice structure, Finite element analysis.*

Many structural and biological materials exhibit distinctly different elastic properties in tension and compression [1, 2], yet mechanical metamaterials, whose properties emerge from architecture rather than composition, offer a route to engineer such asymmetry by design. Recent studies [3] have produced similar bi-modulus effects with architected materials having internal contact between parts of the unit cells, demonstrating that pure geometry can drive pronounced tension-compression asymmetry.

This work presents a planar metamaterial unit cell design derived from a two-dimensional triangular lattice. Tension-compression asymmetry is introduced through a multi-material approach, in which a stiff frame is combined with auxiliary connector elements that are stiff in tension but soft in compression. Experiments were conducted on the fabricated samples to confirm this asymmetric behavior. Finite element analysis was performed in Abaqus, modelling the frame with continuum plane stress elements and the connectors with axial connector elements. Homogenization techniques were used to extract effective elastic characteristics under uniaxial tension/compression and shear loading in multiple directions. Results quantify the achievable tension-compression asymmetric properties and their sensitivity to the geometric parameters.

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Process-Aware Thermomechanical Modeling of Interlayer Bond Formation in Large-Format Additive Manufacturing (LFAM)

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Key Words: *Large format additive manufacturing, Process-structural performance (PSP), interlayer bonding, bio-based polymers, Functional Volume ratio (FVR)*

Large-format additive manufacturing (LFAM) enables rapid fabrication of large-scale polymer composite structures. However, the structural reliability of printed components remains strongly affected by weak interlayer bonding and anisotropic mechanical behavior [1]. This study presents a process-aware thermo-rheological analysis for mechanical characterization of bond line in a LFAM hollow square box made of Carbon-fiber reinforced bio-based polymers (PA11 and rPETG) through a combination of numerical, analytical and experimental approaches.

Interlayer mechanical performance is governed by bead contact and thermal diffusion across deposited layers [2]. In this study, bead contact is analytically quantified through a Functional Volume Ratio (FVR), representing the effective load-bearing portion of the deposited beads, and validated experimentally. Experimental material characterization determines the temperature-dependent thermal, rheological, and mechanical properties required for thermomechanical analysis. These properties, alongside the printing process parameters, serve as inputs to a transient thermal model that predicts the temperature history of interfacial points throughout bead deposition, cooling, and reheating. Calibration against in-situ infrared (IR) measurements and embedded thermal sensor data ensures accurate prediction of the thermal history governing interlayer bond formation.

An analytical healing model links the predicted thermal history to interlayer strength by quantifying polymer diffusion, healing evolution, and bond formation at bead interfaces [3]. The resulting degree of healing is translated into the reduced transverse strength associated with incomplete interlayer fusion. Tensile testing of specimens extracted from the printed structure along two orthogonal directions validate the

predicted strength of the bond calculated through the model. Finally, the robustness of the model is evaluated across different processing conditions, including traveling speed, material feed rate and interlayers deposition time.

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Towards computational soft-tissue mechanics in large-deformation dynamics: arbitrary volume integration of hyperelastic continuum beam elements

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Key Words: *Continuum beam element, Muscle–tendon mechanics, Hyperelasticity, Volume integration*

Beams are slender structures commonly used in structural engineering. From a modelling perspective, beam formulations are particularly attractive for finite element analysis because their reduced dimensionality decreases the number of degrees of freedom and the computational cost compared with full three-dimensional solid discretization. This makes beam models suitable for the simulation of complex systems. However, beam elements have several restrictions, including simplified cross-sectional descriptions and a limited range of applicable material models. These restrictions limit their use in applications involving complex geometries and strongly nonlinear material behaviour, such as biomechanics and soft-tissue mechanics.

Some of these restrictions can be overcome using continuum beam elements based on the absolute nodal coordinate formulation (ANCF). Continuum-based ANCF elements allow material models known from general continuum mechanics to be used without beam-specific material simplifications. This enables the description of nonlinear and hyperelastic material behaviour while keeping the computational advantages associated with beam discretization. Nevertheless, the geometrical description of continuum ANCF beam elements has traditionally been restricted to relatively simple cross-sections.

Recently, a method for representing arbitrary cross-sections within continuum ANCF beam elements was proposed [1]. Although this significantly extends their geometrical capabilities, an important limitation remains: the cross-sectional shape is constant along the beam centerline. This assumption makes it difficult to model structures whose shape varies substantially along their length. In the present work, we address this limitation by introducing an arbitrary volume integration approach, based on the method developed in [2], into the continuum ANCF beam formulation. The proposed approach allows

arbitrary three-dimensional beam-like geometries to be represented using continuum beam elements. Currently, the formulation is restricted to the St. Venant–Kirchhoff material model and is verified using a set of numerical examples.

The initial motivation for this development is the modelling of soft biological tissues, particularly the Achilles tendon and its subtendons. Their slender geometries make beam-based discretization computationally attractive, while their complex geometries and material behaviour are difficult to represent with conventional beam formulations. Realistic soft-tissue simulations also require nonlinear constitutive models, experimentally identified material parameters, detailed geometrical descriptions, and contact interactions between different tissue parts.

These requirements become especially important in large-deformation dynamics and forward-dynamics simulations of human motion, where deformable soft-tissue models are coupled with a multibody description of the musculoskeletal system and evaluated repeatedly during the simulation. In the framework considered here, muscle activation can be determined using model predictive control, while nonlinear finite element models are used to describe the deformation of soft tissues. Experimental measurements are needed for the identification of material and model parameters and for model validation.

The high computational cost of such coupled simulations requires a compromise between geometrical and mechanical accuracy and computational efficiency. The proposed continuum beam approach is intended to provide this balance by retaining the relatively low computational cost of beam discretization while allowing a more accurate representation of the three-dimensional geometry. This provides a basis for future coupled simulations in which nonlinear finite element models of deformable soft tissues are integrated into forward-dynamics models of human motion.

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A FE modelling workflow for gaskets

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Key Words: *FEA, Mechanics, Gasket elements*

Gaskets are static seals that are used to separate and contain various substances within machines and machine compartments. When gaskets perform as intended, they tend to go unnoticed; when their performance is hindered, however, consequences can at worst be of catastrophic nature (Such as in the Space Shuttle Challenger disaster [1]).

Traditional design methods for gasketed joints include e.g. the use of standards and handbooks for (1) the dimensioning of seating grooves in the case of self-energizing seals as well as (2) the calculation of required pretension loading and bolt spacing to ensure leak tightness and structural integrity.

Such traditional methods work well in straightforward cases. However, they impose limitations on the shape of joint and the type of loading that can be considered. Furthermore, one study found that using a standard calculation method led to overestimating a joint's leak tightness under flange rotation when compared to more detailed calculations [2]. Joints, where nonstandard flange geometries are subject to complex loading, thus present an opportunity to tackle the design problem from a simulation-driven perspective. One such application are Wärtsilä marine engines. [3]

Tools for the simulation of gasketed joints have been developed since the 90s. Most notably, Hebert & Webster [4] developed an Abaqus user subroutine which enabled the definition of a gasket's mechanical response to compression in terms of a load-displacement curve instead of traditional material constants. Such a curve is determined either by mechanical testing of the gasket, or by performing a separate, detailed finite element analysis (FEA) of the gasket's compression response, such as was demonstrated by Harland [5]. Nowadays, the Abaqus software suite, for example, features *gasket elements* and *gasket behavior models*, which allow for a similar workflow.

In this presentation, a FEA workflow for predicting the performance of gasketed joints is presented. The workflow has two steps, outlined in Figure 1: (i) characterisation of the gasket's load-displacement behaviour, and (ii) FE discretisation & modelling of the joint and gasket. As a real-life example, a gasketed flange joint in a Wärtsilä engine has been studied. The determination of load-displacement curves by a combined experimental and

FEA effort is discussed, and a gasket behavior model is constructed. Modelling of the assembly process shows a clear and significant effect of the gasket on its surroundings and warrants further investigation into the matter.

While the workflow outlined here is not new, the possible combinations of different types of gaskets and joint geometries to characterize using it are limitless. More specifically, the type of metal O-ring investigated in this work has had little representation in literature and presents an interesting subject to apply the discussed approach to.

The authors' intention is to continue work on the method outlined, specifically step (i), by focusing on improving the gasket behavior modelling process by means of validation with additional experimental measurements.

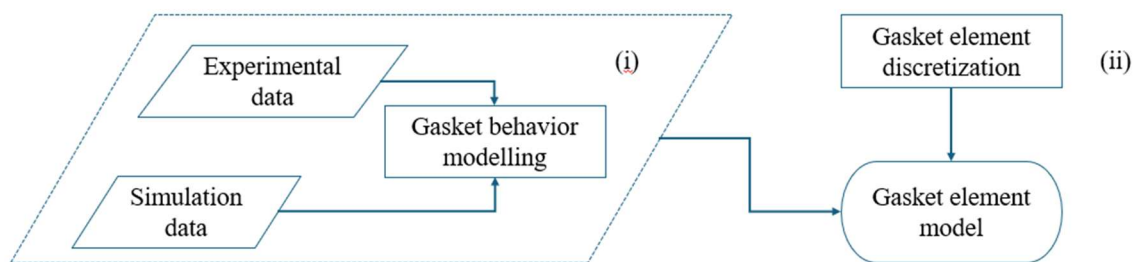


Figure 1. Visualization of the gasket element modelling workflow. The gasket behavior model constructed in step (i) is used as input in the gasket element model in step (ii).

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The effect of ash on optimising shedding in boilers under impact loading

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Boilers are used in energy production, but also as part of several different heating processes, such as kraft recovery boilers and roasters. The operation of a boiler involves collecting heat through the furnace's tube fin walls and through convective pass tubes into the working fluid. During the combustion process, combustion produces various ash fractions, which adhere to these surfaces and reduce heat transfer efficiency [1, 2].

Several methods exist for cleaning power plant boilers such as sootblowing, shot cleaning, detonation waves, ultrasound and rapping [1]. Sootblowing is the most widely used, but it cannot remove the most stubborn deposits. Rapping is therefore preferred in waste heat boilers, gasification plants and roasting plants, where deposits are harder to dislodge [1, 2, 3].

Rapping sheds deposits either with single impacts (transient excitation) or with a continuous vibrator (steady-state excitation). This study focuses on single impacts, such as those produced by the pneumatic impact hammer made by Global Boiler Works Oy [4]. The challenge is to tune the impact load carefully: strong enough to keep the heat transfer surfaces clean, but not so strong that the structures are damaged [1]. Excessive rapping can cause fatigue failures [5].

Rapping has received little attention in the literature. Most studies focus instead on cleaning electrostatic precipitators (ESPs), where collector electrodes are shaken to maintain efficiency [5, 6, 7, 8, 9, 10]. A few papers address rapping in gasification plants [11, 3, 12], and only one covers boiler plants [3] – specifically the cleaning of tube fin walls. More recently, several authors have examined the properties of ash and how it adheres to heat transfer surfaces [1, 13, 14].

The first phase of this study investigates the mechanical properties of ash deposits in order to define what constitutes an optimal impact. These findings will then guide the optimisation of both the hammer parameters and the geometry of the structures being cleaned, with the goal of achieving effective shedding without damage.

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