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Novel approach to damage detection in laminated structures: modal damping as a damage indicator

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Abstract. This paper provides a general overview of the author's Ph.D. research. It emphasizes the criticality of damage detection in composite materials, focusing on interlaminar delamination. It introduces vibration-based non-destructive testing (NDT) techniques and modal damping analysis as a novel damage indicator and highlights their real-time capabilities and sensitivity to subtle defects. Numerical modeling benefits and challenges in understanding modal damping behavior are discussed. The review covers research on modal damping modeling, its application in detecting interlaminar delamination, and composite defect simulation. The findings of the presented study provide insights into delamination behavior and its impact on structural integrity. Overall, this work highlights the effectiveness of vibration-based NDT and numerical modeling for enhanced structural health monitoring and material safety.

Introduction: Challenges in Structural Integrity and the Imperative for Damage Detection

Composite materials, extensively utilized across industries including aerospace [1], automotive [2], and railways [3], exhibit exceptional characteristics such as a favorable balance between strength and weight, resistance to corrosion, and adaptability in design.

Defects in composites: Laminated structures are vulnerable to a range of damage modes influenced by factors such as initial geometric imperfections [4], mechanical properties, boundary conditions, and applied loads [5]. These failure mechanisms are typically categorized based on the location of the defect, distinguishing between intralaminar [6] and interlaminar [7] damages. Intralaminar damage, such as matrix cracking, fiber fracture, fiber/matrix debonding, and fiber pull-out [8], primarily manifests at the free edges of the structure due to stress concentration in these areas. Conversely, interlaminar defects, such as delamination and interlaminar shear cracking, occur within the bulk of the laminate and are often associated with geometric irregularities introduced during manufacturing processes or because of impact loading. One prevalent interlaminar defect is interlaminar delamination (hereinafter, delamination), characterized by a separation between adjacent layers of the laminate [9]. Delamination can occur over a large area or involve multiple regions, posing a significant risk of catastrophic structural failure if left undetected or untreated. Understanding the necessity of detecting subcritical damage initiation in laminates is crucial for ensuring safety and maintenance in composite structures.

The benefits of NDT techniques for damage detection: Non-destructive testing (NDT) techniques play a crucial role in upholding structural integrity and safety in diverse industries, with a particular emphasis on composites and laminated structures. These techniques are indispensable for ensuring the integrity and safety of structures in a range of industries [10]. These techniques offer numerous benefits that are essential for ensuring structural integrity and safety across various industries. Firstly, NDT methods facilitate early defect detection by analyzing material characteristics, internal structures, and surface conditions without causing any impact on the object itself. This proactive approach enables timely maintenance, minimizing downtime, and mitigating the risk of catastrophic failures, which is especially crucial in the case of composite materials prone to delamination or fiber breakage. Secondly, these techniques lead to substantial cost savings by identifying damages at an early stage, thus averting expensive replacements or extensive repairs in composite structures. Thirdly, NDT assures safety by ensuring that composite components meet quality standards and specifications, thereby contributing to safer operations, particularly in critical sectors like aerospace and marine engineering where laminated structures are prevalent [11]. Additionally, NDT offers non-intrusive inspection, preserving the integrity of composite materials during examination, which is crucial for in-service assessments. Lastly, NDT techniques possess wide applicability in the composite industry, capable of detecting both internal and external irregularities, determining material composition, and making precise measurements across various composite materials and structures. In summary, NDT methods serve as essential tools for maintaining safety, prolonging the lifespan of composite structures, and ensuring reliable performance. By integrating different NDT techniques, engineers can conduct comprehensive assessments, particularly in the realm of composite materials and laminated structures [12].

Advanced Composite Defect Detection: Vibration-Based NDT and Modal Damping Analysis

Vibration-based NDT techniques: Unlike most current NDT techniques, which often require out-of-service, offline measurements, oscillation-based techniques offer the advantage of real-time, online applications. Methods like Ultrasound or Acoustic Emission necessitate the equipment to be taken offline for assessment, interrupting operations and potentially delaying defect detection. Conversely, oscillation-based techniques, including Lamb waves and vibration-based Structural Health Monitoring (SHM), enable the detection of damage in real time, facilitating continuous monitoring without disrupting operations. Vibration-based SHM techniques, in particular, present logistical simplicity and cost-effectiveness, making them attractive for widespread implementation. However, it's worth noting that while vibration-based techniques are generally sensitive to large damages, they may exhibit insensitivity to smaller defects [13]. Yet, modal damping, a characteristic of the structure inherent in vibration-based methods, offers sensitivity to subtle damages such as small delamination, providing a nuanced understanding of structural health [14]. Therefore, despite some limitations, vibration-based NDT techniques, especially those incorporating global modal parameters, offer valuable insights into structural integrity in real-time and at a relatively low cost. Before delving into the numerical modeling challenges, it's crucial to understand the behavior of modal damping as accurate predictions are essential for effective damage detection strategies.

Modal damping as a Damage Index (DI): In frequency domain data analysis, identifying structural deficiencies often involves observing alterations in modal parameters, including natural frequency [15, 16], mode shape curvature [17, 18], and modal damping [19, 20]. However, previous research has noted that despite its global nature, natural frequency is generally insensitive to small damages [14]. Similarly, the localized nature of mode shape curvature makes it less suitable for detecting defects occurring in arbitrary locations within structures. The prior experimental research serves as the background for this study, as it demonstrated significant variations in modal damping based on the extent of delamination within a composite structure [14]. Therefore, this study aims to explore modal damping as a reliable damage indicator (DI) in delaminated structures.

Numerical modeling of modal damping: Given the potential of modal damping as a DI in delaminated structures, Utilizing numerical modeling techniques is crucial for gaining a deeper understanding of modal damping behavior in delaminated structures. The utilization of numerical models not only offers numerous advantages but also presents certain challenges that need to be addressed for accurate and reliable predictions. Numerical modeling of modal damping provides several advantages, including the ability to simulate a wide range of loading conditions and damage scenarios [21]. Through numerical simulations, researchers can systematically investigate the influence of various factors, such as material properties, geometric configurations, and environmental conditions, on modal damping [22]. Additionally, numerical models enable the efficient exploration of complex structural behaviors, facilitating the identification of optimal monitoring strategies and damage detection algorithms. Moreover, numerical simulations offer cost-effective alternatives to experimental testing, allowing for extensive parametric studies and sensitivity.

Exploring Modal Damping Modeling and Composite Defect Simulation: Insights from Current Methods

An Overview of Numerical Methods for Modal Damping Modeling: Numerical modeling plays a significant role in studying modal damping, a crucial parameter in structural dynamics that governs the rate at which mechanical energy dissipates in vibrating structures. It offers a powerful toolset to accurately analyze and predict damping characteristics. Modal damping, defined as the ratio of the energy dissipated per cycle to the total energy of the vibrating system, characterizes the structure's ability to absorb and dissipate energy during vibration. Various factors, including material properties, structural geometry, boundary conditions, and environmental effects, influence modal damping. In structural dynamics analyses, modal damping is typically represented using damping ratios associated with each mode of vibration [23]. Regarding numerical techniques for analyzing modal damping behavior in structural dynamics, the Finite Element Method (FEM) is widely utilized. FEM discretizes the structure into finite elements, enabling accurate representation of complex geometries and material properties [24]. While traditional eigenvalue analysis typically neglects damping effects, specialized techniques incorporating damping models such as Rayleigh damping [25], Prony series [26], or material damping [27] formulations can be employed within FEM analyses to account for modal damping behavior. Modal analysis techniques are then employed to extract modal parameters, including natural frequencies, mode shapes, and modal damping ratios.

Although numerical algorithms such as Lanczos iteration [28] or subspace iteration methods [29] are commonly used to solve the undamped eigenvalue problem, they may not fully capture the effects of damping. In contrast, time-domain simulations [30] offer insights into dynamic responses and modal damping behavior under transient loading conditions, providing a more comprehensive understanding of damping behavior. While time-domain simulations are computationally intensive, they offer the advantage of capturing nonlinear and transient effects that may affect modal damping. Reduced Order Modeling (ROM) techniques such as Craig-Bampton or Guyan reduction are employed to mitigate computational costs while maintaining accuracy, generating simplified models that retain only dominant modes of vibration, significantly reducing computational burdens [31]. Despite the advantages of numerical modeling, challenges exist in accurately predicting modal damping behavior. These challenges include numerical damping artifacts, model validation against experimental data, and computational efficiency [13]. Careful consideration of numerical methods and parameters is essential to ensure reliable predictions of modal damping. In experimental works, it is challenging to investigate an exclusive damping mechanism, as multiple damping mechanisms are often present [14]. Therefore, experimental validation of damping models may involve complexities in isolating and characterizing individual damping contributions, further emphasizing the need for comprehensive numerical modeling approaches. Numerical methods have been extensively applied to model modal damping in various engineering applications. Case studies demonstrate the effectiveness of numerical techniques in predicting modal damping behavior and guiding engineering decisions, including aerospace structures, automotive components, and civil engineering infrastructure subjected to dynamic loading conditions [32, 33]. In conclusion, numerical methods play a crucial role in modeling modal damping behavior, offering powerful tools for analyzing and predicting damping characteristics in vibrating structures.

Multi-Scale Modeling of Defects in Laminate Structures: Multi-scale modeling of interlaminar and intralaminar defects in composite laminates is indispensable for understanding and predicting structural performance [34]. These laminates, comprising stacked layers of fibers and matrix, exhibit complex behavior influenced by defects across various scales. At the micro-scale, intralaminar defects such as matrix cracking, fiber breakage, and fiber/matrix debonding occur within individual layers [35]. Microscopic finite element models are employed to capture these defects, considering interactions between fibers and matrix, thus aiding in predicting local stress concentrations and failure initiation sites [36]. Additionally, interlaminar defects, such as micro-voids embedded within fiber bundles, significantly impact mechanical properties but are challenging to detect. Peridynamic models at this scale analyze void-induced stiffness reduction and crack initiation near voids [37, 38]. Transitioning to the mesoscale, models focus on individual layers or ply interfaces, addressing transverse matrix cracking and delamination between adjacent layers [39, 40]. These models consider the interaction between neighboring plies and the effect of defects on stiffness and strength. Furthermore, macro-scale finite element models simulate entire composite structures, incorporating intralaminar defects such as matrix cracks and fiber breakage, thus predicting global stiffness reduction and load-carrying capacity. Meanwhile, delamination at the macro-scale affects overall laminate strength and stability, with cohesive zone models [41] employed to simulate crack propagation along layer interfaces, considering energy release rates and fracture toughness. Comparing these modeling approaches, micro-scale models provide detailed insights into local defect behavior but are computationally expensive. Meso-scale models offer a balance between detail and efficiency, capturing both intralaminar and interlaminar defects, although they may still require significant computational resources. Macro-scale models offer a global view of structural behavior but may oversimplify defect interactions. Cohesive zone models excel at capturing crack propagation but require accurate input parameters. In conclusion, each modeling scale offers unique advantages and challenges. Integrating multi-scale modeling approaches can provide a comprehensive understanding of defect behavior in composite laminates, aiding in material design and structural optimization. However, careful consideration of computational resources, model complexity, and validation against experimental data is crucial to ensure accurate and reliable predictions.

Conclusion

This work provides an overview of the author's Ph.D. research which emphasizes the importance of detecting interlaminar delamination defects in laminate structures to ensure their integrity. By employing vibration-based non-destructive testing (NDT) techniques with modal damping analysis, we accurately identified these critical defects. Supported by numerical modeling, particularly the finite element method (FEM), we analyzed the structure's behavior, considering viscoelastic (VE) and frictional damping mechanisms. We performed dynamic explicit analysis and utilized fast Fourier transform (FFT) for time-to-frequency conversion. Parametric studies rigorously compared defected and pristine structures, assessing changes in resonance frequencies and modal damping. These findings contribute significantly to advancing structural health monitoring (SHM) practices, providing invaluable insights for assessing and maintaining composite structures in service.

References

[1] A. Vedernikov, A. Safonov, F. Tucci, P. Carlone, I. Akhatov, Pultruded materials and structures: A review, Journal of Composite Materials. 54 (2000) 4081–4117. https://doi.org/10.1177/0021998320922894

[2] G. I. Zagainov, G. E. Lozino-Lozinsky, Composite Materials in Aerospace Design, Springer Science & Business Media, 1996. https://doi.org/10.1007/978-94-011-0575-0

[3] D. K. Rajak, D. D. Pagar, A. Behera, P. L. Menezes, Role of composite materials in automotive sector: potential applications, Advances in Engine Tribology. (2000) 193-217. https://doi.org/10.1007/978-981-16-8337-4_10

[4] L. Lui, B. Z. Zhang, D. F. Wang, & Z. J. Wu, Effects of cure cycles on void content and mechanical properties of composite laminates, Composite Structures. 73 (2006) 303-309. https://doi.org/10.1016/j.compstruct.2005.02.001

[5] E. Benvenuti, O. Vitarelli, A. Tralli, Delamination of FRP-reinforced concrete by means of an extended finite element formulation, Composites Part B: Engineering. 43 (2012) 3258–3269. https://doi.org/10.1016/j.compositesb.2012.02.035

[6] S. Hühne, J. Reinoso, E. Jansen, R. Rolfes, A two-way loose coupling procedure for investigating the buckling and damage behavior of stiffened composite panels, Composite Structures. 136 (2016) 513–525. https://doi.org/10.1016/j.compstruct.2015.09.056

[7] Allix, O., & Ladevèze, P., Interlaminar interface modeling for the prediction of delamination, Composite Structures. 22 (1992) 235–242. https://doi.org/10.1016/0263-8223(92)90060-P

[8] M. Saeedifar, H. Hosseini Toudeshky, The effect of interlaminar and intralaminar damage mechanisms on the quasi-static indentation strength of composite laminates, Applied Composite Materials. 30 (2023) 871–886. https://doi.org/10.1007/s10443-023-10123-x

[9] S. A. Ramu, V. T. Johnson, Damage assessment of composite structures—a fuzzy logic integrated neural network approach, Computers & Structures. 57 (1995) 491–502. https://doi.org/10.1016/0045-7949(94)00624-C

[10] A. M. Amaro, P. N. B. Reis, M. F. S. F. De Moura, J. B. Santos, Damage detection on laminated composite materials using several NDT techniques, Insight-Non-Destructive Testing and Condition Monitoring. 54 (2012) 14-20. https://doi.org/10.1784/insi.2012.54.1.14

[11] P.E. Mix, Introduction to Nondestructive Testing: A Training Guide, 2nd ed., John Wiley & Sons, 2005. https://doi.org/10.1002/0471719145

[12] P. Duchene, S. Chaki, A. Ayadi, P. Krawczak, A review of non-destructive techniques used for mechanical damage assessment in polymer composites, Journal of Materials Science. 53 (2018) 7915-7938. https://doi.org/10.1007/s10853-018-2045-6

[13] A. S. Nobari, M. H. F. Aliabadi, Vibration-based Techniques for Damage Detection and Localization in Engineering Structures, World Scientific, 2018. https://doi.org/10.1142/9781786344977_0001

[14] M. Khazaee, A.S. Nobari, M.H.F. Aliabadi, Experimental Investigation of Delamination Effects on Modal Damping of a CFRP Laminate, Using a Statistical Rationalization Approach, in: Vibration-Based Techniques for Damage Detection and Localization in Engineering Structures, World Scientific, 2018, pp. 75-103. https://doi.org/10.1142/9781786344977_0003

[15] A. Paolozzi, I. Peroni, Identification of models of a composite plate for the purpose of damage detection, AEROTEC. MISSILI SPAZIO. 6 7(1988) 119-129.

[16] A. Paolozzi, I. Peroni, Detection of debonding damage in a composite plate through natural frequency variations, Journal of Reinforced Plastics and Composites. 9 (1990) 369-389. https://doi.org/10.1177/073168449000900404

[17] A. K. Pandey, M. Biswas, M. M. Samman, Damage detection from changes in curvature mode shapes, Journal of Sound and Vibration. 145(1991) 321-332. https://doi.org/10.1016/0022-460X(91)90595-B

[18] P. Qiao, K. Lu, W. Lestari, J. Wang, Curvature mode shape-based damage detection in composite laminated plates, Composite Structures. 80(2007) 409-428. https://doi.org/10.1016/j.compstruct.2006.05.026

[19] B. Nanda, D. Maity, D. K. Maiti, Vibration-based structural damage detection technique using particle swarm optimization with incremental swarm size, International Journal Aeronautical and Space Sciences. 13(2012) 323-331. https://doi.org/10.5139/IJASS.2012.13.3.323

[20] T. R. Jebieshia, D. Maiti, Vibration characteristics and damage detection of composite structures with anisotropic damage using unified particle swarm optimization technique. In: Proceedings of the American Society for Composites, 13th Technical Conference, East Lansing, MI, 2015, pp. 28–30. https://doi.org/10.1016/j.compscitech.2015.04.014

[21] D. A. Pereira, T. A. M. Guimarães, H. B. Resende, D. A. Rade, Numerical and experimental analyses of modal frequency and damping in tow-steered CFRP laminates, Composite Structures. 244 (2020) 112-190. https://doi.org/10.1016/j.compstruct.2020.112190

[22] S. E. Hamdi, Z. M. Sbartaï, S. M. Elachachi, Performance assessment of modal parameters identification methods for timber structures evaluation: Numerical modeling and case study, Wood Science and Technology. 55 (2021) 1593-1618. https://doi.org/10.1007/s00226-021-01335-0

[23] S. Adhikari, Structural Dynamic Analysis with Generalized Damping Models: Analysis, John Wiley & Sons, 2013. https://doi.org/ 10.1142/9781786344977_0001

[24] E. Carrera, M. Cinefra, M. Petrolo, E. Zappino, Finite Element Analysis of Structures Through Unified Formulation, John Wiley & Sons, 2014. https://doi.org/10.1002/9781118572023

[25] R. E. Spears, S. R. Jensen, Approach for selection of Rayleigh damping parameters used for time history analysis, The Electronic Journal of Geotechnical Engineering. 6 (2012) 061801. https://doi.org/10.1115/1.4006855

[26] Sh. Kiasat, M. Filippi, A. S. Nobari, E. Carrera, Layer-wise dynamic analysis of a beam with global and local viscoelastic contributions using an FE/Laplace transform approach, Acta Mechanica. 233 (2022) 4747-4761. https://doi.org/10.1007/s00707-022-03349-6

[27] C. W. Bert, Material damping: An introductory review of mathematical models, measures, and experimental techniques, Journal of Sound and Vibration. 29 (1973) 129-153. https://doi.org/10.1016/S0022-460X(73)80131-2

[28] J. K. Cullum, R. A. Willoughby, Lanczos Algorithms for Large Symmetric Eigenvalue Computations, SIAM, 2002. https://doi.org/10.1007/978-1-4684-9192-0

[29] K. J. Bathe, The subspace iteration method–Revisited, Computers & Structures 126 (2013) 177-183. https://doi.org/10.1016/j.compstruc.2012.06.002

[30] X. Y. Li, S. S. Law, Identification of structural damping in time domain, Journal of Sound and Vibration. 328 (2009) 71-84. https://doi.org/10.1016/j.jsv.2009.07.033

[31] M. Kurt, Identification, Reduced Order Modeling and Model Updating of Nonlinear Mechanical Systems, University of Illinois at Urbana-Champaign, 2014. https://doi.org/10.1142/9781118572023

[32] G. Kerschen, M. Maxime, J. C. Golinval, C. Stephan, Nonlinear modal analysis of a full-scale aircraft, Journal of Aircraft, 5(2013) 1409–1419. https://doi.org/10.2514/1.C031918

[33] G. A. Papagiannopoulos, D. E. Beskos, On a modal damping identification model of building structures, Archive of Applied Mechanics. 76 (2006) 443-463. https://doi.org/10.1007/s00419-006-0046-4

[34] K.-N. Antin, A. Laukkanen, T. Andersson, D. Smyl, P. Vilaça, A multiscale modelling approach for estimating the effect of defects in unidirectional carbon fiber reinforced polymer composites, Materials. 12 (2019) 1885. https://doi.org/10.3390/ma12121885

[35] T. A. Sebaey, G. Catalanotti, N. P. O'Dowd, A microscale integrated approach to measure and model fiber misalignment in fiber-reinforced composites, Composites Science and Technology. 183 (2019) 107793. https://doi.org/10.1016/j.compscitech.2019.107793

[36] Y. Fu, X. Yao, X. Gao, Micro-mesoscopic prediction of void defect in 3D braided composites, Composites Part A: Applied Science and Manufacturing. 147(2021) 106450. https://doi.org/10.1016/j.compositesa.2021.106450

[37] A. Yaghoobi, M. G. Chorzepa, S. S. Kim, S. A. Durham, Mesoscale fracture analysis of multiphase cementitious composites using peridynamics, Materials. 10 (2017) 162. https://doi.org/10.3390/ma10020162

[38] M. Zaccariotto, G. Sarego, D. Dipasquale, et. al. Discontinuous mechanical problems studied with an aerodynamics-based approach, Aerotecnica Missili & Spazio. 96 (2017) 44-55. https://doi.org/10.1007/BF03404736

[39] Y. Yu, J. Ye, Y. Wang, B. Zhang, G. Qi, A mesoscale ultrasonic attenuation finite element model of composites with random-distributed voids, Composites Science and Technology. 89 (2013) 44-51. https://doi.org/10.1016/j.compscitech.2013.09.006

[40] S. Kiasat, A. S. Nobari, M. Filippi, E. Carrera, Characterization of viscoelastic damping mechanism in a delaminated structure, Mechanical Systems and Signal Processing. (Manuscript submitted for publication).

[41] S. A. Ponnusami, S. Turteltaub, S. van der Zwaag, Cohesive-zone modelling of crack nucleation and propagation in particulate composites, Engineering Fracture Mechanics 149 (2015) 170-190. https://doi.org/10.1016/j.engfracmech.2015.09.050