Abstract

Structures bear loads, transmit forces, and execute specific functions based on their intended use. Fabricating an entire structure as a single entity is often impractical due to manufacturing limitations and the need to engineer the structure components as per design requirements. A structure, therefore, generally consists of many parts and sub-components that are assembled or joined together to function as an efficient unit. Joints are generally the weakest part of a structure; hence, joining techniques have been optimized through millions of years of evolution. The particular choice of joints required for joining materials/substructures varies depending on several factors, such as applicability, strength-to-weight ratio, required performance, environmental conditions, cost-effectiveness, and others.

Conventional joining techniques, in general, pose several limitations, but for joining composites and thermoplastics, they are particularly unreliable and ineffective. Adhesive bonding has emerged as a preferred alternative to bonding two materials over conventional joining techniques. Adhesive bonding aids in the dispersion of stress across a wider surface, hence decreasing abrupt stress variations and enhancing the effectiveness of joints.

The main objective of this thesis is to develop an understanding of stress distribution, crack initiation, and crack propagation in single lap joints (SLJs) and stepped lap joints under quasi-static loading. It is crucial to efficiently transmit shear-dominated loads over multiple layers in order to enhance the structural performance of these joints. Peel and shear stresses are generated by eccentric loading and longitudinal deformation, resulting in maximum stresses at the interface between the bond layers. The occurrence of these maximum stresses might lead to premature failure and abrupt disbonding.

Advancements in Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) technology are enabling the creation of complex shapes and distinct interface structures, potentially leading to stronger SLJs and stepped lap joints. However, limited information on failure mechanisms in 3D printed joints hinders progress. While geometrical grading of adhesives reduces stress gradients, current literature lacks comprehensive insights into optimizing adhesive properties in both longitudinal and through-thickness directions to enhance joint performance. Gaining a comprehensive grasp of the capabilities and failure analysis of FDM-printed adherend

with geometrically graded surfaces, together with adhesive bonding, is essential in order to fully utilize the potential of 3D printing for improving joint strength. The work commenced by conducting material characterization of thermoplastics in order to create accurate material models for computational analysis. 3D printing technology was extensively used to create parts for material characterization and joint assemblies. Two thermoplastics, Polylactic Acid (PLA) and Polyamide (PA) were characterized for this purpose. In addition, printing conditions was optimized in order to create thermoplastic joints that adhere to specified requirements.

Computational models were developed using the commercial finite element (FE) software Abaqus CAE 6.21. These models incorporated various material behaviours, including ductile damage of polymers, cohesive zone modelling (CZM), hyper-elastic models, and elasto-plastic analysis. Finite element analysis was conducted to gain insights into stress distribution, crack initiation, and crack propagation. Next, the insights gained from understanding the root causes of failure mechanisms and ineffective stress distribution criteria led to geometrically tailoring the adherend or adhesive. This approach aimed to reduce peak stress and distribute stress more evenly over a broader area. As a result, geometrically tailored adherends and adhesives were developed, significantly enhancing joint structural performance. Additionally, parametric investigations were conducted to assess the influence of key geometrically graded tooth parameters on failure load and strain. Finally, the computational findings were validated with experimental results. The thesis provides a comprehensive analysis of computational and experimental methods to improve joint performance by using range of material sets and geometrical grading strategies.

Tailored similar PLA-adhesive-PLA SLJ showed an average strength improvement of ≈27.6% over the baseline PLA-PLA SLJ. Optimized dissimilar "P/PA-A-N/PLA" SLJ demonstrated a 58.5% increase in average strength compared to baseline PLA-adhesive-PA, measuring 1480 ± 51 N. Significant improvement in average fracture strain by approximately 143% is observed in the "P/PA-A-N/PLA" joint, over baseline PLA-adhesive-PA. The observed failure load for tailored three stepped lap joint was 4423 ± 143 N, while single-stepped lap joint recorded a failure load of 1216 ± 65 N. In comparison to joints with longitudinally tailored compliance, peel (35–69%) and shear (21–34%) stresses at the bi-adhesive interface are significantly reduced when the bondlayer's geometric compliance is graded both in the transverse and longitudinal directions. This ensures diffusion of peak stresses away from the bi-adhesive interface without significantly altering the

joint stiffness. The experimental and numerical load-displacement graphs demonstrated a strong correlation. The difference in failure strength was less than ≈ 10% across all similar 3D-printed PLA SLJs and PLA stepped lap joints. For all dissimilar FDM-printed SLJ configurations, the FE predictions slightly overestimated the experimental failure loads. The joint stiffness was nearly identical in both the experimental and numerical results for compliance-tailored bond-layer SLJs.

Keywords: Adhesive bonding, joint design, failure and stress analysis, finite element analysis, 3D printing