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Editorial

Design of Adhesive Bonded Joints

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Adhesive bonded joints have become vital to modern engineering, offering advantages such as weight reduction, enhanced fatigue performance, and improved stress distribution [1]. As a result of these characteristics, the evolution of adhesive technology has significantly influenced engineering practices, leading to widespread adoption in various industries [2]. The design of adhesive joints involves a complex interplay of factors, including adhesive selection, joint configuration, and loading conditions [3]. Despite significant progress, challenges persist, necessitating a critical examination of current design practices [4]. This MDPI Special Issue entitled "Design of Adhesive Bonded Joints" serves as a platform to explore the limitations and opportunities in bonded joint design, emphasizing adhesives, joint characterization, experimental and analytical analyses, and predictive modeling. In this editorial, current design limitations, avenues for improvement, ongoing lines of research, and prospects in bonded joint design are addressed.

Current Design Limitations:

One primary concern is the lack of standardized procedures for adhesive joint characterization. The variability in testing methods and reporting parameters hinders the comparability of results, impeding the establishment of universal design guidelines [5]. Additionally, the absence of a unified approach for predictive modeling and failure analysis poses challenges in ensuring design reliability under diverse loading conditions.

- Experimental limitations: one of the primary challenges in adhesive bonding design is the lack of standardized procedures for adhesive joint characterization. Experimental testing methods vary widely across studies, leading to inconsistencies in results and hindering the establishment of universally applicable design guidelines [5]. Variability in factors such as specimen geometry, loading conditions, and environmental parameters complicates the comparison of results and compromises the reliability of experimental data. Examples of round-robin studies try to mitigate this disadvantage [6]. Moreover, quasi-static testing fails to adequately capture the dynamic behavior of adhesive joints under real-world conditions including dynamic loads and impact, often leading to extrapolations of the material behavior [7]. The impact of factors such as temperature variations, humidity, and loading rates on joint performance remains insufficiently explored [8].
- Numerical limitations: numerical simulations, particularly those based on finite element methods (FEMs), constitute a powerful tool to predict the behavior of bonded joints [9]. However, challenges persist in achieving accurate and reliable simulations. The complexity of adhesive joint behavior, e.g., plasticity, stress concentrations, and initiation and propagation of cracks, requires advanced modeling approaches that surpass the common simplifying assumptions [10]. Cohesive zone models, the most widespread technique to simulate crack propagation in adhesive joints, are limited by the assumptions inherent in their formulations [11]. The estimation of cohesive parameters, such as the cohesive strength and fracture toughness, often relies on trial-and-error procedures, introducing uncertainties in the predictions [12]. Additionally,

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the applicability of standardized law shapes, such as triangular, across different adhesive types and joint geometries remains a topic of ongoing investigation due to the known geometry effects on the cohesive properties [13,14]. While the FEM provides valuable insights, the computational cost associated with detailed simulations of large and complex structures poses a challenge [15].

Improving Existing Design Processes:

Addressing current limitations requires a concerted effort to standardize testing protocols and develop comprehensive design guidelines [16]. Robust methodologies for adhesive joint characterization, including experimental testing and numerical analyses, are essential. Advances in non-destructive evaluation techniques can enhance the understanding of joint behavior, contributing to more accurate predictions of performance.

- Standardization of testing protocols: as previously mentioned, a fundamental challenge of bonded joint design is the lack of standardized testing protocols for adhesive joint characterization. Variations in testing methodologies, specimen configurations, and data analysis hinder the comparability of results across studies [17]. To improve design processes, it is necessary to develop and adopt standardized testing procedures [18]. These protocols should encompass quasi-static, dynamic, and environmental factors, ensuring a comprehensive understanding of adhesive joint behavior.
- Advanced numerical techniques: simplistic analytical/numerical models fail to capture the complex behavior of adhesive joints [19]. To address this limitation, designers should embrace advanced techniques, such as FEM simulations, for a more detailed understanding of joint mechanics, especially post-elasticity [20]. Cohesive zone models and damage mechanics can be integrated into numerical frameworks to provide a more accurate representation of crack onset and growth [21].
- Tailoring adhesives for specific applications: advances in materials science offer an opportunity to tailor adhesives at the molecular level, catering to the specific requirements of diverse applications [22]. Designers can collaborate with material scientists to develop adhesives with enhanced properties, such as improved thermal resistance, durability, and flexibility [23].
- Incorporating non-destructive evaluation (NDE) techniques: the integration of NDE techniques into the design process can significantly enhance the monitoring process of adhesive joint performance under service [24]. Techniques such as ultrasonic testing, thermography, and acoustic emission monitoring provide real-time information on the integrity of joints without causing damage [25]. This approach promotes early detection of potential damage, enabling corrective actions to be implemented before loss of structural integrity.

Current Lines of Research:

The field of adhesive bonded joint design is actively evolving. Structural adhesives, with tailored properties to meet specific application requirements, as identified in the previous section, are a focal point of ongoing investigations [26]. Experimental testing of adhesives under extreme conditions, such as high temperatures or corrosive environments, provides insights into the limits of adhesive performance [27,28]. Numerical analyses, including FEM simulations, are becoming more sophisticated.

- Tailoring structural adhesives: structural adhesives can be tailored to meet specific application requirements [29]. The quest for adhesives with customized properties, such as enhanced strength, durability, and environmental resistance, is driving collaborations between material scientists and engineers. Researchers are exploring innovative formulations, including nanocomposite adhesives and bio-inspired adhesives, to achieve superior performance in diverse operating conditions [30,31].
- Experimental testing under extreme conditions: the performance of adhesive joints under high temperatures, in humid and corrosive environments, and under dynamic loading, is an active area of investigation [32,33]. This line of research not only expands the funda-

mental knowledge but also informs the development of adhesive formulations resilient to harsh operating conditions, crucial for industries like aerospace and automotive [34].

- Advancements in numerical analyses: the refinement of numerical analyses, particularly FEM simulations, is a vital point of research [9,35]. Researchers are incorporating more sophisticated modeling techniques to accurately simulate the intricate mechanics of adhesive joints [36,37]. Cohesive zone models are being fine-tuned to enhance their predictive capabilities [38]. This research contributes to a more nuanced understanding of joint behavior, facilitating the design of adhesive joints.
- Dynamic impact and fatigue testing: understanding how adhesive joints respond to dynamic loading, impact forces, and fatigue conditions is another area garnering significant attention [39–41]. Researchers are conducting experiments to elucidate the dynamic behavior of adhesive joints, providing insights into their resilience and failure mechanisms under varying loading rates [42]. This research is pivotal for applications where structures are subjected to cyclic loading or impact events, such as in automotive crash scenarios or structural components in wind turbines [43,44].

Prospects:

The future of adhesive bonding is driven by advancements in materials science, computational modeling, and manufacturing technologies [45]. Tailoring adhesives at the molecular level will ensure high-performance joints for specialized applications. The integration of machine learning algorithms into predictive modeling can enhance the accuracy of strength and failure predictions [46]. Additionally, the exploration of meshless methods and extended finite element methods (XFEMs) can provide a more efficient and accurate representation of complex joint behaviors.

- Tailoring adhesives at the molecular level: one of the most promising prospects lies in the ability to tailor adhesives at the molecular level [47]. This entails designing adhesives with precise properties to meet the specific demands of diverse applications. Adhesives are expected to have enhanced performance characteristics, such as superior strength, durability, and adaptability to challenging environmental conditions [48].
- Integration of machine learning into predictive modeling: the future of adhesive joint design envisions a seamless integration of machine learning algorithms into predictive modeling [39]. By learning from vast datasets of experimental and simulated results, machine learning algorithms can identify patterns and correlations that might elude traditional predictive methods [49]. Thus, the optimization of adhesive joint designs becomes possible for a wide range of applications.
- Exploration of meshless methods and XFEMs: the traditional FEM faces challenges in efficiently representing complex crack initiation and propagation in adhesive joints [50]. Meshless methods and XFEMs offer alternatives that could provide a more accurate and computationally efficient representation of joint behavior [51,52].
- Emerging technologies: as technology advances, so do the tools available for adhesive joint design. Emerging technologies, such as additive manufacturing, present opportunities to create intricate joint geometries and customized adhesive interfaces [53]. These technologies not only enhance the manufacturing process but also open avenues for innovative joint configurations that were previously impractical or impossible to achieve [54].

In conclusion, this MDPI Special Issue entitled "Design of Adhesive Bonded Joints" provides a timely platform to address the challenges and opportunities in this evolving field. Current design limitations necessitate standardized testing procedures and guidelines, while ongoing research explores advanced materials and improved numerical techniques. The future holds exciting prospects, with a focus on tailoring adhesives, integrating advanced modeling approaches, and embracing emerging technologies to drive the design of adhesive bonded joints to new heights. As the field continues to evolve, collaborative efforts among researchers, engineers, and industry professionals will be crucial in advancing the science and practice of adhesive joint design.

Conflicts of Interest: The author declares no conflict of interest.

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