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Recent Developments in Numerical Modelling of Composite Structures

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Composite materials have become essential in engineering design due to their superior strength-to-weight ratios, corrosion resistance, and direction-oriented mechanical properties. These materials are widely used in aerospace, automotive, marine, and civil engineering applications, where the high strength and low weight are critical [1]. As the complexity of composite structures increases, so does the necessity for accurate numerical modelling techniques to predict their behaviour, optimize their design, and extend their service life [2].

Numerical modelling has significantly advanced over the past few decades, enabling designers to simulate the mechanical, thermal, and failure behaviour of composite structures with precision, when coupled with appropriate failure criteria. Finite Element Analysis (FEA) is the most widely used computational tool, offering a robust tool to assess stress distributions, deformations, and failure mechanisms in laminated and sandwich composites [3]. However, traditional FEA approaches present difficulties in capturing complex damage mechanisms such as matrix cracking, fibre breakage, delamination, and debonding, which triggered the development of advanced modelling techniques. One of the most significant advancements in the field is the implementation of multi-scale modelling approaches. These techniques combine the microscale constituent behaviour and macroscale structural response, which results in accurate predictions of material performance. Castricum et al. proposed a multi-scale model that predicts the non-linear elasto-plastic behaviour of short fibre-reinforced composites by integrating a micro-mechanical approach into a finite element framework [4]. The model accounts for fibre and matrix parameters, volume fraction, and aspect ratio, using Voigt, Reuss, and self-consistent models. Enhanced integration schemes and optimized data storage significantly improved the computational efficiency while maintaining accuracy. J-integral, cohesive zone models (CZM), and extended finite element method (XFEM) have showed excellent results due to their ability to simulate progressive damage and crack propagation in composite materials. Hauck and Szekrényes developed plate FEA elements and a numerical algorithm to compute the J-integral in delaminated composite plates [5]. Using first-order (FSDT) and third-order (TSDT) shear deformation theories, the algorithm ensured element continuity and formulated the J-integral as a matrix multiplication. Since commercial software lacks this feature for laminated composites, a new algorithm was proposed and validated through case studies, improving fracture analysis accuracy. Kaushik and Ghosh presented a fracture model to evaluate mode-II and mixed-mode interlaminar fracture properties in laminated composites [6]. Tests on End-Notched Flexure and Mixed-Mode bending specimens estimated crack initiation energy and delamination propagation. A compliance-based beam method correlated energy release rate with crack growth, integrated into a CZM. Scanning electron microscopy examined fracture surfaces, while numerical simulations using isogeometric analysis and CZM aligned well with experimental results. Rashnooie et al. presented an XFEM-based approach combined with cyclic damage mechanics to model fatigue crack growth, delamination, and bridging in metal-fibre-reinforced plastic (FRP) composites [7]. The model captured crack propagation in metal, adhesive degradation, and FRP damage. Simulations accurately predicted the fatigue behaviour, crack paths, and failure modes, agreeing well with experimental data. Advances have also been produced for bonded joints and repairs on these materials by these techniques [8,9].

In parallel, meshless methods, such as the Element-Free Galerkin (EFG) method and Smoothed Particle Hydrodynamics (SPH), have emerged as promising alternatives to traditional FEA techniques, particularly for problems involving severe distortions and impact loading [10]. These methods offer increased flexibility and accuracy in modelling large deformations, high-strain-rate phenomena, and failure evolution in composite structures due the inexistence of a physical mesh. Another crucial area of development is the integration of artificial intelligence (AI) and machine learning (ML) in numerical modelling [11]. Data-driven approaches are increasingly being utilized to enhance material characterization, optimize computational efficiency, and predict failure with higher reliability [12]. AI-powered surrogate models allow for rapid parametric analyses and design optimization, significantly reducing computational costs while maintaining accuracy [13]. Digital twins, with are virtual replicas of physical structures, are now being employed to monitor real-time performance and predict maintenance needs, leading to smarter and more resilient composite structures [14].

Despite these advancements, challenges remain in achieving fully predictive models that account for manufacturing defects, environmental aging, and multi-physics interactions. Thus, the continuous evolution of the reported numerical modelling techniques is essential to ensure the reliability and safety of composite structures in critical applications, and further significant innovations in this field are expected in the near future.

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