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Editorial

Special Issue on Functionally Graded Adhesively Bonded Systems

Guest Editorial

Adhesive bonding is becoming a preferred means of joining materials and structures in the pursuit of realizing cost-effective, lightweight and efficient structural and/or functional systems in areas as diverse as automotive, aeronautics, microelectronics, biomedical systems, and consumer goods. However, high shear and peel stress/strain gradients and concentrations exist at the ends of the overlap due to abrupt stiffness changes causing concern in many applications such as bonded advanced composites, to the point where mechanical fasteners are utilized to complement the adhesively bonded system, adding cost, weight, and complexity. Therefore, in bonded structural systems, an adhesive that is very compliant relative to the adherends is commonly utilized to achieve a shear-dominated load transfer across the joint and to minimize the propensity of interfacial and/or cohesive failure due to high peel stresses a relatively stiffer adhesive may experience. In many applications, such as advanced structural composites, adhesive resistance to peel stresses is of paramount concern, owing to the low transverse strength of the composite. This requires a careful design of the bonded system.

The choice of an appropriate set of adhesive and adherend materials and the performance evaluation of multilayered bonded systems are the key steps in the design of efficient bonded systems. Nevertheless, adherend materials are chosen *a priori* for functional requirements and the design of bonded systems usually does not provide the design freedom to choose alternative materials for the adherends. The designer, however, is still left with two possible options to realize an efficient bonded systems: (i) geometric and material design of the adhesive and (ii) geometric design of the adherends in the joint region. Numerous geometric design options such as modification of the adherend geometry, the adhesive geometry and utilization of a spew (a bead at the lap ends of the adhesive) geometry have been pursued in the past several decades to minimize deleterious effects of such stress/strain concentrations but production constraints still remains a barrier. On the other hand, much progress has been made, particularly in the last decade at micro- and nano-length scales in developing higher performance adhesives with superior macroscopic properties. For example, the 2017 GMC Acadia sport utility vehicle that has just arrived in dealerships around the US is ~320 kg lighter than the version it replaces, and can go 23 miles on a gallon of gasoline, up from 18 m.p.g., a 28% improvement. One of the secrets to the design of such a lightweight, fuel-sipping car is the use of an advanced adhesive termed "ultra-superglue".

Interestingly, performance metrics such as the strength and toughness of bonded systems can be further enhanced without compromising joint stiffness by utilizing spatially-tailored adhesives which we refer to as "functionally graded adhesives". Research on joints with variable adhesive properties over the bondlength was pioneered in the 1960s. Of late, there is growing interest in this area, *e.g.,* it was experimentally shown that the joint strength can be increased about 50–120% by employing a bi-adhesive bondline. The existing work has as of yet considered only a single-step variation in adhesive over the bondlength, with the step-change in both the modulus as well as the adhesion energy of the adhesive. Several recent theoretical studies have considered smoothly varying elastic properties of the adhesive along the bondlength to provide a framework for the mechanics of stress transfer through the adhesive. However, fabrication of bonded systems with spatially varying adhesive properties along the bondlength is challenging, particularly for very thin bondlines and, therefore, the potential of such stiffness-tailored adhesive designs has not been fully realized.

The ever increasing ability to experimentally realize such systems through both micro- and nano-engineering propels researchers to design and implement efficient bonded systems and to optimize their in-service performance by effectively utilizing stiffness-tailored adhesive designs. The main goal of this Special Issue is therefore to report on very recent progress in the theory, computation, fabrication and testing of functionally graded adhesives and joints operating under a range of loading and environmental conditions. The Special Issue comprises 10 papers focusing on graded systems with tailored materials properties along the bondlength, either to engineer high performance systems or to evaluate the influence of damage induced gradients in adhesive properties on the performance of joints.

Fabrication of bonded systems with variable stiffness adhesive along the bondline has been a challenge. The paper by Chiminelli *et al.*, has explored the potential of this technique for a single lap joint (SLJ) considering property variation in discrete steps along the bondlength. Initially, compaction during the assembly process was simulated using a computational fluid-dynamics model and the effect of compaction on the mechanical response was captured in a subsequent finite element (FE) analysis so as to identify an optimum design. Finally, the optimal design configuration of the graded joint was manufactured using a special device developed for producing graded adhesive joints and then tested. It was shown both numerically and experimentally that a graded SLJ with discrete variation in adhesive properties has 70% more load carrying capacity than an unmodified adhesive joint. The editors strongly believe that a specially developed device which enabled fabrication of graded joints with controllable gradients in adhesive properties along the bondline is a significant achievement. In the analysis of such joints where the elastic

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properties of the bondline vary in discrete steps along the bondlength, tri-material singularities may arise at the material junctions, resulting in a finite element (FE) mesh-dependent response. The study by Breto *et al.*, focused on the characterization and treatment of these type of singularities. The use of an intermediate adhesive to reduce the free edge singularity in a SLJ was particularly examined. A combination of asymptotic analysis of a tri-material interface junction and the FE method was used to select the optimum elastic modulus of the intermediate adhesive. Although the stress singularity at the interface junction of a tri-material joint has been well studied, the paper contains sufficient new knowledge, especially the methodology for using discrete material properties of the intermediate adhesive to model the response of a graded SLJ.

The performance of SLJs with a single step variation in adhesive properties along the bondlength was studied by Hözer and Öz by a non-linear finite element method considering a pressure dependent exponential Drucker-Prager yield criterion with isotropic hardening for the adhesives. Failure loads predicted from the FE analysis were found to be in reasonably good agreement with their previous experimental results, suggesting that the inelastic behavior of the adhesive needs to be considered in numerical failure prediction of bi-adhesive joints.

Carbas *et al.*, have produced a graded adhesive whose elastic properties vary in fine discrete steps along the bondlength by non-uniform dispersion of carbon black in the adhesive. Having the same adhesive (matrix) over the entire bondlength allowed for isothermal curing of a nano-reinforced adhesive either by dielectric or thermal heating. Their study reported that the spatially-stiffness tailored joints were found to have a slightly higher joint strength (~20–30%) compared to joints with a uniform dispersion of carbon black along the bondlength and unmodified adhesive. Nevertheless, a smoothly graded dispersion of nanofillers has the potential to realize joints with significantly enhanced strength and toughness. Along the same line, Stapleton *et al.*, explored the design of functionally graded joints involving a polyurethane adhesive which exhibits a large inelastic deformation (failure strain ~20–60%). Controllable gradients in the adhesive properties were achieved either by varying the weight fraction of acrylate or changing the curing kinetics along the bondlength using a single formulation polyurethane. Their study indicates that by finely controlling the network density gradients of the polyurethane along the bondline, the performance of the joints could be further optimized.

Interestingly, Liew *et al.*, developed a dry, functionally graded adhesive based on a film-terminated silicone foam for potential use for the transportation of delicate objects utilizing the foam's capacity to absorb a huge amount of energy to deliver high surface adhesion. The dependence of adhesion on the thickness of the foam layer and preload was investigated. This type of film-terminated foam-based adhesive was demonstrated as a simpler and less expensive alternative to the complex fabrication process of dry fibrillar adhesives. Combination of such an energy absorbing material and dry adhesives can open new avenues for production of elastic and dry adhesives with high resistance to damage and de-bonding.

The study by Patil *et al.*, has developed a methodology to account for the environmental degradation with the aid of a cohesive zone damage model in order to predict the fracture toughness of degraded adhesive joints using fracture data of accelerated aging tests. Although, the paper does not consider a spatial variation of properties or strength, the proposed methodology is directly applicable to the analysis of adhesive joints with gradient strength or stiffness owing to degradation.

Tippireddy and Kumar investigated the performance of spatially-degraded adhesive anchors considering uncertainty in the variable shear modulus of the adhesive along the embedment depth via a stochastic model. It is interesting to note that fire resistant design of adhesive anchors recommends consideration of spatially varying stiffness and strength of the adhesive due to a temperature gradient that may arise along the embedment length in the event of a fire accident. For the parameters considered in their study, about 45% longer embedment length is required to adequately account for likely in-service damage which causes gradient stiffness/strength along the bondlength in order to avoid premature failure.

Stein *et al.*, conducted a comparative study of the existing analytical models corroborating with FE predictions for planar adhesive SLJs having smoothly graded adhesive properties along the bondlength in order to identify an adequate model for a particular design requirement. It was observed that the mismatch between the maximum and minimum values of the adhesive elastic modulus has a significant effect on the peak adhesive stresses. The paper by Durodola has thoroughly summarized the state-of-the-art of functionally graded bonded systems, in terms of analysis, fabrication, experimental testing and applications. The study also highlights the outstanding issues that need to be addressed in order for wider application to be feasible. Durodola has also outlined the challenges associated with surface preparation such as jigging to ensure all parts remain in the desired position during manufacture, identification of appropriate curing conditions, *etc.*, which limit the ability to produce graded adhesive joints in a controlled manner.

Although functionally graded systems have been widely explored, the mechanics and the mechanisms that lead to improved performance of graded systems, particularly under dynamic fatigue and cyclic-fatigue situations still need to be understood. On the other hand, the growth of 3D printing technology to produce complex multi-material interfaces with spatially smoothly varying properties even at micro- and nano-length scales emulating the motifs observed in nature provides the opportunity to develop high performance graded systems with both strength and toughness, properties that are often mutually exclusive. Damage and fracture resistance of adhesive interfaces can also be improved significantlly via such stiffness tailoring. The state-of-the-art in 3D printing further suggests that stiffness tailoring of the adhesive via 3D printing is a possible and generalizable approach for many bonding and interface-tailoring applications.

Putting together this Special Issue has been an exciting and intriguing experience for the guest editors. The review process provided an opportunity to deepen our insights into various aspects of gradient design of multi-layered bonded systems and to discuss the manuscripts directly with the authors in detail. We would like to express our sincere appreciation to the authors for their patience with the process and the reviewers for providing critical comments and feedback on these high quality manuscripts. We hope that this Special Issue may augment the horizons of the IJAA and create new frontiers and partnerships for research on the topic, not only for interface tailoring of bonded systems, but also for material tailoring of interfaces in general. We hope you enjoy reading this Special Issue in the IJAA.

S. Kumar
Department of Mechanical and Materials Engineering, Masdar Institute, Abu Dhabi, UAE
E-mail address: s.kumar@eng.oxon.org

Robert D Adams
Department of Engineering Science, University of Oxford, Parks Road, Oxford, UK
E-mail address: r.d.adams@bristol.ac.uk