1. Introduction

Highly heterogeneous materials with variable and functionally graded local compliance are widespread in nature. Emulating these natural material solutions, engineering graded materials that are stronger and more damage-resistant than their conventional homogeneous counterparts are of great interest. Grading is particularly important at the interfaces between dissimilar materials, where stress commonly originates.\[1–6\] With the advent of various technologies to synthesize and process materials in 3D, gradations in composition, structure, and properties may now be practically engineered over a wide range of length scales ranging from nanometers to meters.\[3,5,7\] Such grading, either continuous or in ever-finer, discrete steps, across an interface and between two dissimilar materials, has been used to redistribute thermal stresses,\[8\] thereby limiting the stresses at critical locations and thus suppressing the onset of permanent (plastic) deformation, damage, or cracking.\[9–11\] Grading of composition is particularly beneficial at mechanical interfaces between dissimilar materials, where stress and strain jumps naturally arise due to mismatch in elastic properties.\[12–16\] A particularly important engineering application of such grading of interfaces is in multilayers.

Multilayers composed of either similar or dissimilar materials, experience stress, and strain concentrations at the ends of the overlap, where such assemblies fail. The stress and strain concentration is particularly problematic in single-lap joint (SLJ) configurations (see Figure 1a) due to the eccentric load path that introduces bending moments and transverse shear forces into the joint (see Figure S1). Goland and Reissner\[12\] is noted as the first to account for the rotation of the joint due to such load path eccentricities and provided analytical expressions for both shear and peel stress concentrations in the bondlayer. To minimize the deleterious effect of such stress concentration on the performance of joints, several techniques have been proposed, among which geometrical grading such as stepping or tapering of the adherends (e.g., see ref.\[13,14\]) modification of the bondlayer geometry (e.g., see ref.\[15\]) and employing a bead at the lap ends of the bondlayer (called a “spew geometry” e.g., see ref.\[16,17\]) were found to be marginally effective and have numerous limitations restricting their application in practice due to producibility constraints, for example.\[18\] Therefore, a few studies have employed more compliant bondlayers in order to minimize the (most problematic) peel stresses. However, with this approach, the increase in strain-tolerance is achieved at the expense of reduced strength and stiffness of the joint. Moreover, a more compliant bondlayer also requires a longer bondlength to enable shear-dominated load transfer across the bondlayer and accommodation of such a longer bondlength is not always feasible.
Spatially tailoring the elastic properties of the bondlayer along the bondlength to reduce end stress and strain concentrations began with the pioneering theoretical studies of Raphael,[19] Hart-Smith,[20] and Srinivas.[21] That work showed that the peel and shear stresses in the bondlayer could be reduced significantly by using a combination of flexible and stiff bonds. Recently, there is growing interest in this area due to the ability to experimentally realize such systems[5,22,23] through both finite element analysis (FEA), the stress and strain redistributions are shown to impart increased performance of the multi-layer assembly (as a function of volume fraction of compliant bond in the bondlayer), improving performance across all the relevant metrics including strength, load transfer efficiency, stiffness, toughness, and deflection to break.

Figure 1. Compliance-tailored tri-layer single-lap joints (SLJs): a) Conceptual representation of SLJ subjected to a far-field tensile stress $\sigma_{\infty}$ with different bondlayer modulus profiles. Bottom shows the ultimate stress ($\sigma_{\text{ult}}$) for constant modulus bondlayers (either $E_s$ or $E_c$) and compliance-tailored systems as a function of volume fraction of compliant bond $\nu_c = l_c/l; b)$ Optical images of 3D printed SLJs with bondlayer compliance-tailoring considering all three profiles in a), including homogeneous stiff ($\nu_c = 0$) and compliant ($\nu_c = 1$), and tailored ($\nu_c = 0.2$) cases. Scale bar in b) is not repeated in remainder of manuscript.

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2. Experimental Section

Additive manufacturing to realize compliance-tailored bondlayers in the multi-material SLJ system is discussed, followed by experimental methods of joint testing including optical strain mapping.

3D Printing and Compliance-Tailoring of the Multimaterial Joint

We utilize Polyjet photopolymer technology that allows multi-material deposition[29–32] to 3D print compliance-tailored single-lap joints (SLJs), as shown in Figure 1a (top). The emergence of such multi-material and composite 3D printing technologies[33–39] facilitates the design of functionally graded designs at the sub-millimeter scale enabling fabrication of multi-material structures simultaneously exhibiting both strength and toughness, which are often difficult to achieve with homogeneous materials.[40,41]

CAD models of SLJs were created using Solidworks (Dassault Systemes, France) and an Object Connex260 Polyjet 3D printer (Statasys Ltd., USA), having eight simultaneously operating print heads, was used for fabrication. The tool has resolution of 16 $\mu$m in the z-direction (width of joint) and 42 $\mu$m in the x- and y-directions (see Figure 1a, top). The printing direction is known to influence the material behavior of printed specimens,[38,42] although this is not relevant in the comparisons here. The liquid photopolymers are cured by UV light concurrent with deposition, producing a fully cured, fully dense structure with no measurable porosity.

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of overhang portions of geometries and was subsequently removed through water washing.

Mechanical Testing

The 3D printed joints were tested in a Zwick-Roell tensile testing machine with a 2.5 kN load cell. The load cell accuracy is $< \pm 0.25\%$ for the measurement range of 10–2500 N, and $< \pm 1\%$ for the measurement range of 2.5–10 N. The tensile load was applied at a constant crosshead speed of 5 mm min$^{-1}$ and displacement was measured at the grips with a travel resolution of 0.041 μm. Digital image correlation (DIC) was used for full-field measurement of shear and peel strains in the joint as a function of load using a monochrome 5.0 MP camera. Random white/black speckle patterns of acrylic paint were formed on the specimen’s surface using an airbrush prior to testing. Vic-2D software was used to evaluate the evolution of the strain field as a function of load. Each of the bondlayer designs was tested three times to evaluate repeatability.

3. Finite Element Analysis

The SLJ assemblies are modeled as a plane-strain problem to reduce computational effort, utilizing a commercial finite element code, Abaqus/Standard FEA version 6.12. The geometric model represents the experimental study, except in the case of the later analysis where the bondlength $2l$ is increased, and the linear elastic material constants used are obtained from our own material characterization experiments (see Figure S3 and related discussion). The model is meshed using a bilinear plane-strain quadrilateral element (CPE4). The element size for the bondlayer is chosen by carrying out a mesh convergence study (see Figure S3 and related discussion). The model is meshed using a bilinear plane-strain quadrilateral element (CPE4). The element size for the bondlayer is chosen by carrying out a mesh convergence study (see Figure S3 and related discussion).

4. Results and Discussion

The load–displacement response of SLJs with different compliant-to-stiff bondlength ratio (or volume fraction of the compliant bond in the bondlayer), $v_c = l_c/l$ (see Figure 2a, b), under quasi-static tension is shown in Figure 2a. Joint stiffness trends are as expected: the joint with stiff bondlayer ($v_c = 0$) has nearly double the stiffness of the compliant bondlayer joint ($v_c = 1$). Introduction of more compliant bond (recall $E_c \approx 2E_s$) at the ends of the bondlayer improves the joint performance broadly (see Figure 2 and Table 1). Taking joint strength as an example, increasing $v_c$ improves the joint strength versus the stiff bondlayer joint, but the performance starts decreasing beyond a particular $v_c$ and approaches that of the compliant bondlayer joint ($v_c = 0$), as shown in Figure 2b. For a given set of geometric and material parameters, there exists an optimal $v_c$ (near 0.2 in this case) for strength, due to stress and strain redistribution and reduction of the concentrations at the joint end. Table 1 provides the summary of performance of the constant modulus and tailored SLJs. Changes (shown in red) are calculated versus both the stiff and compliant constant modulus bondlayer joints. The highest strength SLJ realized experimentally, at $v_c = 0.2$, is noted to be improved relative to both constant modulus cases across all the joint performance metrics: beyond the large strength increases, joint toughness and deflection at break are increased, while maintaining the joint stiffness of the (stiffest) constant modulus bondlayer assembly, i.e., across all relevant metrics, the $v_c = 0.2$ tailored joint is higher performing. Interestingly, several prior studies demonstrated experimentally that a tailored joint can significantly outperform a constant modulus stiffer joint, but has only marginal merit compared to a (more) compliant joint. Our work shows significant improvements in both constant modulus cases with statistical significance.

Figure 3 shows the strain distribution in the joint region obtained from digital image correlation at a load level of 300 N (in the pre-dominantly linear elastic region for all the joints (see Figure 2a) for different $v_c$. The first row in Figure 3 is for the case of stiff bondlayer joint ($v_c = 0$), the bottom row is for the compliant bondlayer joint ($v_c = 1$) and the middle row is for the highest-performing compliance-tailored bondlayer joint ($v_c = 0.2$). Both shear and peel strains are relatively high in the compliant joint as expected (the bottom row of Figure 3).
Table 1. Summary performance of 3D printed single-lap joints.

| Bondlayer design, \( \nu_c = l_c/l \) | Joint stiffness (N/mm) | Ultimate load (N) | Deflection at break (mm) | Joint toughness (\( \times 10^3 \) N.mm) |
|-----------------------------------|------------------------|-------------------|--------------------------|------------------------------------------|
| \( \nu_c = 0 \) (stiff)          | 173.52 ± 1.1           | 1298.40 ± 31.48   | 5.93 ± 0.27              | 3.56 ± 0.27                              |
| \( \nu_c = 0.2 \)                | 173.44 ± 5.92          | 1594.63 ± 58.09   | 6.68 ± 0.19              | 4.89 ± 0.23                              |
| \( \nu_c = 0.4 \)                |                        |                   |                          |                                          |
| \( \nu_c = 0.6 \)                |                        |                   |                          |                                          |
| \( \nu_c = 0.8 \)                |                        |                   |                          |                                          |
| \( \nu_c = 1 \) (compliant)      | 92.03 ± 1.05           | 784.37 ± 23.95    | 6.38 ± 0.093             | 2.24 ± 0.078                             |

Changes (shown in red) are calculated versus the stiff and compliant constant modulus bondlayer joints, and only statistically significant increases are shown.

compared to those of the stiff joint (the top row of Figure 3). The compliance-tailored bondlayer joint (the middle row of Figure 3) strain distributions are intermediate to the two extremes (constant modulus stiff and compliant) as expected. Optical strain mapping at higher loads, closer to failure, failed due to the large strains, and appearance of cracks and shear bands in the images (see supporting video SV1).

Experimentally, the highest performing SLJ is observed to have a short (\( \nu_c = 0.2 \) bondlayer) compliant bond at the ends. Finite element analyses (FEA) were conducted to better understand and elucidate the reinforcement mechanisms leading to the higher performance, specifically to explore the experimentally-identified \( \nu_c = 0.2 \) region as a global optimum. The developed FEMs (see Figure S2 and related discussion for details) show good agreement with less than 2% difference between predicted versus measured initial (elastic) joint stiffness (see Table S2 and related discussion). Figure 4 shows the normalized peel and shear stress distributions in the bondlayer at a loading of 300 N (See Figure 2a) along the bondlength at \( y = 1.4 \) mm near the top interface (\( y = 1.5 \) mm) as a function of \( \nu_c \), as well as the trend of maximum values for each. The peel and shear stress concentrations in Figure 4b and d follow expected trends for the constant modulus cases, for example, the profiles for the stiff (\( \nu_c = 0 \)) and compliant (\( \nu_c = 1 \)) constant modulus cases are nearly identical due to the relatively small change in modulus between those two cases relative to the stiff adherends. Further, the stress peaks occur at the ends (±) of the bondlayer, with the stress peaks reduced slightly for the constant modulus compliant versus stiff bondlayer. For the compliance-tailored bondlayer cases, we observe a reduction in peak stresses (peel stress is exemplary in Figure 4b) as the compliant bond is added (increasing \( \nu_c \)), with the peak location occurring at the interface of the stiff and compliant vertical interface. The reduction in peak stress is non-monotonic toward the compliant constant modulus bondlayer case (see Figure 4c). For relatively small additions of compliant-bond, the peak stress (particularly peel) reaches a local minimum at \( \nu_c = 0.1 \). Both the maximum peel and shear stresses are minimum over \( 0 < l_c/l \leq 0.2 \), consistent with the structural testing observations discussed earlier. The trends in maximum stress values in Figure 4c and e indicate that the compliant constant modulus case is nearly optimal for shear stress, but analysis of the peel stress distribution reveals that both have a minimum at \( \nu_c = 0.1 \), rather than at \( \nu_c = 1 \). The constant modulus compliant bondlayer also will have a significantly reduced joint stiffness, as observed in the experimental data (see Table 1). Thus, from this stress analysis, the joint with \( \nu_c = 0.1 \) is predicted to be the

Figure 3. Strain field distribution in 3D printed SLJs for different \( \nu_c \) under tensile load by DIC at 300 N (see Figure 2a): a) optical images of the SLJs, b) peel strain \( \varepsilon_{xy} \), and c) tensorial shear strain \( \varepsilon_{xy} \). Note that the legend scale changes for \( \nu_c = 1 \). \( l \) is the length of the compliant-bond corresponding to \( \nu_c \).
The manner in which a multi-material joint carries load is strongly influenced by the overlap length relative to a critical length, usually related to the shear-lag length. The critical length is the overlap length that is needed to fully transfer the tensile load in the adherends across the bondlayer in a purely shear mode, and is the preferred approach if not limited by other constraints. An indication of this \((l > l_{\text{crit}})\) is that the shear stress at the center of the bondlength \((x = 0)\) goes to zero. In Figure 4d, we can see that the SLJs considered thus far have \(l < l_{\text{crit}}\). Cases where \(l < l_{\text{crit}}\) are common in many engineering applications, where the overlap length is limited by other considerations, such as fabrication or application physical constraints. It is known that generally, SLJs with \(l < l_{\text{crit}}\) are more prone to peel-stress driven failures due to higher peel stresses than in a comparable joint with \(l > l_{\text{crit}}\). Therefore, it is of interest to also explore cases

![SLJ stress analysis](image)

**Figure 4.** SLJ stress analysis in the bondlayer via FEA: a) Finite element (FE) model of 3D-printed SLJ with various bondlayers under far field tensile stress \(\sigma_{\text{a0}}\), including the refined FE mesh in the stress concentration zone. \(E_a\) is the modulus of the compliant bondlayer, \(E_s\) is the modulus of the stiff bondlayer, and \(E_a\) is the modulus of the adherends. Recall that \(E_s/E_a \geq 2\), and \(E_s/E_a \approx 1000\). Computed stresses in the SLJ bondlayer for experimentally-tested SLJ configurations at a loading of 300 N (See Figure 2a) along the bondlength at \(y = 1.4\) mm (near the top interface where \(y = 1.5\) mm) as a function of \(v_c\): b) normalized peel stress distribution, c) normalized absolute maximum peel stress, d) normalized shear stress distribution, and e) normalized absolute maximum shear stress.

highest performing across three of the four important SLJ mechanical performance metrics, consistent with the experimental findings. The fourth metric, joint toughness, involves detailed failure modeling in the context of material hysteresis and non-linearity during the failure process (see supporting video SV1). This is considered out of scope for the current work, experimental toughness is noted to be highest in the same \(v_c\) as \(v_c = 0.2\) compliance-tailored bondlayer configuration (see Table 1).

Returning to joint failure and toughness trends, two characteristic failure modes were observed in the compliance-tailored SLJs studied here (see Figure 5): 1) cohesive failure in the bondlayer via a macroscopic shear crack (typically in the stiffer bond) and/or fine bondlayer microcracking near to final failure (typically also in the more compliant bond, and occurring over a relatively large portion of the bondlength), and 2) bondlayer peel failure. Figure 5 shows the deformation and failure behavior of SLJs with different \(v_c\) at different stages of loading unto failure. Representative optical failure images from testing, time-synched with the load-deflection plots, are provided in Figure S5 and can be viewed in supporting video, SV1, with a snapshot presented as Figure S5. The specifics of failure of this model 3D printed tri-layered assembly are not the focus of this study, but it should be noted that material properties of the bondlayer apart from modulus (that drives the stress and strain concentration reduction) such as toughness, strength, and adhesion to each other and the adherend, will also influence joint failure and toughness here. The comparisons in the experimental test matrix to the stiff and compliant constant modulus cases (see Table 1) mitigate this interpretation issue substantially, and no major differences in failure mode are observed in the compliance-tailored bondlayer cases, so these effects on toughness and strength are considered small. Furthermore, recent work with a similar single-lap joint assembly where the adhesive properties between the bondlayer and the adherend were maintained (via embedding compliant features that reduce compliance in an average sense), also created enhanced strength and toughness. The features in the prior work complicate somewhat the interpretation of the direct effects of the compliance-driven mechanics by introducing other failure modes and toughening mechanisms, whereas the current work focuses solely and clearly on compliance effects. Last, it should be noted that failure initiation is also highest for the same \(v_c = 0.2\) compliance-tailored bondlayer configuration, as observed in Figure 5a. Regardless of the failure mode(s) and trajectory, the stress and strain redistribution is expected to play the critical role on the joint toughness and seems to follow the same trend as strength (see earlier discussion).
with $l > l_{\text{crit}}$. The $l_{\text{crit}}$ based on Volkersen's\cite{50} analysis, which considers only tensile deformations of identical isotropic adherends, and shear deformation of the bondlayer, is given by

$$l_{\text{crit}} = \sqrt{\frac{E_a t_a}{2G}}$$

(1)

where, $E_a$ is the Young's modulus of the adherends, $G$ is the shear modulus of homogeneous bondlayer, $t_a$ is the thickness of the adherends, and $t$ is the thickness of the bondlayer. $l_{\text{crit}}$ scales with the modulus mismatch between adherends and bondlayer. For given adherends, high shear stiffness bondlayer reduces the critical length required for complete shear stress transfer. $l_{\text{crit}}$ is estimated to be $\approx 0.3 \text{ m}$ for the SLJs assemblies studied here using Equation 1, which is far beyond the limitations of the build platform for 3DP. Moreover, if bending deformation of adherends due to the eccentric load-path is considered, $l_{\text{crit}}$ is $\approx 1 \text{ m}$, as observed from FEA. We, therefore, analyze the tri-layer SLJ as before (see Figure 4), but with $l = 1 \text{ m} > l_{\text{crit}}$. The results of the stress distributions and the maximum stress trends are shown in Figure 6, following the same format as Figure 4. From Figure 6a and c, we see that both peel and shear maximum stresses are reduced significantly for $l > l_{\text{crit}}$ as expected. Moreover, shear stress at the bondlayer midline is almost zero over 80% of the bondlength indicating that $l > l_{\text{crit}}$. Nevertheless, the maximum peel and shear stresses shown in Figure 6b and d indicate that the global optimum is still at $v_{C} = 0.1$. Unlike the case where $l < l_{\text{crit}}$, the maximum peel and shear stresses in the bondlayer saturate for $l > l_{\text{crit}}$ at $v_{C} > 0.3$ as can be seen in Figure 6b and d, also as expected. Comparing the results from Figure 4 and 6, we note that for the short ($l < l_{\text{crit}}$) overlap case, the reduction in maximum stresses employing compliance tailoring is much greater and that the relative length ($l/l_0$) of compliant bond for maximum stress and strain reduction is also greater, than the long overlap case ($l > l_{\text{crit}}$). It should, however, be noted that for the single-lap configuration considered here, the joint is subjected to significant bending moment in addition to longitudinal tension on account of non-collinear load-path. Therefore, even for $l = l_{\text{crit}}$, the bondlayer is subjected to significant peel stresses at the ends of the overlap in addition to shear stresses. Therefore, failure emanates from the very end of the overlap in the bondlayer as the peel stress

![Figure 5](image-url)  
*Figure 5. Failure behavior of 3D printed SLJs for different $v_C$: a) representative load–displacement response. Optical images of specimens at key points on the loading curve: b) unloaded, c) initial failure as identified visually, and d) near ultimate load.*

![Figure 6](image-url)  
*Figure 6. Computed stresses in the bondlayer for SLJs configurations with $l = 1 \text{ m} > l_{\text{crit}}$ at a loading of 300 N (See Figure 2a) along the bondline at $y = 1.4 \text{ mm}$ (near the top interface where $y = 1.5 \text{ mm}$) as a function of $v_C$: a) normalized peel stress distribution, b) normalized absolute maximum peel stress, c) normalized shear stress distribution, and d) normalized absolute maximum shear stress.*
generated exceeds the peel strength while shear stress generated in the bondlayer is still less than the shear strength of the bondlayer.

5. Conclusions

Multimaterial structural connections/joints are ubiquitous and are often preferred for lightweighting applications over mechanical methods of fastening. Strain-tolerance can be incorporated with a compliant bondlayer, but it may not have enough shear stiffness to transfer load effectively from one adherend to the other. By contrast, a stiffer bondlayer provides for a stiff joint, but may not have sufficient strain-compliance to diffuse stresses at the ends of the overlap where stresses and strains are concentrated. Compliance-tailored SJJs were fabricated combining compliant- and stiff-bonds in discrete steps along the bondlength with multimaterial 3D printing to provide a graded or tailored solution. The performance of compliance-tailored joints exhibited greater than 100% increase in strength and a 60% increase in toughness for a bi-modulus case at \( v_c = 20\% \) (volume fraction of compliant-bond along the bondlength) with respect to a constant modulus compliant bondlayer joint (\( v_c = 100\% \)), while maintaining joint stiffness versus the stiff bondlayer (\( v_c = 0\% \)). This synergetic effect can be explained by the stress and strain distributions in the bondlayer and near failure, for both the cases, where the overlap length is less than (experimentally-realized) and greater than a critical value (for full load transfer in shear). Complementary FEA predictions of stress and strain redistribution are in good agreement with strain fields obtained experimentally. Both the FEA and experimental results suggest an optimal length ratio or volume fraction of compliant-bond of the bondlayer as a design parameter that enhances the mechanical behavior of joints. This study demonstrates 3D printing as a means to create high performance interface compliance-tailored joints. If the correct levels of spatial-tailoring (both properties and scale) in the bondlayer can be achieved, for example, in structural composite adhesive joining, performance may approach what some have called optimal design of such interfaces by bio-mimicking.\cite{13,31–58} While the tailoring considered here imparts large improvements to the multilayer, even a small design improvement of such joints in application can lead to large benefits, for example, the 2017 GMC Acadia sport utility vehicle is 700 pounds lighter than the version it replaced, contributing a 28% improvement in gas mileage, due primarily to the use of improved joining materials.\cite{48} Compliance-tailoring of the bondlayer is an additional and facile approach to improving joint performance in both short and long, relative to critical shear transfer length, bonding applications.

Supporting Information

Supporting information is available online from Wiley Online Library or from the author.

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