Functionally Graded Adhesives Joints with Enhanced Strength

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Functionally graded adhesive bondlines are currently being researched to relax stress concentrations at the re-entrant corner of bonded joints and improve the strength of joints. Bi-adhesive joints have been under development for some time, but lately adhesives with continuous gradation have been shown to theoretically enable more stress reductions and greater strength benefits. Several researchers have shown the potential to create a working adhesive gradation system with very promising results, but adhesive stability over long periods of time has proven difficult to realize. Nearly as important as adhesive development are analysis methods for functionally graded adhesive joints, since the gradation must be designed to yield beneficial results. Therefore, this work addresses the potential gains provided by design of functionally graded adhesive joints driven by finite element analysis. A parametric study on a strap joint with homogenous adhesive is conducted to highlight parameters which influence the global strength of an adhesively bonded joint. A statistical approach is used to identify significant correlations between strength and adhesive material parameters. Results from the statistical study are applied to drive strategies to create joints with optimized gradation and validated by failure analysis within the finite element model. A strap joint is analyzed as example of the potential gain of functionally graded joints.

I. Introduction

ADHESIVELY bonded joints are becoming extensively used in fiber reinforced composites bonding. In fact, traditional bolted and riveted joints can cause considerable stress concentrations in the laminates due to the discontinuities introduced in the material, which can lead to early failure in the composite.

However, one major drawback of adhesively bonded joints is that the load path eccentricity induces a peel stress concentration at the boundaries of the adhesive layer. This not only causes inefficiency, with all of the load carried in a small area, but also encourages early failure initiation and yielding. There has been a vast amount of research conducted in an attempt to reduce these stress concentrations, such as tapering the end of the adherend [2], increasing thickness of the adhesive at the end fillets[3], novel joint geometries [4], and joint insertions [5], to name a few. With the exception of adhesive fillets, sll of these methods involve local details of adherend geometry, which typically increases part complexity and cost.

Material grading occurs in nature at material interfaces to reduce stress concentrations [6]. Biological interfaces such as tendon to bone joints have been found to have graded material properties to distribute stress more evenly across the joint[7]. In this same spirit, material grading is being applied to adhesively bonded joints, where a lower modulus adhesive at the boundaries transfers much of the load to the middle of the joint, thus reducing stress concentrations.

Much of the research on functionally graded adhesives involves using two different adhesives[8–14]. While large gains have been shown, the effectiveness of the joint has been shown to be highly sensitive to the interface between the two adhesives. More recently, functionally graded adhesives with continuously graded properties have been of interest in the research community. Early theoretical work has shown that the stress reduction potential for a continuous gradation is much greater than that of discretely graded adhesives [15,16]. Since these reports, there have been many theoretical studies on functionally graded joints [17–23] using analytical formulations or finite elements.

While there have been many theoretical studies on functionally graded adhesive joints, there have been very few experimental studies. In one of the first examples, the gradation was created using differing concentrations of glass beads [15]. However, this method was difficult to repeat and manufacture. More recently, a gradation was created by

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differing amounts of induction heating along a joint, which effectively varied the amount of curing in the joint [24]. However, post-cure effects lead to unstable benefits [25]. More recently, graded acrylic adhesives deposited in multiple steps have been created, though not yet fully explored [26]. For the first two examples, where real strength gains in joints have been shown, the manufacturing of joints was always accompanied by detailed models in order to fully yield gains from the more expensive, time-consuming process of grading adhesive properties. The current research involves the failure analysis of a strap joint, with the aim to not only reduce stress concentrations but also to enhance the global strength of the joint. A statistical approach is proposed to find significant correlations between adhesive mechanical properties and joint strength for linear elastic and elastic-perfectly plastic material models. The statistical study is limited to homogenous adhesively bonded joints but the results will be used to drive gradation strategies in continuously graded joints. The optimized gradation is validated by failure analysis in the finite element model and two fictitious adhesive gradation systems are compared.

II. Joint Element Model Formulation

The model used is a design model previously developed by the authors[27], and involves an element whose shape functions are derived by solving a structural model for two plates under cylindrical bending between an elastic foundation. By solving for shape functions rather than prescribing them, one element can be used through the thickness of the joint and one element along the joint when material properties remain linearly elastic. Additionally, a co-rotational formulation was included to consider large rotations, [28] and adaptive shape functions and an internal adaptive mesh include the effects of material nonlinearities and crack growth [29]. Finally, a modified Von Mises formulation is used to include plasticity of the adhesive layer in the framework of a thin adhesive layer constrained by two stiff adherends[30], along with the interpolation strategy between data curves for the continuously graded adhesive.

III. Method

Early theoretical work has shown that stress reduction is possible where a lower modulus adhesive is used[31]. However, those results are limited to linear elastic studies. The present work aims to propose gradation design guidelines to enhance joint strength, extending the study to failure analysis on the proposed strap joint in Fig. 1a.

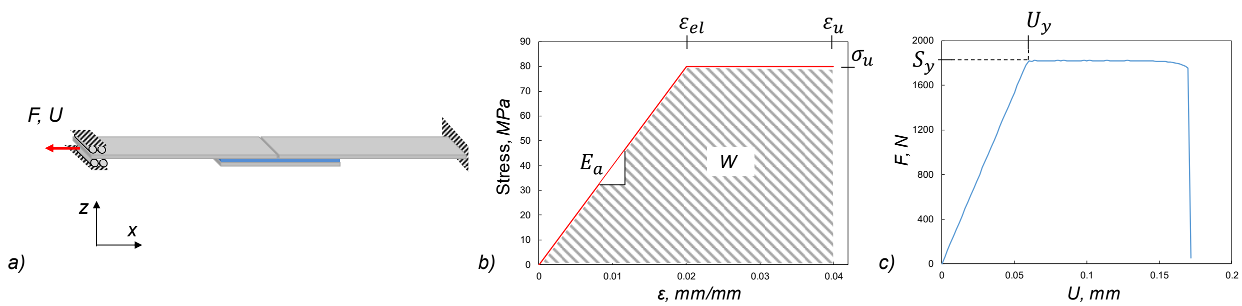


Fig. 1 a) Strap joint, b) input parameters for elastic-perfectly plastic adhesive material model and c) output parameters from load vs. displacement curve.

A. Statistical Study of Homogenous Adhesives

A parametric study on a strap joint (Fig. 2) with a homogenous adhesive system is presented for linear elastic and elastic-perfectly plastic adhesive material models. A total of seven parameters are considered for the statistical study; the two output parameters from the model are joint yeld strength (S_y) and displacement at yelding (U_y). The five input adhesive material properties are Young's modulus (E_a), stain energy density (W), ultimate strength (σ_u), elastic limit strain (ε_{el}) and strain to failure (ε_u). Correlations between the model inputs and outputs are shown in Figure 3 for linear elastic material models; joint strength is choosen as the stress at which the first crack in the adhesive occurs (Fig. 1c). Similar studies considering linear elastic-perfectly plastic models and the final failure within the adhesive layer have been performed but are not shown. However, similar trends to the ones shown in Fig. 3 are observed in all cases. The correlation matrix highlights strong correlation between joint strength S_y and strain energy density W, which is consistent with the failure criterion implemented in the model; furthermore, ε_u is also highly correlated with S_y. Young's modulus is shown to have a negative correlation with S_y, which is consistent with results from previous works demonstating stress relaxation by decreasing E_a. For the linear elastic parametric study the number of input parameters was reduced to four due to the fact that $\varepsilon_{el} = \varepsilon_u$.

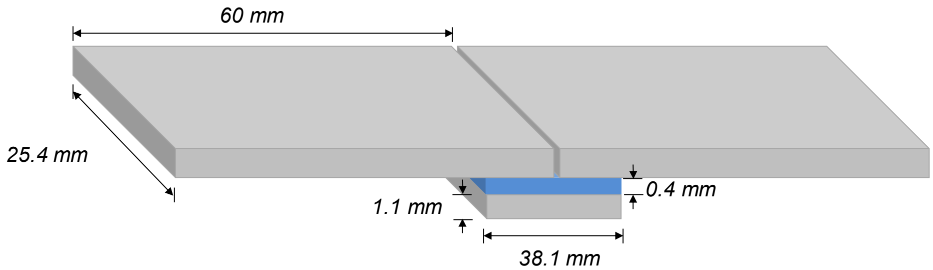


Fig. 2 Strap joint geometry.

Results from Fig. 3 are used in the next section to optimize strategies for the design of functionally graded joints and implemented in the presented finite element model.

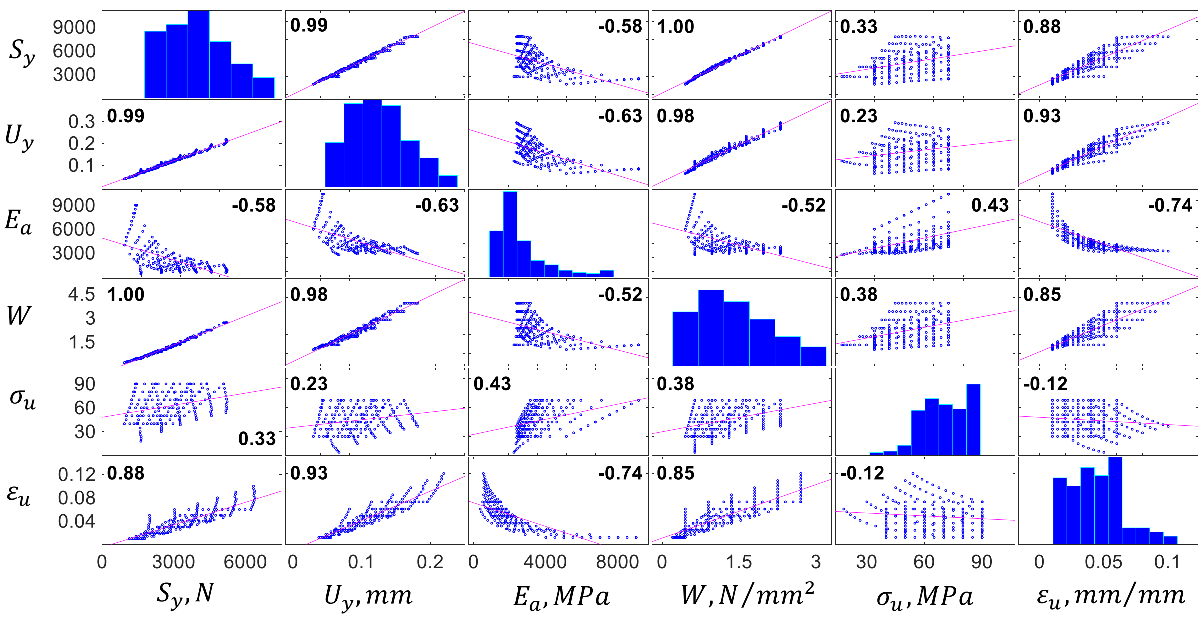


Fig. 3 Correlation matrix of the parametric study on homogenous linear elastic adhesive material models for a strap joint.

B. Adhesive Material Models

To reduce the number of variables in the gradation design, two fictitious gradation system were considered. In the first approach the adhesive strength σ_u is held constant, and the gradation is defined by the change in the adhesive strain to failure ε_u and the strain energy density W. In the second case, the strain energy density is kept constant within the graded adhesive; while varying ε_u and σ_u. The input adhesives material models for both approaches are shown in Fig. 4, where the continuous lines represent the input material models and the dashed lines represent interpolated curves between neighboring material models. For the interpolated curves, the failure stress is calculated by linearly interpolating between the two next neighbor curves. In the first case the gradation can be implemented with only two curves because the adhesive strength is constant within the graded adhesive. In the second approach, a higher number of input curves has to be considered to keep the strain energy density constant and to minimize the error due to the interpolation.

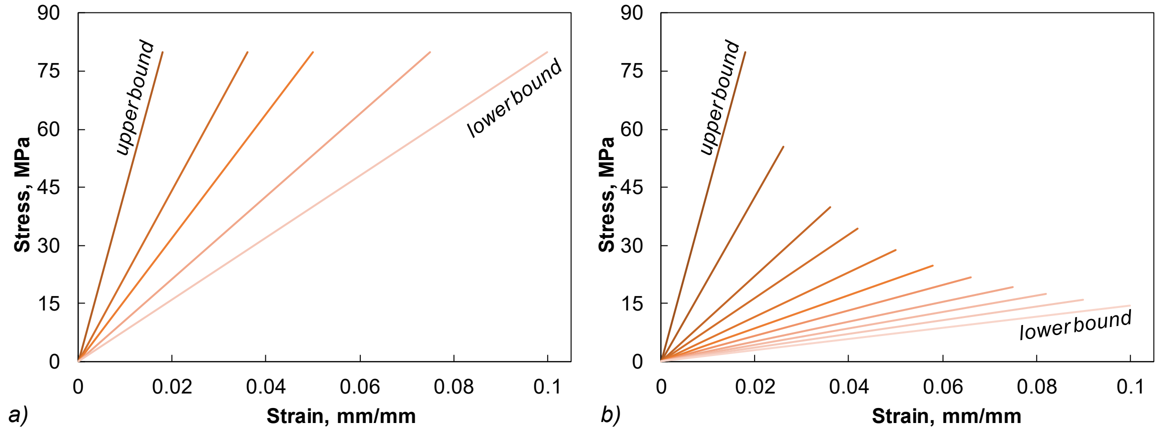


Fig. 4 Two fictitious gradation systems, a) for a functionally graded adhesive (FGA) with constant σ_u b) input material curve for FGA with constant strain energy density W

C. Gradation Design

The strap joint presented in the above section is used as numerical example for the functionally graded adhesive study. The bonded region of the joint is implemented in the joint element software using two elements, as shown in Fig. 5. One element is used to represent the homogenous part of the adhesive, whereas the second element defines the graded part of the adhesive using the adhesive material input curves shown in Fig. 4. The adherends were considered to consist of carbon fiber reinforced composite with a Young's modulus of 105 GPa. The ratio l_0/l is investigated in the results section, where l_0 is the length of the graded part and l is the total length of the overlap region; an example of the gradation strategy is presented in Fig. 6. In the first part of the results section strap joints with linear graded adhesive are considered, while in the last section more complex gradation shapes have been also investigated.

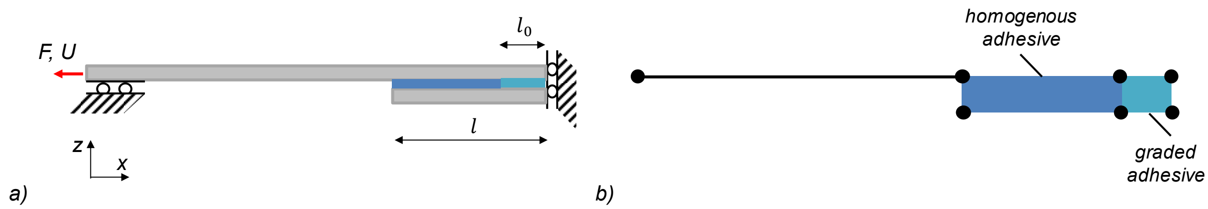


Fig. 5 Strap joint example with a) gradation parameters and boundary conditions and b) mesh in joint element model.

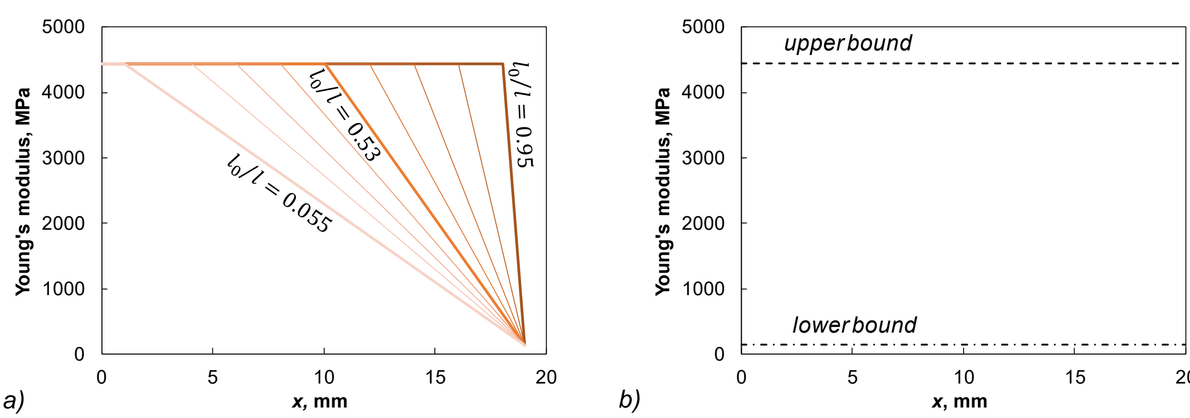


Fig. 6 Young's modulus along adhesive length for a) functionally graded adhesive with linear gradation considering different gradation length l_0= 1.05, 3.05, 5.05, 7.05, 9.05, 11.05, 13.05, 15.05, 18.05 mm and b) homogenous adhesive upper and lower bounds

IV. Results and discussion

An example of the optimization of the graded adhesive length l_0 is presented in Fig. 7. The graded length is varied within the total adhesive length as shown in Fig. 6. The upper adhesive input curve has maximum stress of 80 MPa and failure strain of 0.018 while the lower adhesive curve has the same maximum stress of 80 MPa and failure strain of 0.1 (Fig. 4a).The load vs. displacement curves of the upper and lower bound of homogenous adhesive (dashed lines) are compared with the the curves of the functionally graded joints for different lengths of graded adhesive (continuous lines). The load corresponding to the first failure in the adhesive is considered representative of the global joint strength and is compared with the strength of the joints with homogenous adhesive. It can be observed that the functionally graded joints with smaller length of gradation ($l_0 < 4.05$) show a catastrophic failure, while for longer gradation lengths the joint is able to maintain similar loads after the first failure in the adhesive. This is due to a more uniform distribution of stresses in joints with longer gradations; however, the maximum strength is observed for $l_0 = 3.05$. It's worth noting that a non optimal choice of gradation length can lead to functionally graded joints with lower strength with respect to the homogenous one. This highlights the importance of guidelines from numerical models to ensure the successful design of an FGA.

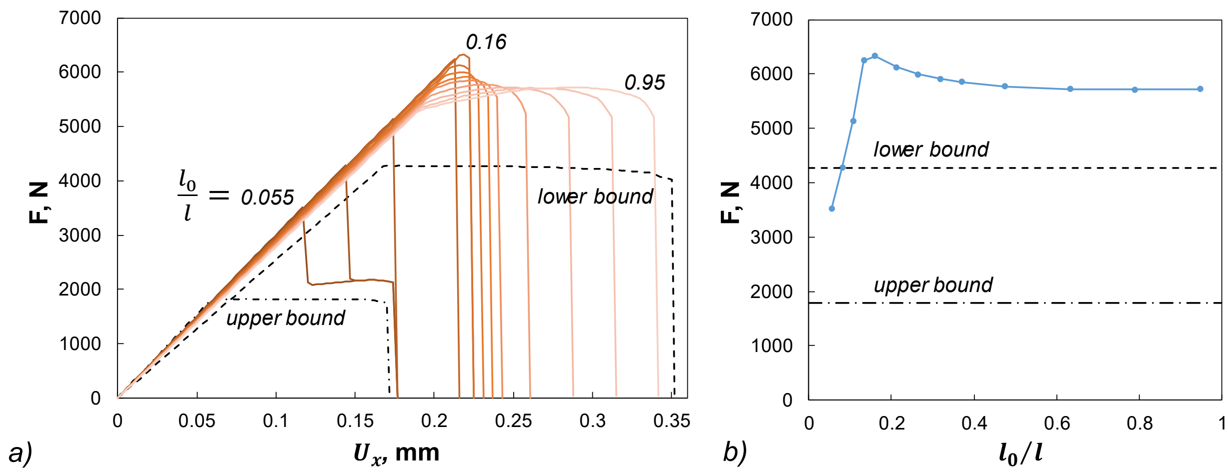


Fig. 7 a) load vs. displacement plot for FGA joint (continuous lines) and homogenous adhesives (dashed lines) b) failure load vs l_0/l ratio of FGA compared to homogenous joints strength.

A. Parametric Study with Fixed Adhesive Strength

In this section, a parametric study on a strap joint is discussed using the gradation strategy presented in Fig. 4a. The upper adhesive strain to failure was fixed at 0.018, whereas the lower adhesive strain to failure was varied from 0.036 to 0.1. A normalized parameter $\bar{\varepsilon}$ is introduced:

$$\bar{\varepsilon} = \frac{\varepsilon_{low}}{\varepsilon_{up}} \tag{1}$$

where ε_{low} represent the lower bound adhesive strain to failure and ε_{up} represents the upper bound adhesive strain to failure. The parametric study was performed for different values of adhesive strength σ_u= 60, 70, 80 and 90 MPa. The FGA strength was normalized with respect to the homogenous joint strength and is denoted as $\bar{S}$:

$$\bar{S} = \frac{S_{FGA}}{S_{hom}} \tag{2}$$

where S_{FGA} is the strength of the graded joint and S_{hom} is the strength of the homogenous joint. Results are summarized in Fig. 8. In all the cases investigated, the peak value in the relative strength of the FGA increases for higher values of $\bar{\varepsilon}$, and a maximum improvement of strength around 50% compared to homogenous joints is observed. The sharp peaks for small values of $\bar{\varepsilon}$ suggest that the FGA strength is more sensitive to the length of gradation if small ranges of strain to failure in the graded adhesive are considered ($\bar{\varepsilon} < 4.17$), hence wider ranges of $\bar{\varepsilon}$ ensure a relatively larger gain in strength and also a reduced sensitivity to variations in gradation length.

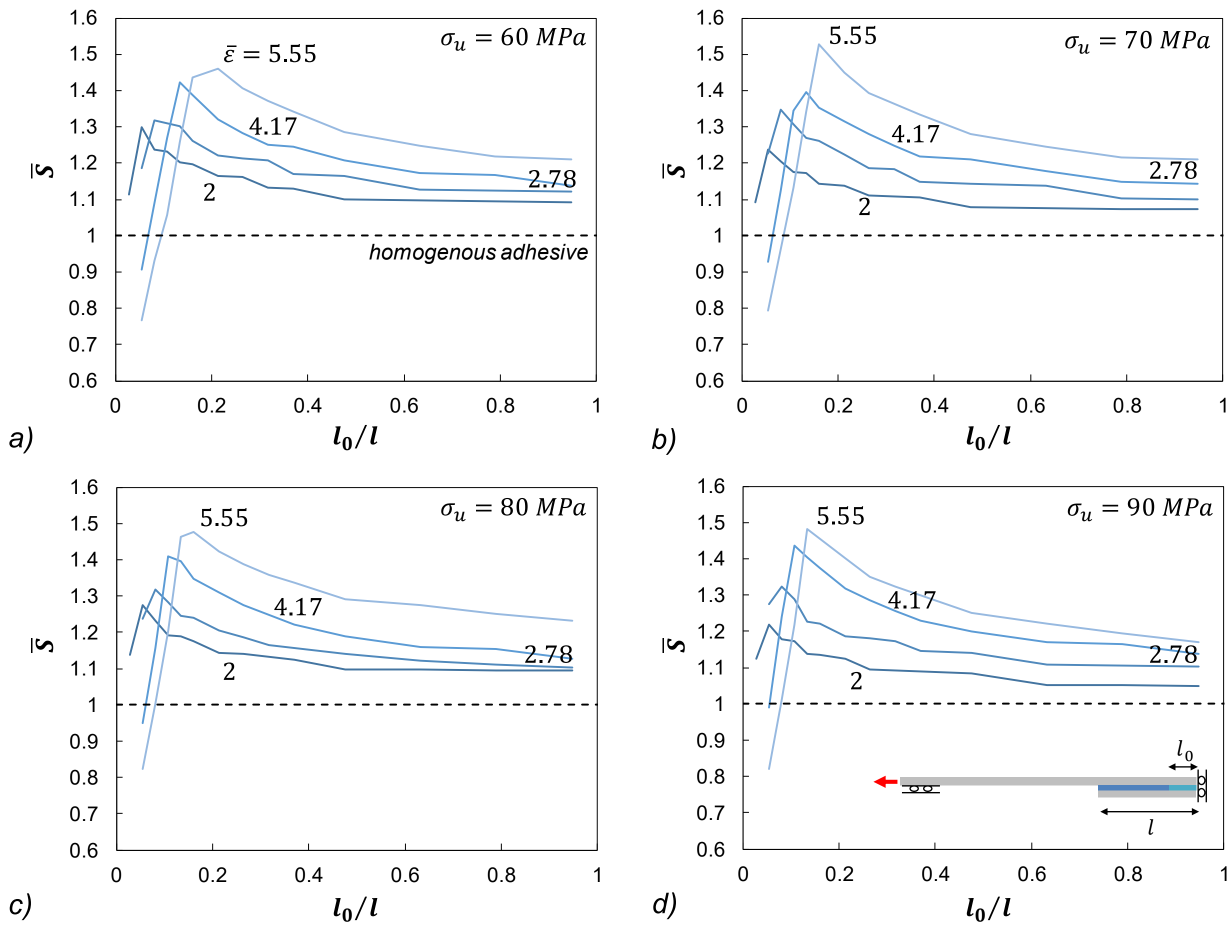


Fig. 8 $\bar{S}$ vs l_0/l plots for different values of adhesive strength σ_u= 60, 70, 80 and 90 MPa.

B. Parametric Study with Fixed Adhesive Strain Energy Density

A similar study was conducted on the same functionally graded strap joint but keeping the strain energy density of the graded adhesive constant, as shown in Fig. 4b. The upper adhesive strain to failure was fixed at 0.018 and the lower bound of strain to failure was varied from 0.036 to 0.1. This time, the parametric study was performed for four different values of adhesive strain energy density W = 0.54, 0.63, 0.72 and 0.81 N/mm^2. Knowing the values of strain energy density and strain to failure, the values of the maximum stress for adhesive input curves were calculated accordingly to $W = \frac{1}{2}\sigma\varepsilon$. The results are presented in Fig. 9 as s function of the normalized strength $\bar{S}$ and normalized length of graded adhesive l_0/l. A similar trend to the one observed in Fig. 8 can be observed. The gain in relative strength reaches values of up to 80% for $\bar{\varepsilon} = 5.55$ for all levels of strain energy density investigated. It is worth noting that for $\bar{\varepsilon} = 5.55$, the sensitivity to gradation length considerably decreases and the relative strength becomes relatively stable above a threshold of $l_0/l = 0.2$.

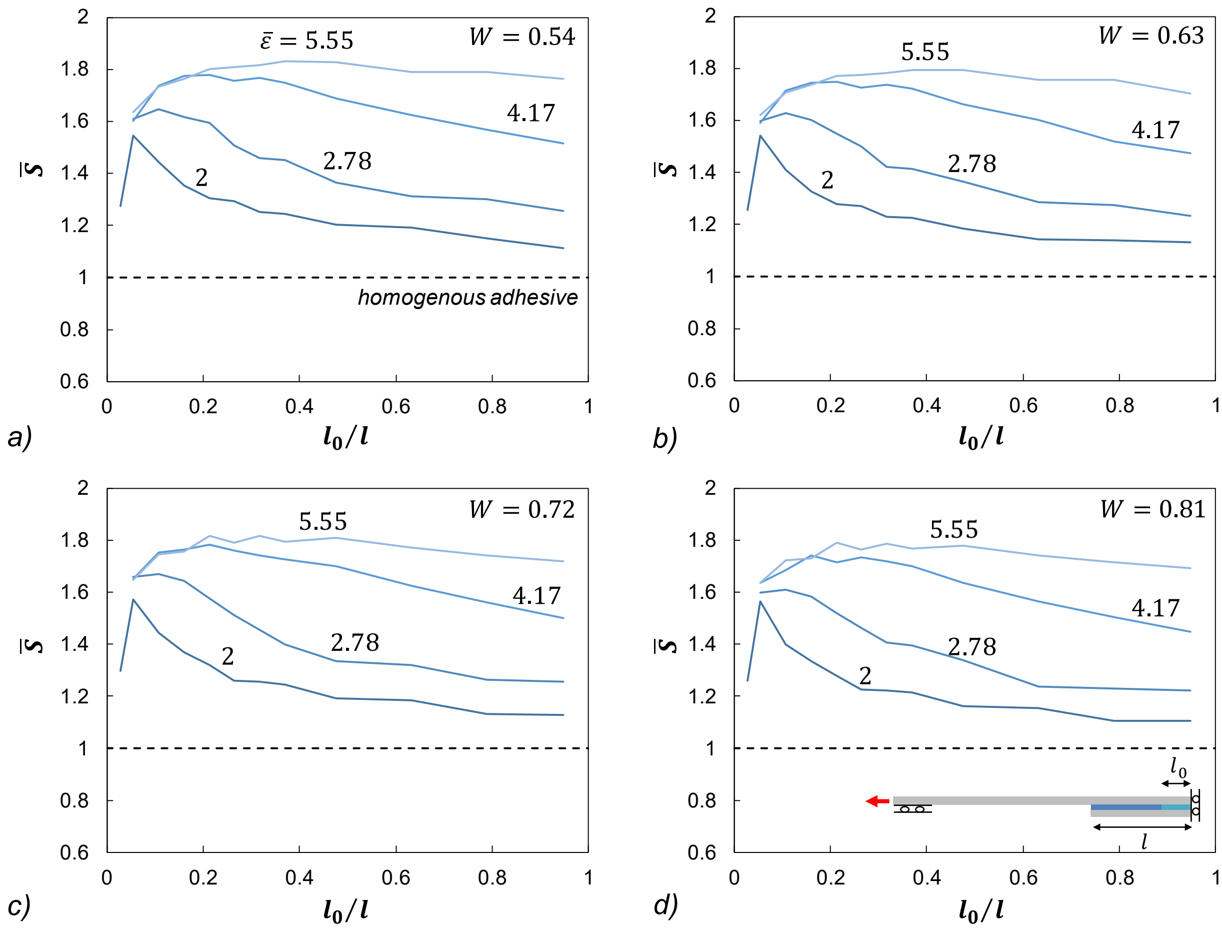


Fig. 9 $\bar{S}$ **vs** l_0/l **plots for different values of adhesive strain energy density** W **= 0.54, 0.63, 0.72 and 0.81** $\mathrm{N/mm^2}$**.**

The two strategies of gradation presented in this section are compared in Fig. 10. The peaks in the normalized strength curves from Fig. 8 and Fig. 9 are plotted as a function of $\bar{\varepsilon}$. A linear trend is observed for the two sets of data and it is noted that the slope for the FGA with fixed strain energy density is higher than that seen in the case of fixed adhesive strength. This means that the relative strength increases faster for graded adhesives with fixed strain energy density highlighting this as a more efficient strategy to implement gradations in FGA.

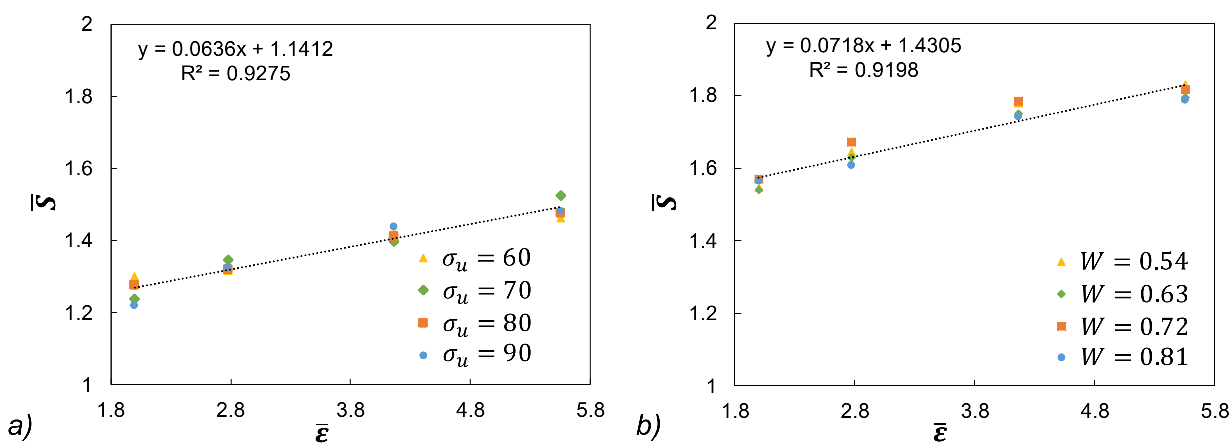
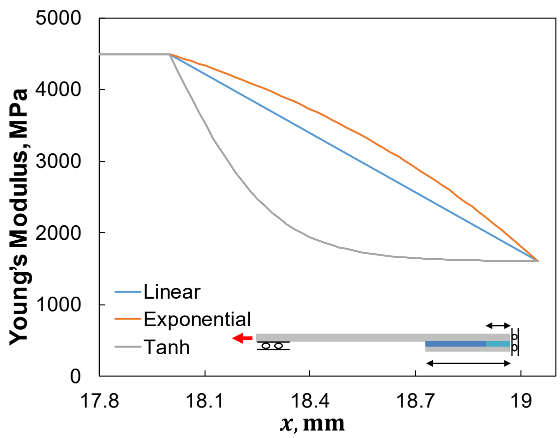


Fig. 10 $\bar{S}$ **vs** $\bar{\varepsilon}$ **plot for a) FGA with fixed** σ_u **and b) FGA with fixed** W**.**

C. Gradation shape optimization

In this section the influence of the gradation shape is investigated. In the previous case studies presented here the adhesive was assumed to be linearly graded. Here more complex gradation shape are considered and the the results from the linear case are taken as a reference. The upper adhesive strain to failure is fixed at 0.018 and the lower adhesive strain to failure is fixed at 0.1; the maximum stress is fixed at 60 MPa. An exponential function is chosen as example of convex gradation, whereas a *Tanh* function is used as concave gradation. Fig. 11 shows the results for the different shapes of gradation considered. The exponential function achieves the maximum gain in strength and is the least sensitive to gradation length. The *Tanh* function seems not to improve the strength of FGA compared to the homogenous adhesive joints. However, because only a single case was investigated, while the result can be used as reference for further investigation on gradation shape, general conclusion can not be drawn. Nonetheless, the results suggest that a convex gradation function could further improve the strength of the FGA.



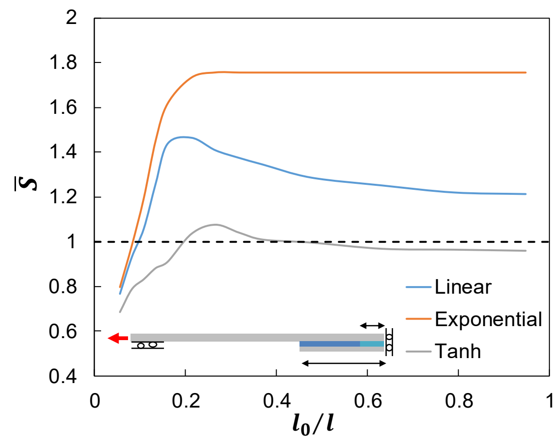


Fig. 11 a) Young's modulus along graded adhesive length for Exponential, Tanh and Linear functions for l_0= 1.05 mm b) $\bar{S}$ vs l_0/l plots for different shapes of gradation.

V. Conclusions

To highlight the importance of guidelines from numerical simulations in creating FGAs with enhanced strength, failure analysis on strap joints with functionally graded adhesive have been presented. A statistical study on strap joints with homogenous adhesive is conducted to identify relevant parameters which drive the global strength of joints. Parameters with the highest correlation are investigated to design graded joints. Two approaches are presented in this theoretical work. The first approach infers a fictitious gradation in the adhesive by keeping the adhesive maximum stress constant within the gradation, whereas the second strategy is driven by keeping constant the adhesive strain energy density. A parametric study to characterize the optimal ratio of gradation l_0/l for linear gradation is presented. Results show that both gradation strategies lead to considerable gains in FGA strength by increasing the graded adhesive strain to failure ratio $\bar{\varepsilon}$. This results also in FGAs with less sensitivity to gradation length, which can be a relevant factor in manufacturing functionally graded joints. Graded adhesives with constant strain energy density exhibit gains in joint strength of up to 80% compared to homogenous joints, whereas the maximum gains observed in graded adhesives with constant σ_u were up to 50%.

This parametric study demonstrates the potential of numerical simulations to aid the design of functionally graded joints and achieve relevant gains in graded joint strength. In fact, to ensure beneficial results in FGAs the design must be driven by careful definition of the gradient in adhesive properties. Inoptimal design of such gradations could lead to poor performance in terms og joint strength when compared to the effects of the optimized grading of adhesive properties.

In the last part of the work more complex gradation functions were explored to further improve FGA strength. Convex gradation functions show potential to outperform linear gradations, whereas concave gradation functions seems to be less promising. In particular, convex gradation functions appear to be less sensitive to l_0/l once a critical threshold length is exceeded. However, the study on gradient shape should be extended to a more relevant number of cases to draw general conclusions.

Acknowledgments

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