EFFECT OF THE SURFI-SCULPT PROTRUSION DENSITY ON THE STATIC MECHANICAL PROPERTIES OF COMPOSITE-METAL

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Abstract:

The effect of the surfi-sculpt protrusion density on the static mechanical properties of composite-metal joints strengthened by surfi-sculpt is experimentally studied. In the study, the quasi-isotropic layup is adopted and the thickness of composite is constant, only the surfi-sculpt protrusion density changes. Joints without surfi-sculpts are manufactured as references. The surfi-sculpt protrusions, manufactured by electron beam surfi-sculpt (EBS) on the bonding surface of metal adherend, resist unstable (rapid) delamination growth along the bond line of composite-metal joint. Compared with the references joints, the Initial damage load (IDL) is increased by 22.87%; the ultimate failure load (UFL) is increased by 423.41%; the joint extension (EX) is increased by 924.79% and the absorbed energy is increased by 1615.59%. With increasing protrusion density, the failure mode changes from bonding line cracking to composite intra-laminar failure and surfi-sculpt protrusions breakage in mixed load of shear and bending.

Keywords:

Composite, Composite-metal joint, Surfi-sculpt, EBS

1. Introduction

Joining dissimilar material such as carbon fibre reinforced plastic CFRP and metal with robust joints has been challenging. The most common joining technologies are adhesive bonding and mechanically fastened joints. For bonded joints, adhesive bonding is usually sensitive to surface preparation and its adhesive strength and toughness are low. Moreover, inspection of bonding interface during structures services is also difficult. The failure of bonded joints is usually abrupt and catastrophic. For mechanically fastened joints, fasteners need holes in the composite, the intrinsic brittleness of CFRP composites makes composite laminate sensitive to bolt holes[1]. The use of mechanical fasteners reduces structural integrity and increases weight, decrease the potential weight saving with composite.

An innovative joining technology, Surfi-Sculpt technology [2], adopting the idea of z-pinning technology in composite-composite joint, creates arrays of macro-scale surfi-sculpts on the surface of metal part to archive mechanical joining as bolts. This advanced hybrid joint better combines the respective advantages of bonded joint and mechanically fastened joint with less manufacture damages in composite part. In this work, electron beam surfi-sculpt (EBS) makes protrusions on metal adherends through multiple relative movement between electron beam and the metal surface [3, 4] and form surfi-sculpts using the material of metal adherends.

The purpose of this study is to evaluate the effect of surfi-sculpt protrusion density on the mechanical properties of composite-metal joints strengthened by surfi-sculpt experimentally.

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Four joint types with different surfi-sculpt protrusion density and a reference joint are tested and joint mechanical properties including initial damage, ultimate failure and absorbed energy are compared.

2. Single lap joint (SLJ) Manufacture

Single lap joints, shown in Figure 1, are adopted in the present work. Although single lap joints introduce normal stresses especially at the ends of the joints' overlap, affectting the apparent shear strength, they can be used for the comparison of bonding process in research and development[5]. Moreover, the joints simplify the manufacture process and make the joints quality more reliable for it is difficult for double lap joints to achieve desired joints shape [6]. Single lap joints provide more freedom for composite layup design (stacking sequences) and are convenient to detect their damage growth [7].

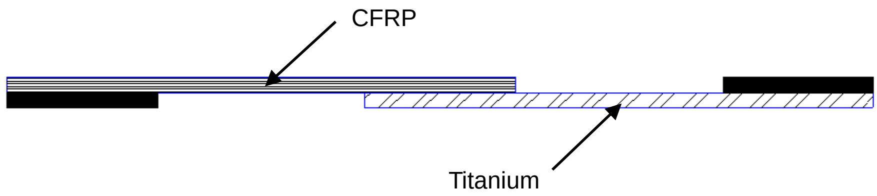

Figure 1 Single lap joint

The objective of this study is to investigate the effect of the surfi-sculpt protrusion density on the mechanical properties of the advanced hybrid joints. The experiment matrix is shown in Table 1. In the surfi-sculpt protrusion density effect study, four types of joint with different surfi-sculpt protrusion density are tested. Unstrengthened joints are tested as references. For each type of joint, at least two samples are tested.

Table 1 The experiment matrix

Joint type	CFRP nominal thickness (mm)	Composite layup	Surfi-sculpt array	Joint No.
Reference	2.6	45/0/45/0/45/0/45/0/45/0/45/0/45	no surfi-sculpt	R
Protrusion density effect	2.6	45/0/45/0/45/0/45/0/45/0/45/0/45	5, 6, 5, 6, 5, 6	DEN1
		45/0/45/0/45/0/45/0/45/0/45/0/45	6, 7, 6, 7, 6, 7, 6, 7	DEN 2
		45/0/45/0/45/0/45/0/45/0/45/0/45	7, 8, 7, 8, 7, 8, 7, 8	DEN 3
		45/0/45/0/45/0/45/0/45/0/45/0/45	9,10,9,10,9,10,9,10,9,10	DEN 4

2.1. Materials

Ti-6Al-4V [4, 8] is used to manufacture metal adherend, which is usually adopted in hybrid structures with carbon fibre reinforce plastic (CFRP). The composite used to manufacture CFRP adherend is SE 84LV [9]. SE 84LV is hot-melt, epoxy prepreg. The fibre of the prepreg is RC200T which is a woven fibre.

Electron beam surfi-sculpt (EBS) is adopted to manufacture surfi-sculpt protrusions on the bonding surface of the metal adherend [3, 4]. The EB generated by Electronic Beam Gun impacts metal surface though special track. Meantime, the external metal on the track is melted. The melted metal is displaced due to surface tension and vapour tension of melted metal to form a projection [10]. Then part of the melted material solidifies, after which the EB scan is repeated one or more times. Desired protrusions can be formed with special tracks, tailored rule, proper speed and energy of EB. Figure 2 shows the surfi-sculpt protrusion shape.

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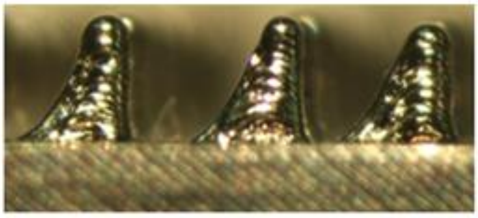

Figure 2 Surfi-sculpt protrusions

2.2. Joints manufacture

The integration of metal and composite adherends is completed using vacuum bag processing [9]. Before the vacuum bag processing, the full thickness of the CFRP adherend is built up using prepreg and is placed onto the metal adherend. During the vacuum bag processing, the pins are pressed into the uncured laminate with the pressure provided by vacuum bag. The assembly is finally co-bonded on a hot plate, after which the composite is trimmed to size. Bespoke tooling is used to ensure thorough consolidation of the CFRP and minimise any misalignment of the laminate and the metal adherend.

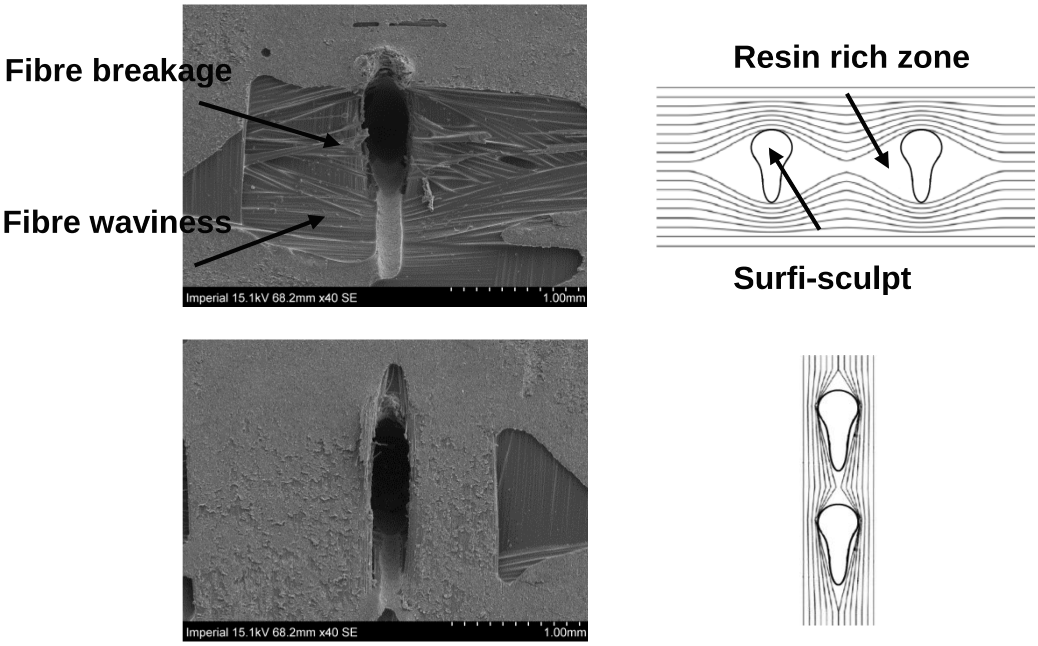

Figure 3 Initial damages in CFRP

The insertion of surfi-sculpt protrusion into composite introduces resin rich zone and fibre damages shown in Figure 3. To avoid the linkage of these resin rich zones, the distance between two adjacent protrusions in both horizontal and vertical direction need to be extended as far as possible. So the odd rows offset a half surfi-sculpt protrusion distance along the row direction. Take joint DEN1 for example, the final surfi-sculpt protrusion array design of joint DEN1 is shown in **Figure 4**.

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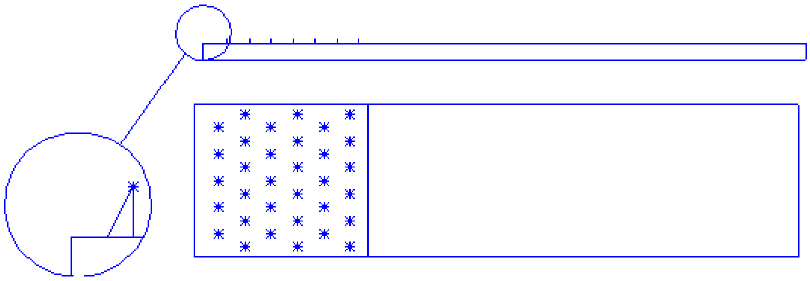

Figure 4 Surfi-sculpt protrusion array for DEN1

3. Experimental

3.1. Testing at quasi-static rates

Single lap shear tests are carried out on an Instron 3369 at ambient temperature. The tests are displacement-controlled. The cross head rate is 0.3mm/min, much lower than that specified in ASTM D5868 [11], for a low rate can allow more small changes in a joint compliance to be recorded. During the test, the extension of the gauge length is determined with an extensometer Figure 5.

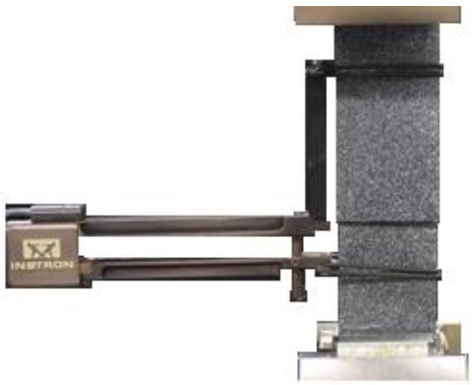

Figure 5 Single lap shear test setup

4. Results and discussion

4.1. Load Displacement curve

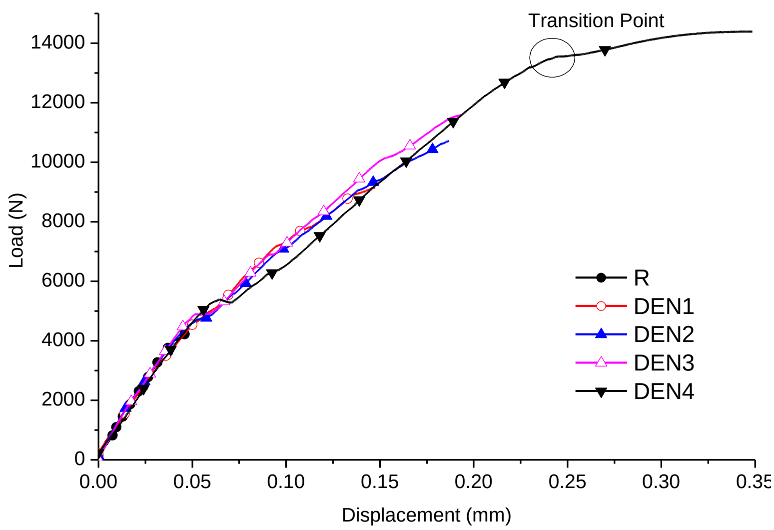

Figure 6 Typical quasi-static load vs displacement curves

Figure 6 compares the typical load-displacement curves of the reference joints to the

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strengthened hybrid joints with different protrusion densities.

The curve of the reference joint rises linearly up to 4000N, at which the compliance of the joint experiences obvious changes due to the initiation of the joint bond-line cracking at the end of composite adherend. This load is defined as initiation damage load. Finally, the joint is damaged by unstable delamination of the joint bond-line after a small increase of the tension load (about 200 N). The resulting delamination propagates rapidly and the joint failures catastrophically because the joint geometry under the tension load presents an increasing energy release rate with crack propagation and the interface is relatively brittle [12].

The curves for the strengthened joints increase linearly before the initial damage appears. It should be noticed that all joints, with same composite layup design, show the same increase rate given the experimental variation, indicating that the initial joint stiffness is not affected significantly by the changes of surfi-sculpts density. All the strengthened joints, except for joints DEN4, experience a compliance change at about 4400 N and are still able to withstand further load and fail with much higher ultimate failure load. Joints DEN4's experiences the compliance change at about 5000 N.

The load-displacement line of joint DEN4 shows three different loading stages. The first is linear stage before its damage initiation. Then the load increases almost linearly to about 13000N. With following loading increase, the line becomes nearly horizontal. Experimental observation shows that surfi-sculpt protrusions near both the metal and composite end begin to be pulled out after this point. . So the load point of 13000N is defined as transition point. Because the surfi-sculpt protrusion's pulling out in single-lap joint is unstable and the joint's strength increase is relatively small (about 6%) after the transition point, it is suggested that the transition point is more reliable to characterize the damage failure (The following data analysis of joint extension and absorbed energy also support this suggestion).

For all strengthened joints, the stiffness of joints remains the same value after their damage initiation (after damage initiation and before transition point for DEN4) given the experimental variation and the observation of initial bonding line cracks shows the cracks are hold up near the first line of surfi-sculpt protrusions, implying the initial bonding line cracks are hold up at a similar crack propagation length.

4.2. Initiation damage load

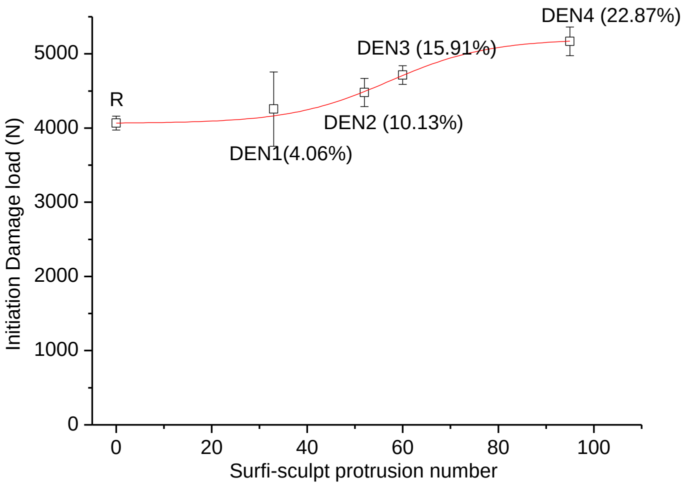

Figure 7 Initiation damage load

Figure 7 shows the initiation damage load of the reference and strengthened joints. Surfi-sculpt protrusions can increases the joint initiation damage load slightly for all the three strengthened joints. The initiation damage load rises with increasing surfi-sculpt protrusion density in general. When the Surfi-sculpt protrusion number is less than 25, the initiation damage load sees no obvious change and is about 4000N. When the Surfi-sculpt protrusion number increases from 25 to 80, the initiation damage load increases almost linearly. Then the initiation damage load reaches a plateau value of about 5000N at the protrusion number of 80, irrespective of further protrusion number increase. The maximum increase is 22.87% for joint DEN4.

4.3. Ultimate failure load and damage mechanisms

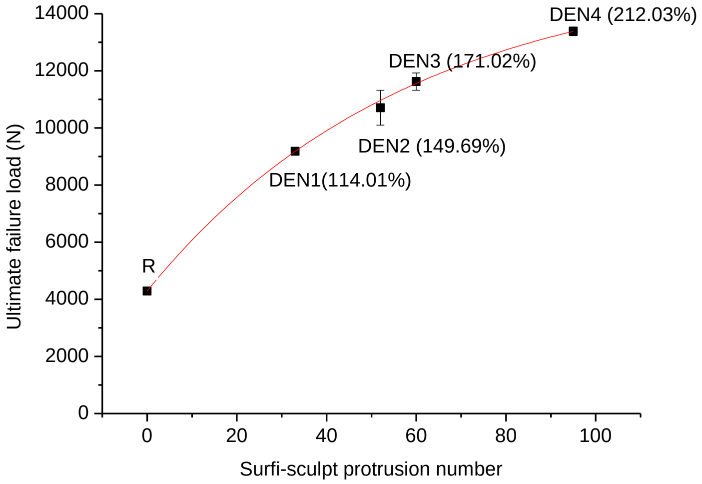

Figure 8 Ultimate failure load

Figure 8 compares the ultimate failure load of the references and strengthened hybrid joints. All the strengthened hybrid joints are stronger than the referenced joints, and the ultimate failure load increase with more surfi-sculpt protrusions, indicating that surfi-sculpt protrusion can improve the joint ultimate failure load effectively. DEN4 is the strongest joint (the ultimate failure load is 13381.35 N) and achieves the maximum increase by 212.03% compared with reference joint R (the load capacity is 4288.43 N). DEN1, DEN2 and DEN3 are increased by 114.01%, 149.69% and 171.02% respectively. Nevertheless, the ultimate failure load's increase rate decreases with more surfi-sculpt protrusions.

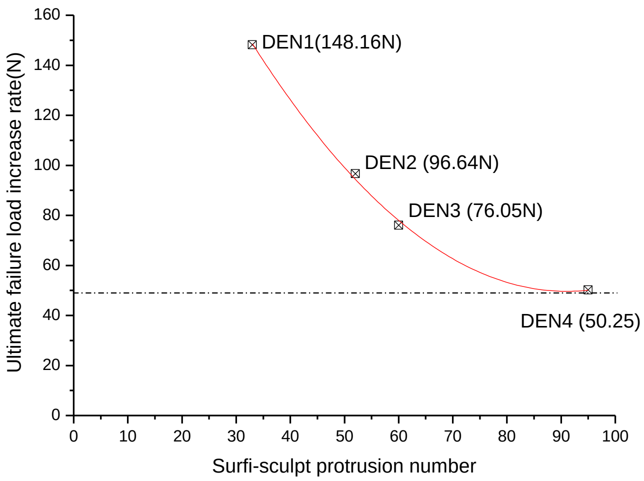

Figure 9 Ultimate failure load increase rate

To compare the efficiency of added surfi-sculpt protrusion for joints with different protrusion

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number, ultimate failure load increase rate (UFLIR) is defined as:

$$UFLIR_{DEN(i+1)} = \frac{UFL_{DEN(i+1)} - UFL_{DEN(i)}}{N_{DEN(i+1)} - N_{DEN(i)}}$$

UFL : Ultimate failure load

$N_{DEN(i)}$: The number of surfi-sculpt protrusions of the joint DENi; DEN0 refers to the Reference joint

Figure 9 shows the comparison of UFLIR for DEN1 to DEN4. It is obvious that the efficiency of added surfi-sculpt protrusion decreases with increasing protrusion number. DEN1, with the least surfi-sculpt protrusion number, achieves the largest UFLIR. On average, per added surfi-sculpt protrusion can increase the ultimate failure load by 148.16 N compared with reference joint. DEN4, with the most surfi-sculpt protrusion number, has the least UFLIR. On average, per added surfi-sculpt protrusion increases the ultimate failure load by 50.25 N compared with joint DEN3. When the surfi-sculpt protrusion number is larger than DEN4, the efficiency of added surfi-sculpt protrusion reaches a lower limit of about 49 N.

The damage mechanisms are different for all types of joints, as summarized in Table 2 (The composite damage caused by surfi-sculpt protrusion's insertion is not included). The reference joints fail with rapid, unstable bond-line delamination and two adherends separate catastrophically, following the damage initiation. Joint DEN1 only sees the breakage of surfi-sculpt in shear. Joint DEN2 and DEN3 experience similar damage mechanisms: surfi-sculpt break in shear and composite compression failure. Joint DEN4 experiences surfi-sculpt break in mixed load of shear and bending, composite compression failure.

Table 2 Damage mechanisms in hybrid joints

Joint	Damage Mechanisms	
R	Unstable bond-line delamination	
DEN1	composite	almost intact
	surfi-sculpt	breakage in shear
DEN2	composite	composite compression failure
	surfi-sculpt	breakage in shear(62.5%); breakage in mixed load of shear and bending(37.5%)
DEN3	composite	composite compression failure
	surfi-sculpt	breakage in shear(50.0%); breakage in mixed load of shear and bending(50.0%)
DEN4	composite	composite compression failure
	surfi-sculpt	breakage in shear(20.0%); breakage in mixed load of shear and bending(80.0%);

4.4. Joint extension and energy absorption

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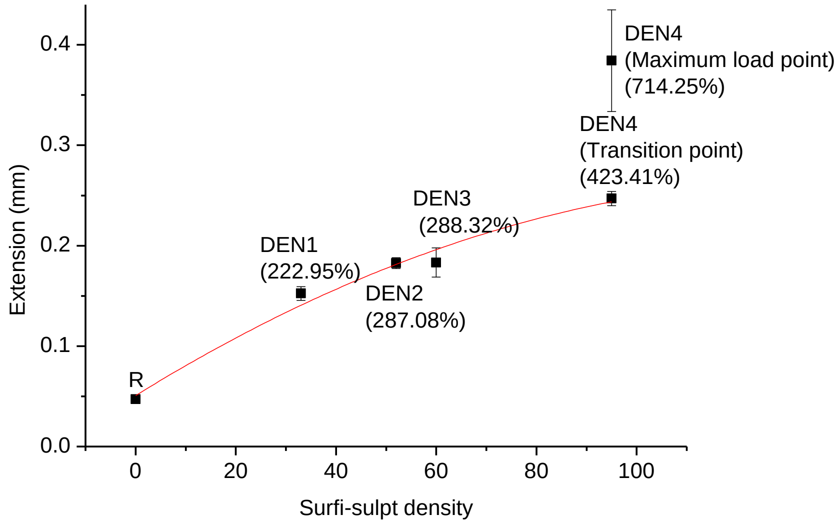

Figure 10 Joint extension

Figure 10 shows the comparison of the joint extension of the references and strengthened hybrid joints. All the strengthened joints can withstand higher extension than reference joints.

It should be noticed that although joint DEN4 shows a higher extension value at the maximum load point, it has a much wider error bar, indicating that the extension value is not stable. In contrast, its extension value at the transition point is more stable. The comparison verify that the pulling out of surfi-sculpt protrusion from composite is not stable and it is reasonable to take the transition point as the characterization of joints' final failure.

The joint extension value increases with the surfi-sculpt protrusion number. Joint DEN4, with the most surfi-sculpt protrusions, shows that the average extension is increased by 423.41% compared with reference joint. Joint DEN1, with the least surfi-sculpt protrusions, achieves the least extension increase of 423.41% compared with reference joint. The extension of joints DEN2 and DEN3 are increased by 287.08% and 288.32% respectively. The figure also shows that the extension value increase rate decreases as the surfi-sculpt number increases.

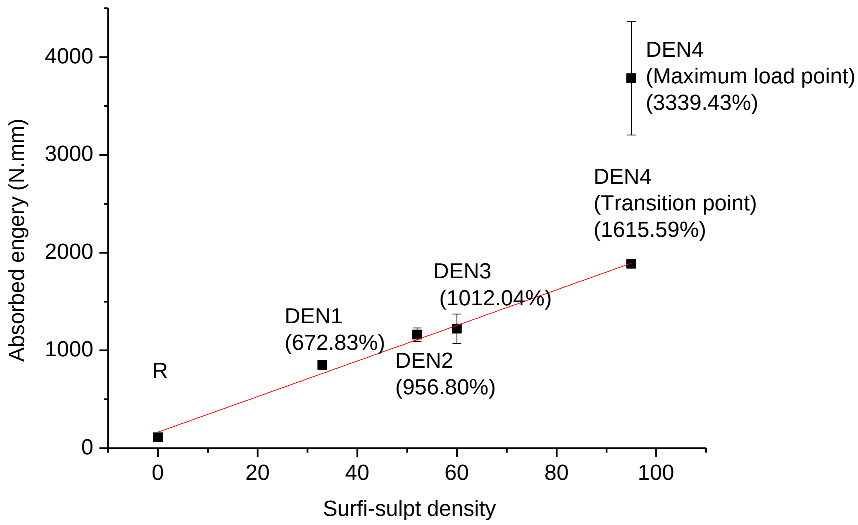

Figure 11 Energy absorption

The joint absorbed energy is defined as the area under load-displacement curve. The improvement of joint ultimate failure strength and extension results in remarkable increase in joint absorbed energy.

Figure 11 shows the comparison of the absorbed energy of the references and strengthened hybrid joints. It also shows that although joint DEN4 shows a much more absorbed energy at the maximum load point, it has a much wider error bar, indicating that the absorbed energy is not stable. In contrast, its absorbed energy at the transition point is more stable. The comparison double verify that the pulling out of surfi-sculpt protrusion from composite is not stable and it is suitable to take the transition point as the characterization of joints' final failure.

The absorbed energy increases linearly with the surfi-sculpt protrusion number, indicating that most energy absorption is due to the failure of surfi-sculpt protrusions. Joint DEN4, with the most surfi-sculpt protrusions, shows that the average absorbed energy is increased by 1615.59% compared with reference joint. Joint DEN1, with the least surfi-sculpt protrusions, achieves the least energy absorption increase of 672.83% compared with reference joint. The absorbed energy of joints DEN2 and DEN3 are increased by 956.80% and 1012.04% respectively.

5. Conclusions

The effect of the surfi-sculpt protrusion density on the static mechanical properties of advanced hybrid joints is experimentally studied. Four joint types with different protrusion density are tested and corresponding results are compared with that of unstrengthened reference joint. It has been shown that hybrid joints are able to offer significant improvements in joint mechanical properties at static load. Surfi-sculpt protrusions are able to increase joints static mechanical properties significantly. With the surfi-sculpt protrusion density increase, the static mechanical properties of hybrid joints increases and joints damage mechanisms change from bare bonding line delamination to the combination of bonding line delamination, surfi-sculpts bending, surfi-sculpts breakage and composite compression.

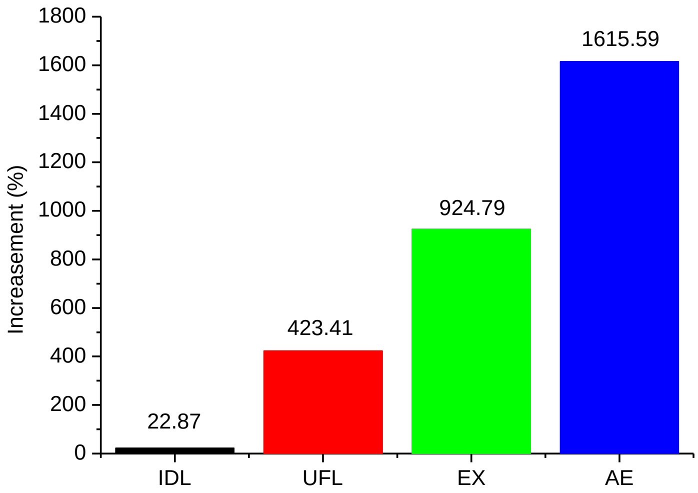

Figure 12 the mechanical property improvement of strengthened joints

Figure 12 shows the mechanical property improvement of the joint DEN4 which is with the most surfi-sculpt protrusion number. The Initial damage load (IDL) is increased by 22.87%; the ultimate failure load (UFL) is increased by 423.41%; the joint extension (EX) is increased by 924.79% and the absorbed energy is increased by 1615.59%.

Further test and simulation are necessary to get insight into the effects of the surfi-sculpt

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protrusion density and to figure out how the surfi-sculpt behavior in joints under external load.

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