Hybrid and adhesively bonded joints with dissimilar adherends: A critical review

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Abstract:

This paper reviews the reported literature on dissimilar (non-matched adherend) adhesively bonded joints (ABJs), currently used bonding processes, and the mechanisms by which these types of joints fail when subjected to structural loading and environmental conditions. Additionally, approaches to improve the performance of dissimilar ABJs, through geometrical and material modifications, are also discussed. Many studies have reported on the strength and failure behaviours of adhesively bonded joints, but of those, few have reported on the performance of dissimilar ABJs. Unlike matched ABJs, the absence of accepted design approaches for dissimilar ABJs arises from their inherent inhomogeneity, which introduces complexities in load transfer mechanisms, in the distribution of stresses through the joint, and in the mechanisms by which the joint ultimately fails. Several authors have proposed approaches to improve the performance of adhesively bonded joints, variously through geometrical or material modification means, but there remains unmet research needs to better understand novel dissimilar ABJ designs.

Keywords: adhesive joint; dissimilar adherends; hybrid joint; environmental durability; impact

1. Introduction

Over the years, vehicle manufacturers have tried to reduce weight, aiming for lighter and more damage tolerant structures. The increased use of dissimilar components (adherends) within structures (such as those made from metals and composites), requires more attention in this field, specifically concerning the investigation of the load-carrying capacity of joints made from dissimilar adherends. This is of particular interest because the difference in the material properties of the dissimilar adherends results in a more complex fracture mechanism and asymmetric stress distribution [1] in comparison to joints with similar adherends, increasing design risk. In addition, selecting the most suitable joining method is another challenging task in order to exploit the advantages of dissimilar joints which are design flexibility and lightweight structure. Here financial feasibility of the assembling procedure is just as critical as required mechanical strength of joints. For instance, from a manufacturing perspective, joining of carbon fibre reinforced polymer (CFRP) composites and metal stack-ups are costly due to the required number of steps to produce a final structure, which this cost could contribute to the half of the total cost of the products [2]. Mechanical fasteners and adhesive bonding are other methods that have been used by manufacturers to bond multi-material components in simple structures. There are several disadvantages of using mechanical fasters in joining components such as weight increase, low sealing capacity, micro-crack in structures due to the drilling process, and smaller cross-sectional area due to the presence of the holes. On the other hand, adhesive joints have attracted more attention in the past decades due to easy manufacturing, more uniform stress distribution, better sealing capacity, flaw-free effect in composite structures and the possibility of joining dissimilar adherends. However, there are still some barriers in utilising adhesive joining techniques in practice due to a lack of an accepted theory, which describes the fracture mechanism of the dissimilar joints and summarises the factors affecting the performance of the joints [3].

As it is shown in the conceptual scheme of the review in figure 1, this work initially investigates the available works for characterisation of the adhesive layer in dissimilar bonded joints subjected to various loading conditions. Then, the effort to optimise the performance of dissimilar bonded joints using geometrical and material modifications were reviewed. Another potential area of concern is the durability of the dissimilar bonded joints under aggressive environmental conditions, and a review of this area has been carried out. Finally, the advantage and disadvantage of available hybrid joining methods were assessed for dissimilar bonded joints.

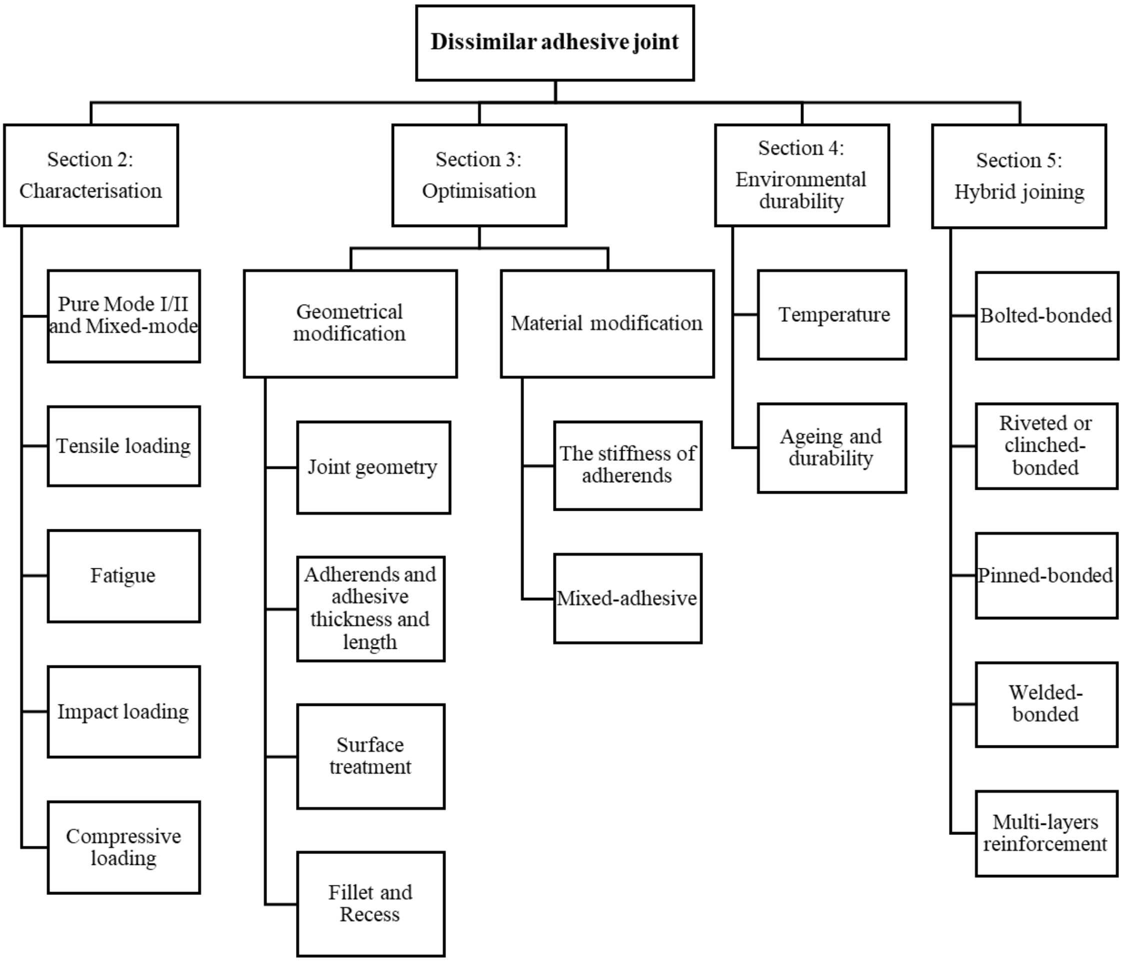

Figure 1: conceptual scheme of the review

2. Characterisation of Dissimilar Adhesive Joint

Adhesive bonding is now widely used in the manufacture of complex structures, particularly in industries such as aerospace, automotive, maritime and civil engineering, due to advantages over traditional fasteners; which includes easy manufacturing, more uniform stress distribution, light-weighted structures, the possibility of joining dissimilar adherends and retardation of galvanic corrosion between electrically conductive components [2][3]. Adhesively bonded joints of dissimilar materials are often required to withstand static, cyclic and impact loads for significant periods without any adverse impact on the structure's load-bearing capability [4]. However, a lack of acceptable material models and failure criteria has resulted in a risk to overdesign adhesive joints. Thus, developing reliable designs and predictive techniques could lead to more efficient use of adhesives. This section discusses the characterisation of the adhesive properties in dissimilar joint and their behaviour under various loading conditions.

2.1. Pure Mode I/II and Mixed-Mode

In many industries, joining metals (aluminium, steel, titanium) to composite (carbon and glass fibre reinforced plastics) adhesively is a common connection practice when dissimilar materials need to be bonded. It can provide significant weight saving and excellent design flexibility for complex structures.

Although adhesive bonding between similar components (e.g. composite-composite or metal-metal) are well known, and the procedure of obtaining their strength and fracture behaviour is standardised [5][6], there is the lack of methodologies and design methods for dissimilar bonded joints due to the complexity of failure modes and the load transfer mechanism.

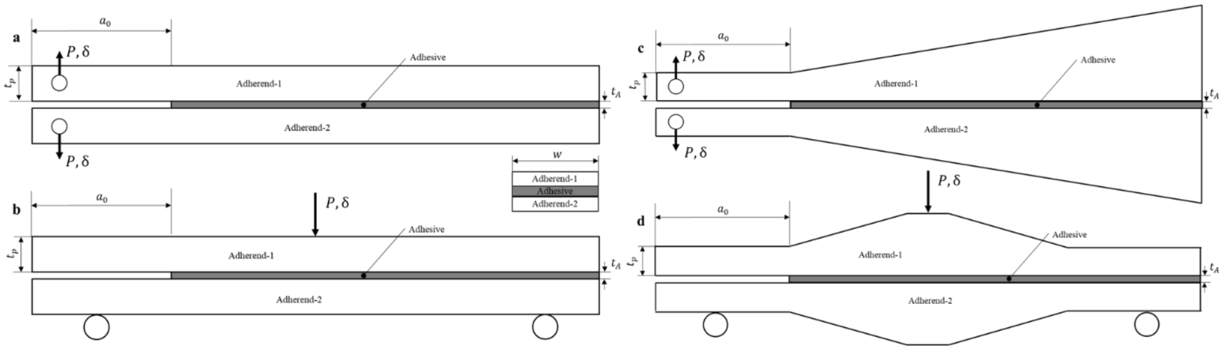

Figure 2: (a) double cantilever beam (DCB) (b) end-notched flexure (ENF) (c) tapered double cantilever beam (TDCB) and (d) tapered end-notched flexure (TENF) specimens

Ouyang et al. [7] introduced a theoretical method based on the classical beam theory to estimate the pure mode-I fracture parameters for dissimilar joints. Their results showed high accuracy in comparison to the numerical and experimental results. Later, few researchers [8][9][10] carried out numerical and experimental investigation by using double cantilever beam (DCB) to obtain the fracture toughness of adhesive for the metal-composite joints (Figure 2).

In composite-metal DCB test, the failure starts cohesively at the first stage of the crack then developed along with the interface between the adhesive layer and composite adherend [8]. Moreover, the secondary interlaminar crack could happen in the composite laminate after the initiation of the interfacial disbanding on the adhesive layer which proves that the composite itself can be considered as "weak link" of these type of joints [9]. This can be justified by the big difference between the stiffness of the composite and metal adherends. Therefore, specific attention should be given to design new DCB specimens to provide pure mode I failure. This can be achieved by an asymmetric DCB (Figure 3) using different thickness for composite and metal adherends to ensure crack propagation in the bonded layer [9]. However, in this case, the modified compliance formula from Kanninen's theory [11] should be used instead of the classical reduction methods [12] to calculate energy rate in mode I. Katsivalis et al. [13] noted that the validated traction and fracture toughness depend on design parameters, including bond layer thickness, the adherends' stiffness and surface chemistry. Moreover, Delbariani-Nejad et al. [14] showed that the probability of de-bonding growth is more sensitive to the initial crack length, the width, and the thickness of adherends in comparison to the other parameters in metal-composite joints.

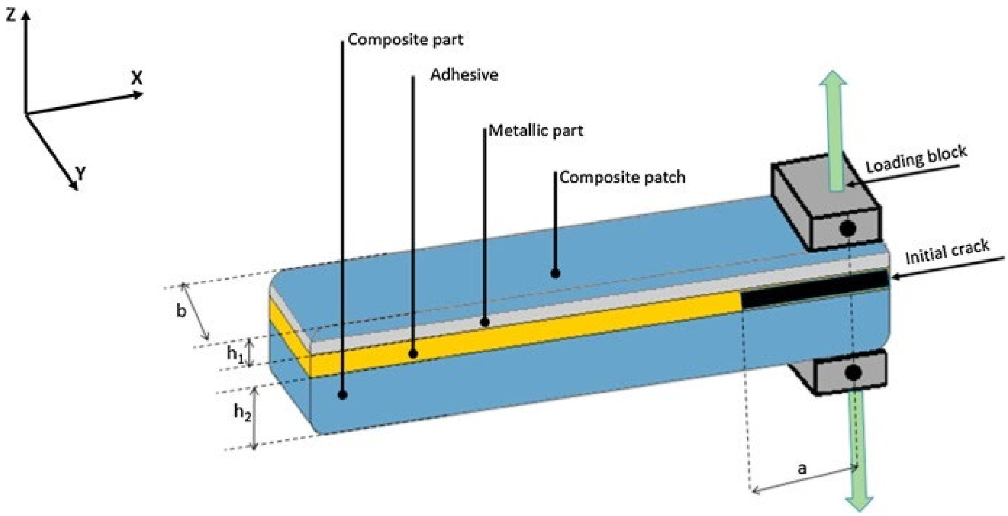

Figure 3: Illustration of a composite/metal DCB specimen with a pre-crack of length a [9]

Few studies [15][16][17][18][19] have been carried out to understand the effect of design parameters on pure mode II fracture energy using dissimilar end-notched flexure (ENF) and tapered end-notched flexure specimens (TENF) (Figure 2). One of the challenges to perform composite-metal ENF test is to have the neutral line position in the correct location. Therefore, the correct thickness should be selected for composite adherend to equalise the flexure stiffness between metal and composite adherend and confirm that the neutral line is located in the adhesive layer [15]. This can be achieved with equation 1 [16] where, h_1 is the thickness of the aluminium and h_2 is the thickness of the composite, E_1 is the Young modulus of the aluminium and E_2 is the Young modulus of the composite.

$$\frac{h_2}{h_1} = \left(\frac{E_1}{E_2}\right)^{1/3} \quad (1)$$

Ouyang and Li [16] theory to calculate fracture energy from the ENF test is only valid if the thickness of the adhesive is much smaller than the thickness of adherends. However, in many industrial application, the thickness of the adhesive is not negligible in comparison to the thickness of the adherends. The new model is introduced by Alía et al. [15] based on Bernoulli-Euler beam theory to calculate mode II fracture energy by incorporating adhesive thickness. Their model confirms that the fracture energy is higher in the dissimilar ENF when an adhesive layer had a non-negligible thickness, compared to the dissimilar joint with negligible adhesive thickness. This shows the influence of the adhesive thickness [15] and the plastic zone radius [17] on the fracture energy of the dissimilar joints.

The adhesion strength is also affected by the metal-polymer adherends surface topography which links the macroscopic adhesion strength to microscopic energy dissipation mechanism during fracture [18]. This can be proved by fabricating micro-patterns on the metal surface to show the effect of the mechanical interlock on the fracture toughness of ENF specimens [18]. Wang and Qiao [19] compared shear-mode (model II) fracture toughness of the Wood-Wood and Wood-FRP by using tapered end-notched flexure (TENF) specimens. The fracture toughness of the Wood-FRP interface is lower than the value of the Wood-Wood bonded interfaces.

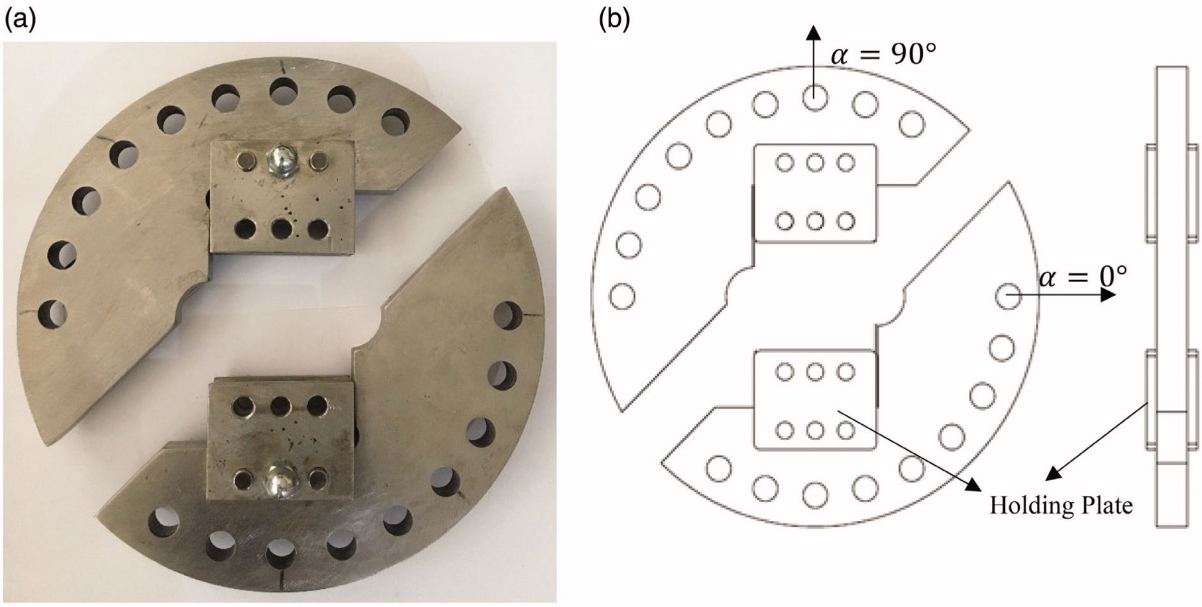

Figure 4: (a) Modified Arcan fixture and (b) schematic Arcan fixture [20]

Crack propagation can occur in more than one mode (Mode I and II components of the strain energy release rate). Therefore, it is important to carry out the mix-mode crack propagation tests in addition to the pure mode test. The mixed-mode bending (MMB) test is the most commonly used method which uses a combination of DCB and ENF test to investigate mixed-mode I/II fracture behaviour. There are limited studies regarding dissimilar materials adhesively bonded joints under mixed-mode [18][21][22]. Arcan fixture [23] is another useful method that can be used to characterise the properties of the adhesive layer under mixed-mode by simply rotating fixture in the testing machine. Hossein Abadi et al. [20] found that by increasing the loading angle from 0° (Mode I, in the x-direction) to 90° (Mode II, in the y-direction) in modified Arcan fixture (Figure 4), the fracture loads are increased by 332.65% and 332.02% for dissimilar specimens with initial cohesive crack and initial interface crack, respectively.

2.2. Tensile loading

In recent years, several experimental works have been conducted on dissimilar joints that explore factors affecting the strength of adhesive joints under tensile loading for various structural applications.

There are two main mathematical approaches for analysing of adhesively bonded joints: closed-form solutions (analytical methods) and numerical methods (i.e. finite element analysis) [4]. The available work with an explicit closed-form analytical solution of the dissimilar bonded joints is limited due to mathematical complexity in such a layered structure. Volkersen [24] and Goland and Reissner [25] introduced the first modern simple lap joint theory to predict stress distribution in a thin adhesive layer.

Carpenter [26] noticed errors in Goland and Reissner solution for stress in an adhesive layer which was neglecting shear deformation of the adherends, inconsistently using plane stress and plane strain for adherends and inconsistently using shear stress and shear strain for the adhesive layer. Wu et al. [27] corrected Goland and Reissner (G-R model) solution by modifying their classical equation for analysing the adhesive layer in dissimilar adherends with different thicknesses and lengths. In the G-R model, the adhesive layer is modelled as a two-parameter elastic foundation [28]. The major disadvantage of the model of the G-R type is that this model does not satisfy the zero shear stress at the end of the bond-line, which violates the equilibrium condition of the adhesive layer [29]. Another major drawback associated with the G-R type model is that these types of model assume uniform peel and shear stress through the thickness of the adhesive. However, there is a close relation between adherends failure mode and the magnitude of the through-thickness adhesive peel stress [30]. Moreover, it is important to analyse the interfacial peel stress at the end of the bond-line to assess the potential debonding and predicting where the debonding can initiate [31]. Wang and Zhang [31] developed a three-parameter method by introducing the transverse displacement of the adhesive layer as a new parameter which regains the missing degree of freedom in the two-parameter method (G-R method). In this method, the peel (normal tensile) stress in the adhesive interface can be predicted and also the violation of the equilibrium condition in the G-R type model is eliminated. The three-parameter method stratifies zero shear stress at the free edges of the bond-line, and it predicts different peel stress distribution at the top adherend/adhesive and bottom adherend/adhesive interfaces. However, the two-parameter model underestimates the peel stress at the free edges of the bond-line, and also predict similar peel stress along with two interfaces of the adherend/adhesive.

Finite element method (FEM) is one of the most popular methods to predict the strength of adhesive joint over the analytical method due to its ability to determine stresses in any geometrical shape under various loading conditions [32]. For instance, when a single lap joint is under tensile loading, the stresses are transmitted via an adhesive layer and through the adhesive/adherend interface from one adherend to another which could cause three types of failures within the adhesive layer, i.e. cohesive, adhesive failure or the combination of the adhesive/cohesive failure. Thereby it is important to consider these types of failure in finite element (FE) modelling to assess the behaviour of the adhesive joint accurately. There are two available failure models (strength-based [33] and energy-based [34][35]) to analyse failure load, failure mode and stress distribution in adhesive joints. In the strength-based method, bulk properties are used for the linear and non-linear simulation to calculate the stress/strain in the joint. In the energy-based, the fracture properties are defined, and the joint would experience failure after reaching the critical stress values. The significant developments were made in the last decades by introducing new energy-based methods to model damage growth by combining the FEM with Cohesive Zone Modelling (CZM) [36]. Cohesive Zone Modelling (CZM) has been widely used in the simulation as it allows multiple failure paths in the middle of the adhesive or along the interface to predict failure.

There are various techniques (direct and indirect methods) to obtain CZM parameters (t_n, G_{IC}, t_s, G_{IIC}) by using double cantilever beam (DCB), end notch flexure (ENF) and single-lap joint (SLJ) tests. The extended finite element method (XFEM) is another new technique suggested by scientists to model damage growth in structures. XFEM model is Introduced by T. Belytschko and T. Black [37] based on the partition of unity finite element method [38], which utilises elastic properties of the material for crack initiation and strain for the assessment of failure.

Goudarzi and Khedmati [39] developed two-dimensional (2D) and three-dimensional (3D) model using cohesive zone technique to analyse the behaviour of the Al-Glass Fibre Reinforced Polymer (GFRP) single lap joint (SLJ) and double butt lap joint (DBLJ) under tensile load. There was a small difference (less than 5%) between predicted failure loads from 2D and 3D models. However, the comparison of the numerical and experimental failure loads shows that joint configuration affects the accuracy of the numerically predicted failure load. In addition, the cohesive parameters in Mode II have more effect on the failure load in comparison to the Mode I irrespective of joint designs. Anyfantis [4] developed a new method based on an embedded process zone (EPZ) to analyse the behaviour of steel-GFRP double lap bonded joint with a ductile adhesive under tensile loading. In the numerical model, the adhesive material was represented entirely by interface or cohesive elements capable of modelling the kinematics embedded in the EPZ. The EPZ model predicted failure load with smaller error in comparison to the damage zone theory (DZT), though this method underestimated the failure load for the dissimilar joint with thick adherend and overestimated the failure load for the dissimilar joint with thin adherends. Stuparu et al. [40] simulated the behaviour and strength of dissimilar aluminium-CFRP single-lap joints under tensile loading using a combination of Cohesive Zone Modelling (CZM) and eXtended Finite Element Modelling (XFEM). The conclusion drawn was that dissimilar Al-CFRP joints could successfully maintain the assembly stiffness (in contrast to the similar AL-AL joints), but that their strength was reduced by the delamination and pull-out of carbon fibres.

Most of the previous numerical works used a single layer of the cohesive element in the bond-line to simulate the adhesive layer, which is accurate enough for identical adherend joints. Nonetheless, the method cannot describe the failure process for the dissimilar adhesively bonded joint and estimate the strength of the joint accurately. Since the change of the adherend changes the interaction between adhesive and adherend due to different roughness and chemical links [41].

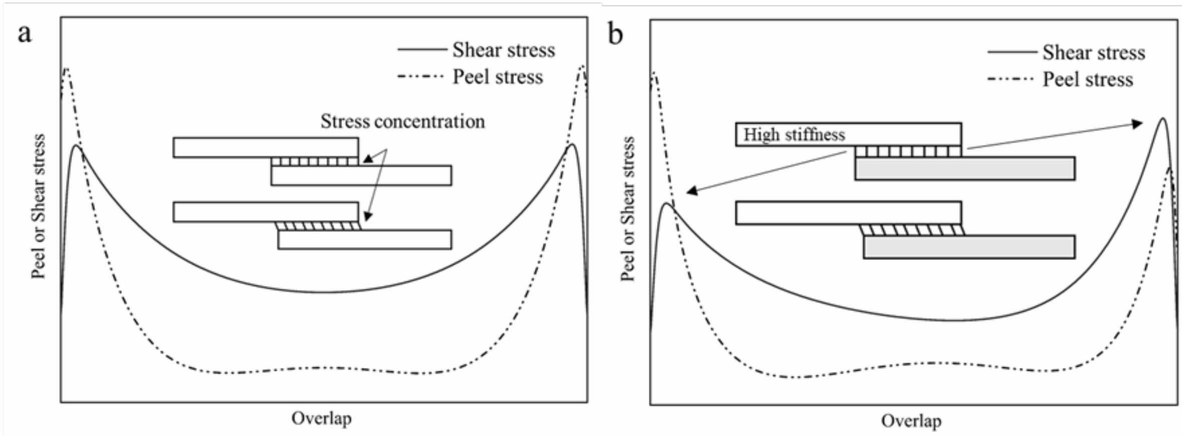

Figure 5: The general trend of stress distributions for simple lap shear joint with (a) similar (b) dissimilar adherends [42]

The general trend of normal and shear stress distribution in simple lap shear joints under tensile loading showed that both peel and shear stresses are more uniform at the middle of overlap region with higher peak stresses at the edges (Figure 5a) [43], which are caused, respectively, by the rotation of adherends [44] and the geometrical discontinuity of the adherends at the free edges [45]. However, in dissimilar lap shear joints, shear stress concentrations are higher near the free edge of the interface between the adhesive and lower Young's modulus adherend [46] resulting in asymmetric stress distribution (Figure 5b) due to different longitudinal deformations at the overlap edges [47]. The peel stress distribution showed similar asymmetric behaviour but with lower stress concentration toward high stiffness adherend due to smaller rotation [47]. The higher peak stresses at the free ends of overlap are important as it is likely that crack initiates at this location, especially if the adhesives are brittle, which are more sensitive to the stiffness of the adherends due to the higher peak stresses and instability in damage propagation [48].

Due to the complexity of the failure mechanism in adhesive joints, it is important to perform mechanical testing and numerical modelling to find suitable configurations to have a maximum efficiency of the bonded joint [49]. Pinto et al. [50] evaluated the tensile strength of single-lap joints with different adherends (polypropylene (PP), polyethene (PE), carbon-epoxy, and glass-polyester composites). Increasing the adherends' stiffness diminishes stress at the overlap edges and, consequently, increases the joint strength. Hunter-Alarcon et al. [51] showed that the manufacturing process of composite plates (hand lay-up and Vacuum Infusion with different pressures) in dissimilar lap shear joint has more effect on the joint with thick adhesive (here 1.3 mm) in comparison to thin adhesive (here 0.7 mm). Reducing the resin concentration within the layers of glass fibre lamination increases the vacuum pressure, consequently, increases the strength of dissimilar lap shear joint. Rudawska [52] concluded that a similar and dissimilar joint could have higher strength with ductile adhesives in comparison to brittle adhesives. This can be justified with larger plasticisation in the ductile adhesive, which can redistribute the load and make use of the less stressed parts of the overlap. Sun et al. [53] utilised the charge couple device (CCD) cameras and digital image correlation method (DIC) analysis to investigate the adherend deformation and the fracture process in lap-shear joints under tensile loading. The fracture process, including the crack initiation and the crack propagation, was symmetrical in the bond-line for the joint with similar adherends. At the same time, asymmetric behaviour is noticed for the dissimilar joint where the crack initiation located in the lap end on the interface of the adhesive/adherend with lower yield strength.

Further to the macro-scale analysis of the multi-material joint under tensile loading. The molecular mechanism of the adhesion between adhesive and adherends interface can be obtained at the micro-scale. Various feature of the material's micro-structure such as effects of absorbed water, the roughness of the interface, the stiffness of adherends/adhesives and bonding temperature can be assessed based on geometry-optimised structures, adhesion energies, and forces. This study potentially can provide a better understanding of the interaction between adherends interface and adhesive at the molecular scale.

2.3. Fatigue

Fatigue is a dynamic periodic of loading condition for adhesively bonded structures. In many cases, a structure could experience failure with a significantly small percentage of static strength under a fatigue loading [54]. Thus, it is essential to analyse the influence of the fatigue loading on the stress distribution, strength and damage tolerance of the adhesively bonded joints. Predicting accurate fatigue life for the bonded structures is a challenging job, due to the complex nature of fatigue crack initiation and propagation under various loading conditions.

For dissimilar adhesively bonded joints, Ishii et al. [55] developed the fatigue failure criterion under a state of concentrated multiaxial stress to estimate the strength of the different configurations of the CFRP-metal adhesively bonded joints. The fatigue strength was controlled by the fatigue resistance of the CFRP plate. Moreover, The fatigue strength decreased by increasing the thickness of the CFRP plate due to the increase in the fibre volume fraction of the CFRP plate. This can be justified as the increase in fibre content reduce the bonding strength of the composite material, resulting in rapid stiffness degradation [56]. The fatigue crack initiated at the early stage of fatigue life at the free end of the overlap regardless of the overlap length then propagated along with the adhesive/adherends interface or through the middle of the adhesive layer in lap joints [57]. The fatigue crack also could experience crack growth within the first ply of the composite adherend adjacent to the adhesive [58]. Deng and lee [59] successfully used the backface-strain approach to detect the crack initiation, and measure crack growth for steel I-beam bonded with CFRP plates. Cracks initiated and propagated in Model-I before Mode-II in bonded joints. Azari et al. [60] found that adherends' modulus had a more significant effect than the adherends' bending stiffness on the fatigue performance of the adhesive joint. Li et al. [61] investigated the overloading fatigue for notched steel I-beams strengthened with the CFRP plate. The notch was introduced at the middle of the I-beam on the tension flange. The overloading damage was mainly initiated at the notch location and then propagate along with the interface between the CFRP plate and the adhesive.

2.4. Impact loading

The impact strength is one of the significant factors in the automotive industry as the vehicles must provide sufficient safety for the passenger during collisions. Another example of commercial application is using the bonded structures in the defence industry to face up to ballistic impacts, with extraordinarily high impact velocities [62]. Therefore, it is essential to understand the behaviour of the dissimilar joints under an impact load for designing stronger and safer light-weight structures.

Raykhere et al. [63] studied the dynamic shear strength of metal-composite butt joints for different adhesives. The dynamic strength was 2-4 times bigger than the static strength depending on the adhesive and adherends combination. Yildirim and Apalak [64] Investigated the effect of transverse low-speed impact tensile loads on the plastic dissipation history of dissimilar adhesive joints (Al/Steel). The residual plastic strain increased in both the adhesive layer and adherends by increasing the impact energies. Liu et al. [65] showed that by increasing the strain rate (10^{-5} m/s 2.5m/s and 5m/s), the strength of the CFRP/Al SLJ increased and the failure mode in the joint changed from adhesive failure to fibre-tear in the composite. The effect of the temperature on the strength of the CFRP/AL SLJ is investigated by Avendano et al. [66] under impact loading. The strain sensitivity was much lower at the low temperature due to very brittle behaviour of the adhesive which causes high peel stress at the free end of the bond-line.

The dynamic strength of the single-lap joint is influenced by the stiffness of adherends with considerably lower strength for the joint with dissimilar adherends in comparison to the joint with similar adherends [67]. This can be explained by the difference in maximum value (peak value of the strain wave) of the strain in the adherends, resulting in higher stress wave propagations and interface stress concentration toward lower stiffness adherend [68]. Machado et al. [69] suggested that a crash-resistant adhesive can be used for bonding dissimilar components in automotive structures without significant sacrifices in energy absorption and failure load under impact loading. Moreover, the performance of these joints could be estimated by utilising a cohesive zone model to reduce the need to run experimental testing.

2.5. Compressive loading

The use of composite with steel, particularly in the strengthening of steel structures has received significant attention in the recent year. The use of FRP plates with adhesive layer shows a positive effect in delaying compressive buckling as unlike steel, the properties of FRP plates can be adjusted by altering the fibre directions and amount of fibres in any specific direction. There are several numbers of failure modes for such composite-steel bonded beams under compressive loading condition, including (a) in-plane bending failure [70] (b) lateral buckling [71], (c) plate-end debonding [72] and intermediate debonding due to local cracking or yielding of composite adherends [71].

Debonding in the adhesive layer between steel and CFRP was found to be the main reason for the failure of the strengthened structures under compressive loading [73], though in some experimental work crushing of the CFRP are also observed [74]. Thus, more research is required on debonding behaviour in the buckling failure modes of composite-metal dissimilar structures under compressive loading.

The plate-end debonding occurs in the fibre-reinforced polymer (FRP)-steel plate owing to high peel, and shear stresses near the plate end. Several factors, such as the bending moment and shear force in the beam, affect the magnitudes of these localised interfacial stresses [75]. However, intermediate debonding happens typically due to a defect (e.g. crack) [75], or near a location with high concentrated plasticity of the steel adherends [71] where the FRP adherend is highly stressed.

In practice, dissimilar adhesive joints experience bending moments in the automotive, aerospace and maritime applications [76]. Sawa et al. [77] and Liu et al. [78] studied the effect of different design parameters on the similar and dissimilar adhesive butt joint and single-lap joint, under external bending moments. The fracture occurs from the interface of the lower stiffness adherend. Sawa et al. [79] also found that the maximum bending stress decreased by increasing the number of steps in dissimilar stepped-lap joints. Belingardi and Scattina [80] investigated the bending behaviour of thin-walled box beam for a different type of adherend materials (steel and composite) and joining technologies (adhesive layer and spot weld). It was noticed that the adhesive joining approach made it possible to build the hybrid joints, resulted in 28% weight reduction and higher stiffness and the elastic limit.

3. Optimisation of the dissimilar adhesive joints

The increased use of dissimilar joints such as bonding composites to metals in aerospace, maritime and civil and transport structures in the past decades makes it essential to find a method to improve the performance of this type of joints. Several methods have been discussed in the review papers [81]–[83] to optimise the performance of the adhesively bonded joints. These methods can be categorised into two major groups: geometrical and material modifications. This section presents the available work from the perspective of the optimisation of the dissimilar joint to investigate the effect of geometrical modification (e.g. joint geometry, adherend/adhesive thickness and length, surface treatment and fillet and recess) and material modification (the stiffness of adherend/adhesive and mixed-adhesive).

3.1. Geometrical modification

Geometrical modification attempts to change the shape of adherends or adhesives. The most popular methods are tapering, rounding and notching of the adherend/adhesive, changing adherends shape, optimising the adherends/adhesive thickness and length [84]. All these methods try to minimise the shear and peel stress concentration at the overlap edges. These stress concentrations at the bond-line edges are essential as the crack would probably be initiated at those areas due to high stresses.

3.1.1. Joint geometry

In the design of dissimilar bonded structures, choosing the correct joint configuration is a challenging task due to the difference in the material stiffness and different deformation effects which could lead to higher peel and shear stress concentration at the bond-line edges. A wide variety of joints are available to designers, as discussed by Adams et al. [85]. Single-lap joints are amongst the most studied and commonly used designs in various engineering applications due to their lower cost and simplicity. Other common joint configurations in literature are scarf joints, stepped-lap joint, double-lap joints, half-lap splice joints and butt joint for either similar or dissimilar components. Depending on the application, there are also some studies for bonded joints such as T-shaped joint, L-shaped joint, double-doubler joints and tubular-lap joint. A lot of thorough research into the failure of such joints made from identical adherends (for example aluminium [86][87][88][89] and composite [90][91][92][93]) has already been conducted, and the findings are rather well known. However, there is only a few works focus on the case of dissimilar adherends. Therefore, there is a need for a study to compare the most common joint designs with dissimilar adherends to provide comparative information about stress distribution and strength of each design.

3.1.2. Adherends and adhesive thickness and length

Sawa et al. [46] studied the effects of the thickness ratio of the adherends to adhesives and the adherends length on the interface stress distribution of the dissimilar single-lap joints and showed that the stress singularity increased at the free edge of the interface in the adherend with thinner thicknesses. Pinto et al. [94] showed that in dissimilar joints, the use of various adherend thickness weakened the joint strength. This can be explained by the higher peel stress value at the end of the thicker adherends due to smaller longitudinal deformation.

Anyfantis et al. [95] showed that the effect of the adhesive thickness on the experimental strength of the dissimilar joints was significantly less than that of the overlap length under static tensile loading. Increasing the adhesive layer thickness results in a decrease in the residual plastic strain in the adhesive layer, the strength of adhesive layer and the size of the damaged area in dissimilar joints [96][97]. On the other hand, increasing the overlap length showed significant improvement in the failure load of the dissimilar single-lap joints [98][99]. Meanwhile, higher peel and shear stresses at the over-lap edges of the adhesive are also associated with larger over-lap length [99]. This can be justified as increasing the overlap length increases the transmitted load, resulting in higher longitudinal deformation and bending moment [100].

In FRP-steel single-lap joints, the bond strength initially increases by enlarging the overlap length, but when the overlap length reaches to a threshold value, the further enlargement of the overlap length does not enhance the bond strength [101]. This threshold overlap length value is recognised as the effective overlap length [102], where the shear stress contact stress is either at 97% or 99% of the ultimate strength of the bond [103]. Al-Zubaidy et al. [104] showed that effective bond-length was not sensitive to the loading rate (2mm/min, 3.35, 4.43 and 5 m/s) for steel/CFRP double strap joints with a different number of CFRP layers.

Imanaka et al. [105] evaluated the influence of the thickness ratio of the dissimilar double cantilever beam with acrylic and epoxy adhesives on the fatigue crack growth rate. The ratio of the thickness of the lower adherend to the upper adherend is a vital factor in determining the mode ratio G_{II}/G_{I} (where $G_{I}$and G_{II} are strain energy release rate in mode I and II, respectively) and the stress distribution at the crack-tip.

3.1.3. Surface treatment

The surface treatment of the overlap plays an essential role in the bonding process. Appropriate surface treatment can potentially improve the interface properties and the bonding strength between the adherends and the adhesive. A clean surface alone is not sufficient; surface tension, surface roughness and chemical composition also affect bond durability [41][106].-

The failure mechanism and joint strength of the composite-metal bonded joint depend on surface treatment [107]. In FRP-steel bonded joints, the adhesion failure can occur at the interface between steel/adhesive. This typically happens when FRP is applied through a wet lay-up process on site. However, this type of failure could be avoided when a pultruded FRP plate/strip is utilised. The composite plates would normally contain a peel-ply on the surface which can be removed immediately before bonding (to prevent possible contamination of the surface) to provide a rough and clean surface for bonding. In case peel-ply is not available, composite plate/strip should be lightly abraded with sandpaper to avoid damage to fibres [108]. Kim et al. [109] utilised the combination of the mechanical, chemical, and energic surface treatment to increase the wettability of dissimilar aluminium-steel joints by measuring the contact angle of water droplets on the treated aluminium adherend. The combination of flame treatment with sulphuric acid etching (SAE) was reported to have the highest shear bond strength in comparison to other surface treatments (Figure 6). Using silane coating as a secondary surface treatment after primary surface treatment could increase the joint strength even furthermore [109][110].

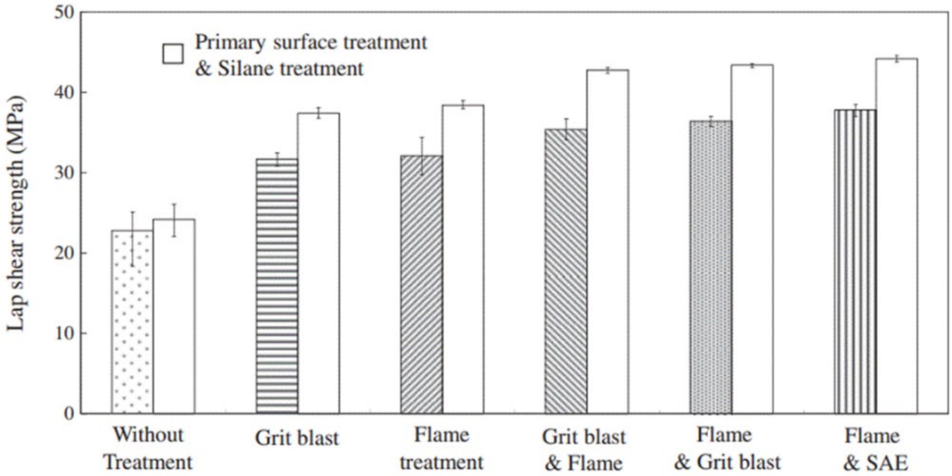

Figure 6: The strength of dissimilar lap shear joint with a different type of surface treatment including flame treatment, grit blast, flame and sulphuric acid etching (SAE) [109]

Perrut et al. [111] introduced an alternative surface preparation methodology for oil and gas applications to treat corroded steel surface in CFRP-steel adhesively bonded double-lap joints. This method used a portable machine that can treat the steel surface by use of rotation and impact. Despite the fact that the CFRP/steel bonded joints treated with the proposed method provided the same quasi-static and fatigue performance in comparison to joints prepared by grit blasting, the productivity of the proposed method is low, therefore, it is only recommended to be used for spot repair. Kwon et al. [112] investigated the effect of residual oils on the performance of metal-FRP bonded joints. In order to obtain enough adhesion strength, the residual oil on the bonding interface should be less than 1.0 g/m^2 and flame treatment should be carried out. Kwon et al. [113] used three different types of sandpaper (P120, P220 and P400) to find the effect of the lapsing time (30, 60 and 180 seconds). A sanding time of 30 second provides higher surface roughness regardless of grit size in comparison to 180s, which is due to the uniformity of the interface roughness after longer sanding time. Although the effect of surface roughness is essential for a higher bonding strength, a non-uniform roughness due to short sanding treatment resulting in a lowered adhesive force.

3.1.4. Fillet and recess

Many ideas have been introduced to reduce the peak stresses such as using tapers, holes, fillets, round corners and notches in the adherend/adhesive. The most of these works in literature [114]–[122] used similar adherends in adhesively bonded joints, and only a few works are available that analyse the effect of these geometrical modifications in dissimilar joints.

Adam et al, [123] studied various configurations of dissimilar double lap joints (Figure 7) to find a solution for peel stress failure of composite adherends. The peel stress at the free end of the bond-line can cause failure in composite adherend before the adhesive layer due to the low transverse (through the thickness) tensile strength of composite material. In designs 2 and 3, the outer and inner taper were used respectively. However, they had almost no effect on the load transfer and stress concentration. In design 4, the adhesive fillet is utilised which improved the stress concentration significantly (the peak stress concentration reduced by 50% with a 45° fillet). The shear stress reduced even further more in design 5 (about an eighth of that of design 1), where the combination of the inside taper and a 17° fillet were used. The failure in design 1,2 and 3 were predicted to be initiated in composite adherend and design 4 and 5 in the adhesive layer.

Hildebrand [124] studied the influence of the fifteen different shapes of the adhesive layer (e.g. tapering, rounding or denting) at the adhesive-free edges on the strength of the metal-FRP SLJs. The numerical simulation predicted that careful adhesive free-end design can increase the joint strength by 90-150%. Lang and Mallick [125] studied the effect of the various spew fillets design on the stress distribution of the adhesive layer by utilising the linear FEA method. A larger spew fillet for triangular and rounded design causes a higher reduction of the peel and shear stress concentrations at the free end of the bond-line. Belingardi et al. [126] research indicated that the spew and chamfer angles of 45 degrees are sufficient in steel-FRP bonded SLJs to reduce peak peel and shear stress at the free ends by five and two times, respectively.

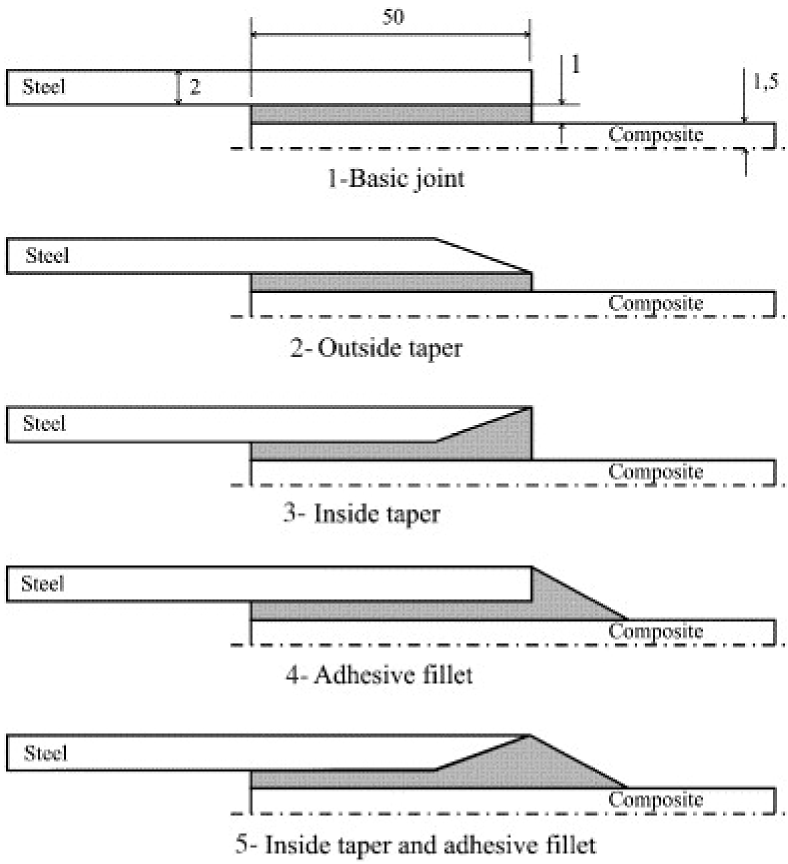

Figure 7: Designs of double lap joints (not to scale, dimensions in mm) [123]

Kilic et al. [127] studied the effect of free edge shapes (square-end fillet, chamfered-end fillet and spew fillet) in dissimilar bonded joints by using global elements coupled with FEM to capture the accurate stress distribution in at the critical region of the bond-line (where the singularity occurs). The energy release rate and stress intensity factors were smaller for joints with spew fillet in comparison to other shapes. The effect of different taper angle (3°, 5°, 10°, 15°, 30° and 45°) of the adherend in dissimilar double lap joint was studied by Choupani [128] and showed that the adherend with the angle of 3° had the best performance.

Hua et al. [129] investigated the performance of recessed composite-titanium single-lap joints with and without spew fillets. The presence of the spew fillet decreased the peak stress concentrations at the corners by 45.2%, leading to a 36.3% improvement in the joint strength in comparison with those of a single-lap joint with a square end. Kanani et al. [130] introduced a novel design for dissimilar SLJ to minimise peak stress concentration by using notches in the middle of the bonding area. The existence of notches along the overlap length divides the overlap area to smaller sections, which assists the modified SLJs to spread the load more efficiently between each section, leading to significant improvement in the joint strength.

3.2. Material modification

Geometrical modification techniques have been utilised extensively in the automotive industry to reduce peel and shear stress concentrations [131]. However, these techniques such as tapering the adherends, forming an adhesive fillet or changing the joint geometry have some disadvantages. For instance, creating spew fillet for low viscosity adhesive is difficult, and changing adherend shape could damage fibre structures when using fibre reinforced composites, resulting in a loss in bending stiffness and strength [132]. An alternative technique is to use a material modification of adherend and adhesive which aims to optimise the stiffness of the adherend and adhesive to decrease stress concentration at the overlap edges. This can be achieved by eliminating the strain gradient of the adherends or by optimising the adhesive stiffness along the bond-line to produce smaller stress gradients at the over-lap edges.

3.2.1. The stiffness of adherends

Material modification aims to homogenise stresses by grading Young's modulus (E) of the adherends/adhesive in a way to reduce peak stresses at the overlap edges. Ganesh and Choo [133] changed the braiding angle of composite fibre to optimise the modulus along the bond-line to increase the joint strength. Their FE simulations showed a 20% reduction in the peak shear stress and more uniform shear stress distribution in the adhesive layer for the case with adherend longitudinal modulus grading. Vinson [134] found that increasing the flexural and extensional stiffness of the adherends can minimise the peak peel and shear stresses at the overlap edges. This can be justified by the smaller rotation of the specimen due to the increase in the bending stiffness of the joint which promotes a more uniform stress distribution in the adhesive layer [1][135][136].

3.2.2. Mixed-adhesive

Another material modification is the use of mixed-adhesives joint (MAJ) which is introduced by Raphael [123], which are also recognised as a bi-adhesive or dual adhesive in the literature. The high stiffness adhesive develops higher peel and shear stress concentration at the free end of the bond-line. This high-stress concentration can be reduced by using low modulus adhesive (flexible adhesive) at the free end of the bond-line. Das Neves et al, [137] developed an analytical model to investigate a mixed-adhesive single-lap joint (SLJ) and double joint (DLJ) that can perform in low and high temperature. The high-temperature adhesives (HTA) are brittle at low temperatures which increases the risk of sudden crack initiation at the free end of the bond-line. On the other hand, lower temperature adhesives (LTA) is too flexible to carry the applied load under a high-temperature environment. To overcome this issue, the high-temperature adhesive was utilised in the middle of the bond-line and a low-temperature adhesive at the ends of the overlap. Moreover, Neves et al, [138] used their analytical work to perform a parametric study to investigate the effect of the constant temperature change on mix-adhesive single-lap and double lap joints. The optimum length of the LTA should be around 0.5 of the length of HTA in both SLJ and DLJ to perform low to high temperatures. To the best knowledge of the author, there is not an analytical model for mixed-adhesive with dissimilar adhesives. This study could be useful for parametric studies and design purposes of the dissimilar bonded joint with mixed-adhesives.

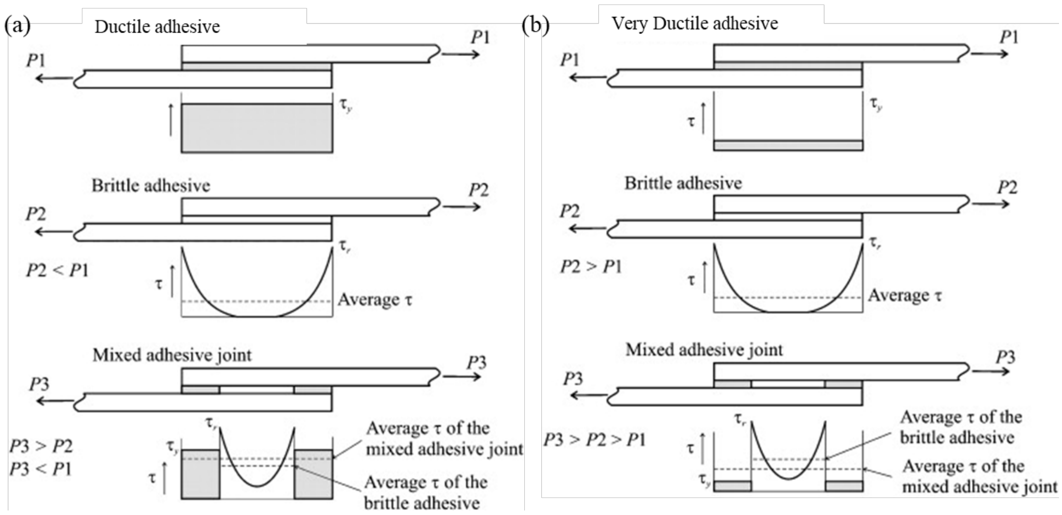

Figure 8: schematic of adhesive shear stress distribution for joint (a) brittle and ductile adhesive (b) brittle and very ductile adhesive [139]

One of the challenging parts to manufacture mix-adhesive joint is to make sure two adhesive does not mix. da Silva [139] utilised silicone rubber strip as a separator between the adhesive to guarantee that two adhesives do not mix. For the joint with mixed adhesives to be stronger than the joints boned individually with brittle or ductile adhesives, the load-carrying capacity of the brittle adhesive should be higher than the ductile adhesives (Figure 8). Kannai et al, [130] introduced a novel design by using notches between epoxy and polyurethane adhesives which avoid mixing adhesives in the bonding area. The combination of the epoxy and polyurethane adhesives gave a higher failure load than its individual one in dissimilar SLJs. This was explained as the polyurethane adhesive provided more uniform stress distribution by transferring stress concentration to the interior part of the overlap region [130].

da Silva et al. [140][141] numerically investigated the performance of the metal-composite joints under a wide temperature range by using the combination of two types of adhesives, one suitable for HTA condition and the other for LTA condition. The load-carrying capacity of the dissimilar joints improved with mixed-adhesive (LTA at both ends and HTA in the mid-section) under-considered temperature (range from -55 to 200ºC) especially when the thermal coefficients of expansion of two adherends were high. Bond strength was higher with a larger portion of the ductile adhesive in the bond-line edges and a smaller portion of brittle adhesive at the centre of the bond-line [142].

4. Environmental durability of dissimilar adhesive joints:

The adhesively bonded joints are vulnerable to aggressive environmental conditions, such as high/low-temperature conditions and hydrothermal ageing, which adversely affect the joint durability. This section overviews the studies on dissimilar adhesively bonded joints under severe conditions.

4.1. Temperature

Temperature variations such as freezing temperature [143]–[147] and elevated temperatures [148]–[151] can affect the performance of adhesively bonded joints. The recent developments in joining multi-materials with adhesive bonding for stronger and lighter and fatigue-resistant structures help to understand the behaviour of these joint under extreme temperature. The resin matrix, adhesive and fibre/matrix interface are well known to be vulnerable to temperature variations in adhesively bonded composite-metal joints [152]–[154].

Kang et al. [143] studied the bonding performance of CFRP-Al double-lap joints at room temperature and cryogenic temperature (-150 °C) for three different adhesives. At the room temperature (25 °C), the strength of the double-lap joint bonded with the ductile adhesives was lower than the strength of the bulk ductile adhesive specimens, while at -150 °C double lap joints and bulk adhesives have similar strength. On the other hand, the epoxy adhesive does not follow the same tendency, as the strength of the bulk brittle adhesive specimens is higher than its double lap joint strength at -150 °C and 25 °C. Agarwal et al. [144] evaluated the performance of steel-CFRP single-lap joint under freeze-thaw cycle. The bond strength of joints was observed to decrease significantly by increasing the number of freeze-thaw cycles. Agarwal et al. [145] studied the long-term durability of CFRP-steel lap joints under freeze-thaw cycles. The major reduction in strength occurred during early exposures of freeze-thaw cycles with a little degradation in the lap joint strength after a certain number of cycles. Anes et al. [146] investigated corrosion failure at a low temperature (-50 °C) in the Airbus A320 CFM56-5b intakes, which are attached to the power plant frame by dissimilar bonded joint. The significant low temperature had an adverse impact on the strength of the adhesive bond-line, in addition, the micro-cracks were found to be initiated due to thermal loads under zero degree Celsius, even for an adhesive without any ageing. The adhesive/matrix rheological and thermomechanical properties had a significant effect on the CFRP-steel bond strength and failure modes under infrastructural sub-zero thermal environments (from -40 ℃ to 20 ℃) [147].

The debonding failure and a significant decrease in ultimate joint load is expected at a temperature near and greater than glass transition temperature (T_g) due to the increase in adhesive softening and degradation in properties. Al-Shawaf [148] investigated the characterisation of the bond for CFRP-steel double-lap joints under elevated temperature exposures with a range of environmental temperatures in the range of 20°C to 60°C for three epoxy resins: (i) Araldite 420 A/B, with a tested T_g of 41.66 °C, (ii) Mbrace Saturant, with a tested T_g of 55.5 °C, and (iii) Sikadur-30, with a T_g of 62 °C. Nguyen et al. [149] examined the mechanical performance of CFRP-steel double-lap joints with different overlap lengths at elevated temperatures. At transient temperature (T_g) of adhesive, the joint failure mode changed from adherend failure to cohesive failure in the adhesive layer. Moreover, the joint strength reduced by 15%, 50% and 80% when the temperature reached at T_g, 10 °C above T_g and 20 °C above T_g, respectively. The effectiveness of the bond-line length near T_g was found to be twice larger than room temperature.

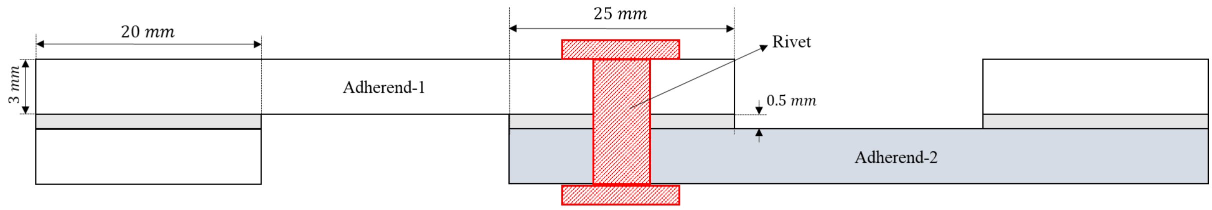

Figure 9: Geometric configuration of the hybrid single-lap joint used in ref [154]

Korta et al. [150] carried out humidity-temperature cycling tests on similar and dissimilar single-lap joints. The specimens were made of CFRP, Al and two types of advanced steels: abrasion-resistant and high-strength, which were bonded with two different epoxy adhesives for moderate and elevated operating temperatures. The temperature expansion coefficient was noted to be a curial parameter for the performance of dissimilar adhesively bonded joints. The performance of CFRP-Al single-lap bonded joints subjected to a wide range of temperatures was investigated under tensile loading condition by [153][154] and quasi-static and impact conditions [155]. Chen et al. [154] showed that in hybrid single-lap joints (Figure 9) the failure load and energy absorption were highly depended on the substrate material and testing temperature (Figure 10). Where the T_g was 75 °C and 121 °C for adhesive and CFRP respectively.

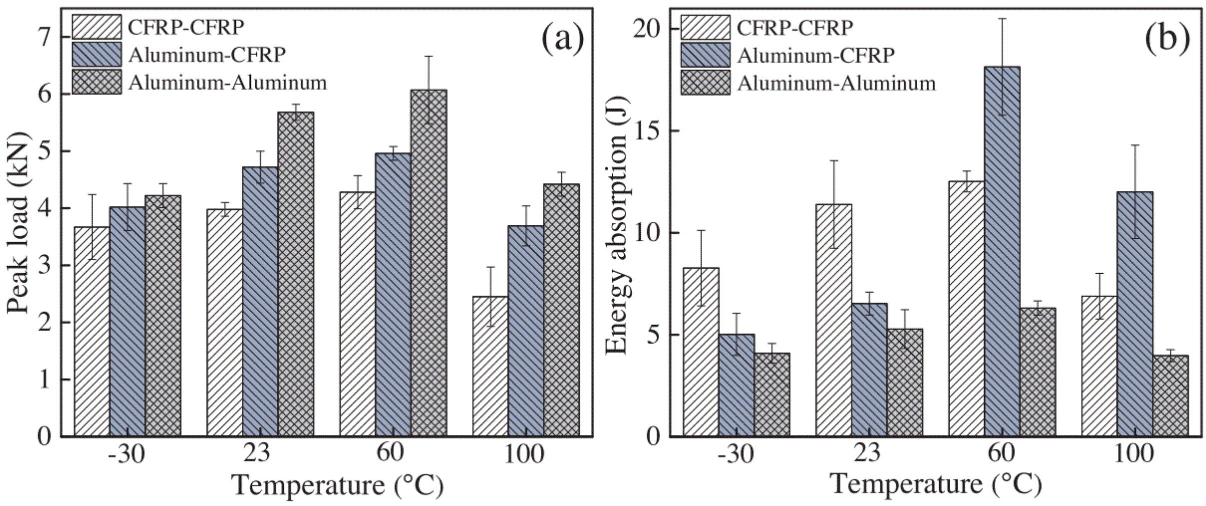

Figure 10: (a) Peak tensile load values and (b) energy absorption values of SLJs using a different combination of substrate materials under various temperatures [154]

4.2. Ageing and durability

The surrounding, where the joints are exposed, plays a crucial role in the joint durability. For instance, water is commonly thought to be one in all foremost worrying agents that have an adverse effect on the properties of adhesives and interface between the adhesive and the adherends. Several studies [156]–[163] have been reported on the effect of ageing under the severe conditions for adhesively bonded joints.

Dawood et al. [156] tested different methods to increase the bond durability of steel-CFRP double-lap joints under severe conditions for different durations, up to six months. The use of silane coupling agent enhanced the durability of the joints significantly. Nguyen et al. [157] found out that in steel-CFRP bonded joints, in the first 2-4 months of exposure to sea-water, strength and stiffness (E-modulus) of the adhesive decrease significantly. The rate of degradation became slow, and the strength of the joints remained at 85% and 74% of the initial values under 20°C and 50°C conditions, respectively (Figure 11)

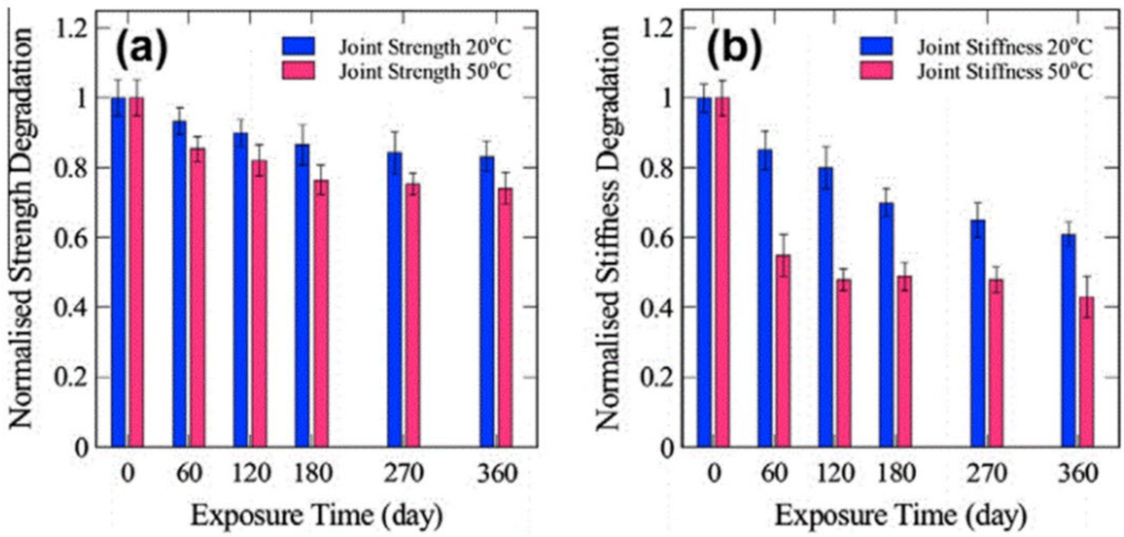

Figure 11: Degradation of strength and stiffness of steel-CFRP immersed in simulated sea-water for different exposure time [157]

Galvez et al. [158] studied the durability of steel-CFRP SLJ in bus structured bonded with polyurethane adhesives immersed in an aggressive environment. The steel-CFRP SLJ lost reliability over time in the presence of humidity and temperature condition. Mariam et al. [159] studied the influence of hydrothermal ageing in tap water (at 50°C) with variable immersion periods up to 120 days on the similar and dissimilar aluminium-composite single-lap adhesively bonded joints under tensile and fatigue load conditions. As the exposure time of water immersion increased, the moisture content and the failure strain of the joint's material increased, while the strength and the joint modules of adhesively bonded joints reduced [139].

Zhang et al. [161] evaluated similar and dissimilar (steel-Al) SLJs exposed to cyclic hydrothermal environments (Figure 12). Trapezoid and triangle temperature profiles aggressive environments at the same temperature and humidity (Figure 12(b)). In these profiles, the temperature changed from 23°C to 80°C while the cyclic number of both scenarios were the same (480 cycles). In trapezoid profile, the total length of the cycle was three hours: half an hour increasing the temperature from 23°C to 80°C, one-hour constant temperature of 80°C, half an hour decreasing the temperature from 80°C to 23°C and finally one-hour constant temperature of 23°C. In triangle profile, the total length of the cycle was one hour: half an hour increasing the temperature from 23°C to 80°C and half an hour decreasing the temperature from 80°C to 23°C. As seen in Figure 12(a), the joint strength decreased by 35% and 10% after 20 days exposure to the constant 80°C and 40°C hydrothermal environment, respectively, while cyclic triangle profile reduced joints strength by only 16%. In addition, the strength of the Al-steel joint decreased significantly in comparison to the Al-Al joint after exposing to 80°C for 20 days (40% vs 10% respectively).

The effect of thermal cycling is more significant in an adhesive layer rather than adherends [163], though the bonded surface of adherend is experienced oxidisation, the thermal stability and T_g reduction owing to thermal cycling.

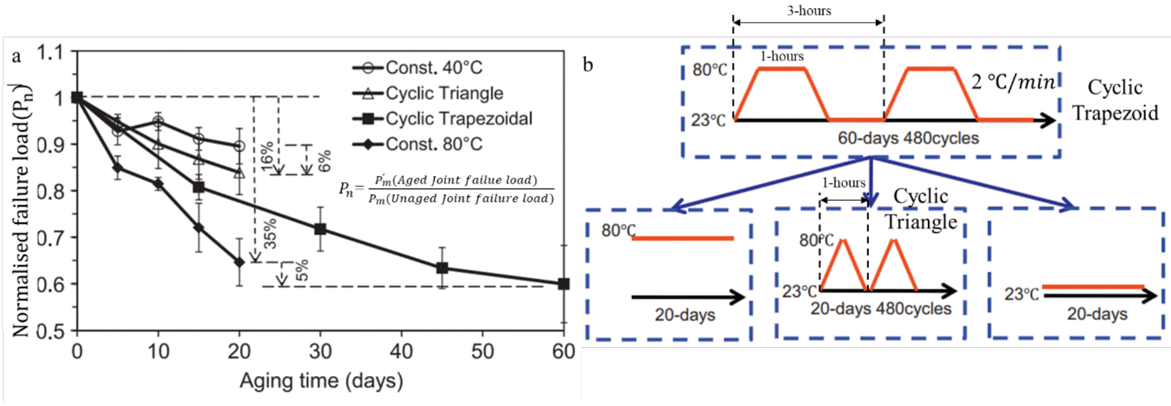

Figure 12: (a) Normalized failure load (P_n) of aluminium–steel SLS joints after constant and cyclic hydrothermal exposures. (b) Long-term cyclic temperature profile represented by some short-term constant temperature profile [161]

5. Hybrid joining of dissimilar adherends

Composite materials are commonly considered as the first choice where it is essential to save weight. However, an entire composite structure is not possible in many large-scale applications due to weak through-thickness strength and a low heat resistance of the resin matrix in these materials [164]; therefore composites must be bonded with metals [165]. The main drawback of the bonded joints is delamination and poor damage tolerance [3]. Therefore, several novel methods have been proposed to increase the strength of adhesively bonded joints with dissimilar adherends. The use of adhesive bonding in combination with different joining methods (bolting, riveting, Z-pinning and welding (Figure 13) could be a potential solution for engineers to design hybrid joints with better performance compared with those techniques alone.

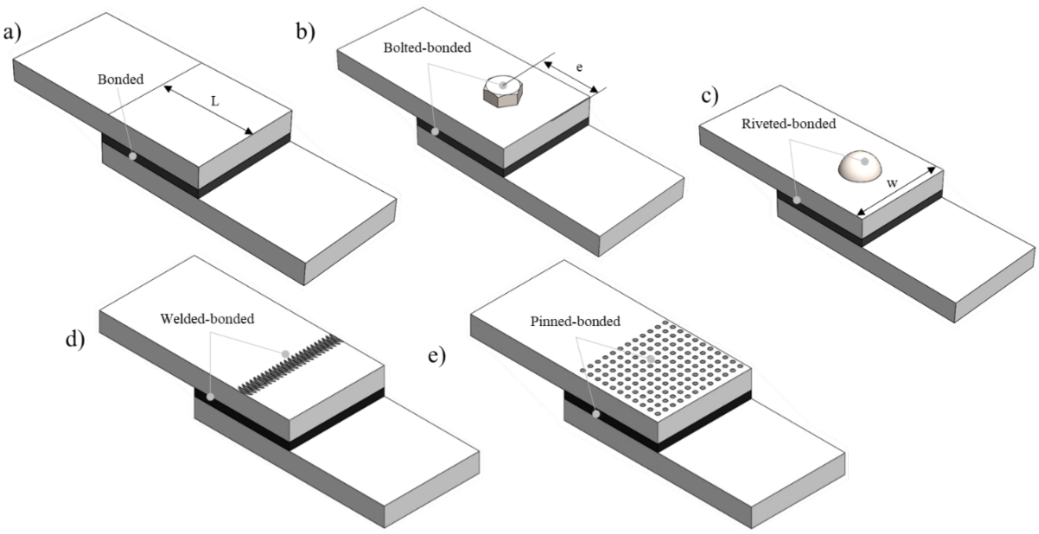

Figure 13: Single-lap joint with various joining technique: (a) bonded, (b) bolted-bonded, (c) riveted-bonded, (d) welded-bonded and (e) pinned-bonded

5.1. Bolted-bonded

The combination of adhesive bonding with bolting is one of the most common hybrid joining methods. Hybrid bolted bonded (HBB) joints experience continuous load transferring along bond-line due to the adhesive layer. The existence of fasteners could guarantee the functioning of joints, even if the failure occurs in the adhesive layer [166], [167]. The HBB joints have been studied in the literature especially for single-lap joint and double-lap joint under tensile loading [168] and fatigue loading [54] conditions, though few works have been conducted on the HBB joints with dissimilar adherends.

The effect of adding bolts and nuts to a bonded joint was studied by Kweon et al. [169] on the joint's strength of dissimilar double-lap joints. Two types of adhesives (film and paste types) were used with fasteners to bond composite to aluminium. Table 1 shows that the joint strength of double-lap joints with film adhesive did not change noticeably by adding a bolt mechanism. The joints with paste adhesive experienced a significant increase in the joint strength by adding a bolt. Therefore, the hybrid joining can potentially increase joint strength when mechanical fastening is stronger than the bonding.

Table 1: The experimental results of various double-lap joints [169]

	bonded (film-type)	**bonded (paste-type)**	**bolted only**	**hybrid joint (film-type)**	**hybrid joint (paste-type)**
Joint strength (MPa)	453	67.1	162	440	192

Matsuzaki et al. [170] proposed a bolted/co-cured hybrid joining method to improve the strength of GFRP/aluminium co-cured single-lap joints. The fatigue and static tests were performed by utilising a different type of specimens: co-cured bolted and bolted/co-cured hybrid joints. The hybrid joints first experienced adhesive failure and then behaved as a bolted joint until reaching maximum failure load which is 1.84 times of the failure load in co-cured joints only. Lee et al. [171] studied the effect of the width-to-diameter (w/d) ratios, edge-to-diameter (e/d) ratios and adherends thicknesses on the strength of bolted-bonded double-lap joints for ten different cases. The HBB joint with w/d ratio of 4 and e/d ratio of 1.2 achieved the highest failure load. In addition, HBB failure loads were identical to those of only adhesively bonded joints and were nearly two times larger than those of the mechanical joints. Bois et al. [172] studied the ability of an analytical model to predict the load transfer of the bolt and adhesive double-lap joints under a static loading by comparing analytical model results to those obtained by the finite element analysis. The analytical model was validated from experimental results, and it was found that the accuracy of the analytical model significantly depends on the bolt stiffness.

Tajeuna et al. [173] investigated the behaviour of HBB Al-GFRP and Al-steel single-lap joints. The effect of the adhesive layer on the strength of Al-Steel bolted joint was not noticeable due to the higher stiffness of adherends and the strength that is produced by only bolted plates. In contrast, the adhesive layer was found to improve the elastic behaviour and strength of the GFRP-steel joints. Mariam et al. [174] investigated the effect of adherends' stiffness with combinations of similar and dissimilar adherends (Aluminium alloy (AA7075) and glass fibre reinforced epoxy (GRE)) on the joint strength of mechanically fastened Huck bolted, adhesively bonded, and hybrid (bolted/bonded) single-lap joints under static and fatigue loadings.

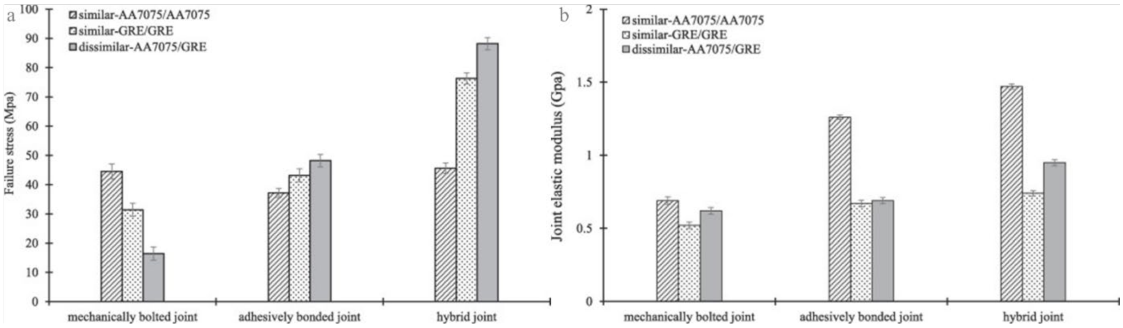

Figure 14: (a) Ultimate failure stresses for the different joining techniques and (b) Joint elastic modulus for the different joining techniques [174]

Figure 14 shows that HBB joints with dissimilar AA7075/GRE adherends achieved the highest joint strength in comparison to those of bolted and bonded single-lap joints. Thus, the stiffness of the hybrid joint was four times higher than those of the other joining configurations. In addition, the failure mechanism analysis showed that in mechanically bolted joints net adherend yielding occurred in similar AA7075/AA7075 joints while similar GRE/GRE and dissimilar AA7075/GRE experience bearing failure on GRE composite (Figure 15(a)). In adhesively bonded joints, mixed-mode adhesive failure occurred in AA7075/AA7075 and dissimilar AA7075/GRE joints while cohesive failure happened in GRE/GRE (Figure 15(b)). The hybrid joint experienced two failure stages with primarily adhesive layer failure and followed by secondary Huck bolt failure (Figure 15(c)).

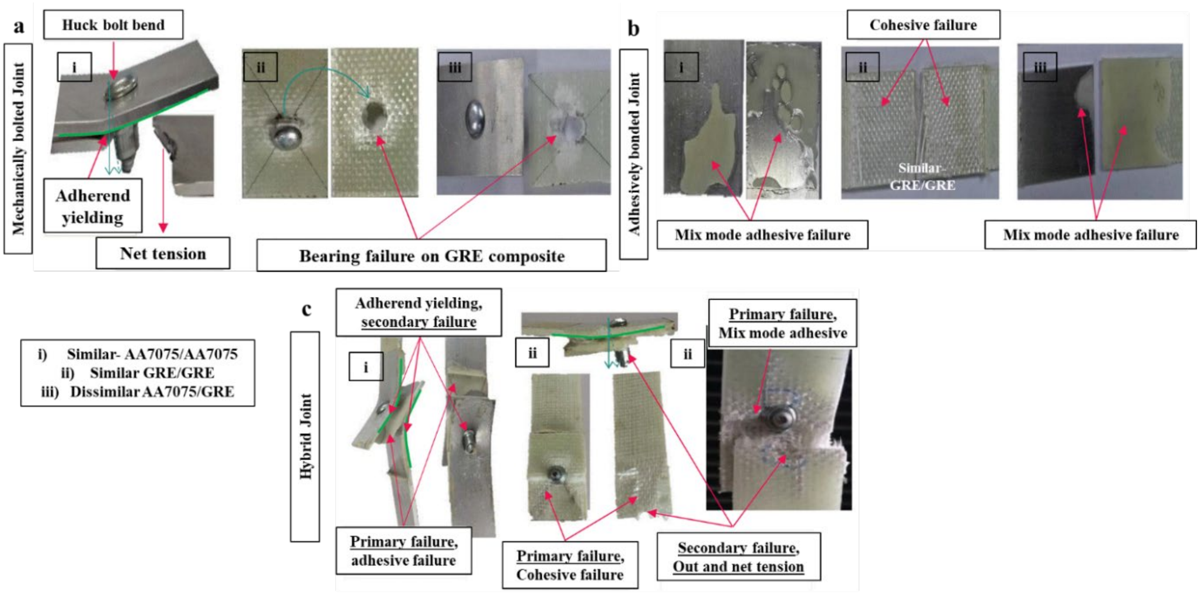

Figure 15: Types of failure mechanism for (a) bolted, (b) bonded, and (c) hybrid joint configurations [174]

5.2. Riveted or Clinched-bonded

The combination of rivets and adhesive is another method similar to bolted/bonded joint, which can potentially increase the performance of dissimilar joints. Researchers introduced several methods for joining polymer to the metal in hybrid structures by using injection clinch (ICJ) [175] and self-piercing rivet (SPR) [2], but few of them [34], [176]–[178] used a combination of riveted/clinched and adhesive layer for joining multi-material components. Pitta et al. [176] conducted a numerical and experimental study on the performance of different aircraft-lap joints repair configurations (metal-metal and metal-composite) under tensile loading. The lap joints were manufactured with pure riveted, pure bonded, and hybrid (riveted and bonded) techniques by using aluminium and Carbon Fibre Reinforced Epoxy (CFRE) substrates. Table 2 shows a comparison of the averaged strengths of AA 2024-T3–AA 2024-T3 and AA 2024-T3–CFRE lap joints in relative percentage. The joint with pure adhesive is nearly five times stronger than joints with pure riveted in both metal-metal and metal-composite joints. Although the riveted-bonded metal-metal joint out-performed the bonded joint, the riveted-bonded metal-composite did not exhibit any improvement. Thus, the failure of the composite substrate around holes does not allow joint to reach its full capacity. Numerical analysis indicates that hybrid and pure bonded joints have lower stress concentration along the overlap in comparison to those of the riveted joints. This can increase the load transfer capacity of the adhesive layer.

Table 2: Comparison of averaged strengths of AA 2024-T3–AA 2024-T3 and AA 2024-T3–CFRE lap joints under riveted, bonded and hybrid configurations [176].

Joint configuration		AA 2024-T3–AA 2024-T3			AA 2024-T3–CFRE		
		Riveted	Bonded	Hybrid	Riveted	Bonded	Hybrid
AA 2024-T3–AA 2024-T3	Riveted	X	423%	519%	107%	355.7%	305.5%
	Bonded	24%	X	123%	24%	84%	72%
	Hybrid	19%	82%	X	19%	69%	59%
AA 2024-T3–CFRE	Riveted	94%	396%	458%	X	333%	286%
	Bonded	28%	119%	146%	30%	X	86%
	Hybrid	33%	138%	170%	35%	116%	X

Di Franco et al. [34] investigated the effect of the space between rivets in self-piercing riveting in combination with a structural adhesive layer under static and fatigue loading. The best performance in terms of tensile strength was achieved with the joint having a spacing of 60 mm between the two rivets (Figure 16). Di Franco et al. [177] attempted to determine the optimal joint configurations for dissimilar SLJs made by combining adhesive bonding and self-piercing riveting (SPR). Using angle-ply laminates instead of cross-ply laminates can approximately double the energy absorption of the joints. This can be explained by the debonding of the cross-ply laminate around the rivet while angle-ply laminate fails due to high pull out of the rivet.

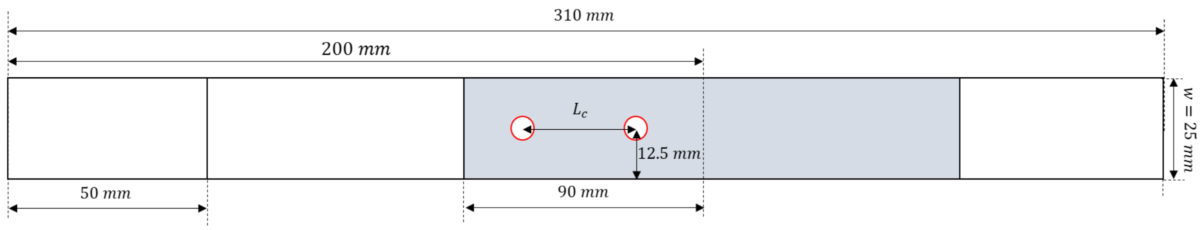

Figure 16: Geometric configuration of the riveted bonded joint [34]

5.3. Pinned-bonded

The aim of using pins as reinforcement is to overcome the disadvantages of bonded and bolted joints. The main disadvantage of bolted metal-composite joints is that the drilling process damages the fibres of the laminate. A combination of Z-pinning (Figure 17) with an adhesive layer does not require expensive pre-treatment of drilling holes and would suggest a possible increase in the strength of bonded joints [179]. Different methods have been utilised to produce pins on the surface of a metallic part for hybrid joints, which can be categorised as surface restructuring or the addictive layer process [180], [181].

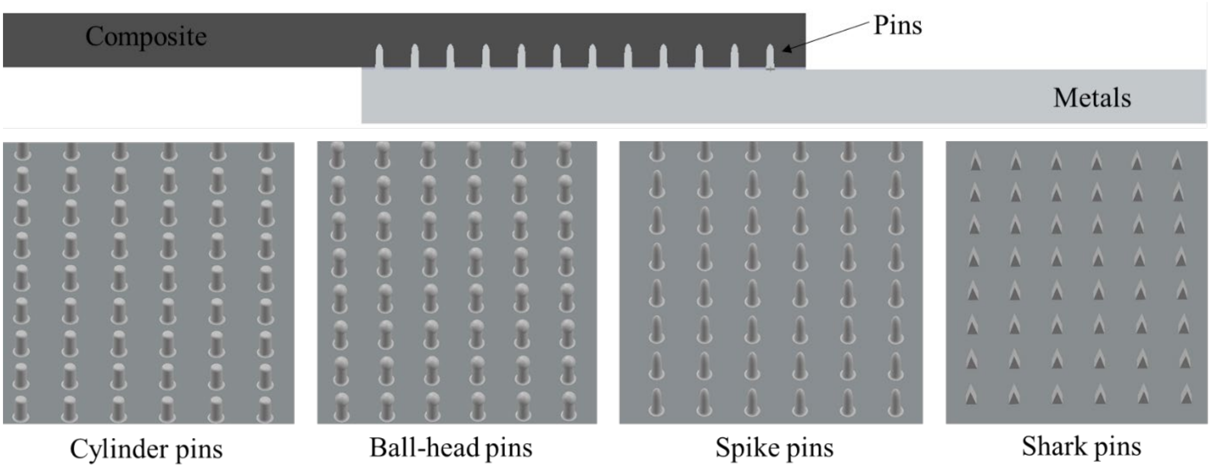

Figure 17: Pin shapes in hybrid joining methods

Ucsnik et al. [180][182] used double-lap shear specimens (DLS) to compare pin-reinforced adhesively hybrid joints with only adhesively bonded joints. The hybrid joint is made of stainless steel 304 and a thermoset CFRP with two different shapes of the Z-pin (cylinder and ball-head pins) in the bonding area. A significant improvement was observed in the performance of the cylinder pin reinforced bonded joints with an increase in maximum failure load and local strain at failure and energy absorption capacity by 11.13%, 470% and 27 units, respectively, in comparison to adhesively bonded joints. Moreover, the modified joints with ball-head-pins experienced an improvement of 52.30% in maximum failure load and of 1000% in the local strain at failure. Parkes et al. [164][181] studied the effect of hybrid penetrative reinforcement (HYPER) on the strength of the dissimilar single-lap joints. Pins were built on the interface of titanium in the bonding area using additive manufacturing, and the adhesive layer was used to bond the titanium to CFRP. Their results showed a 650% improvement in the failure load of the pinned Ti-CFRP SLJ in comparison to those of the unpinned Ti-CFRP SLJ since the pins delay the initiation of adhesive cracking by reducing the peak peel/shear stresses. Besides, an ultrasonic inspection technique, C-Scan was used to capture the damage propagation. An interface disbandment initiated at the corners of the lower stiffness adherend with no visible damage to the laminate or pins.

Graham et al. [183] investigated strength, mechanical fatigue, damage tolerance and durability of the reinforced metal-composite single-lap and double-lap joints. Their results show that pinned hybrid single-lap and double-lap joints were stronger than their standard control specimens without pins in both quasi-static and high-rate tests. The modified hybrid joints had higher damage tolerance than standard hybrid joints. For instance, a 13J impact resulted in a 42% disbanded area and 18% reduction in strength for the standard SLJ, while no significant loss in the strength of pinned hybrid SLJ was observed, even with up to 30% disbanded area. The failure mode of hybrid joints was found to be extraordinarily complex and highly depended on the baseline strength of the adhesive layer. Di Giandomenico [184] used micro-milling (MM) to create Shark or Spike pins (Figure 17) on the interface of the titanium adherend to improve the load-carrying capacity of adhesively bonded joints. Their results show that the dissimilar hybrid double-stepped and double-scarf joints achieved higher ultimate load with shark pins in comparison to spike pins when both compared with the control configuration of the dissimilar hybrid double-stepped and double-scarf joints without surface features. Islam et al. [185] studied the influence of the Z-pinning arrangement, the direction of GFRP layers (weft or warp directions) on the static strength and damage tolerance of the hybrid mild steel-GFRP single-lap joint. Placing pins near over-lap edges and increasing the number of pins in the bond-line could increase the joint strength significantly. The effectiveness of Z-pinning reinforcement can explain the reduction of peel stress near over-lap edges. Moreover, the specimen group with all GFRP layers in warp direction exhibited a larger failure load and displacement in comparison to those of the specimen with all GFRP layers in the weft direction.

In 2018, Huaqing et al. [186] developed a novel joining method to enhance the mechanical performance of the metal-composite adhesively bonded SLJ. The metal and composite adherends were adhesively bonded together with some thin through the z-axis pins covered with adhesive in the overlap region of joint. Under tensile loading, the ultimate strength of the novel SLJ increased by 25% in comparison to the traditional SLJ. Under a fatigue load, the same trend was observed as the number of cycles to failure increased from 998 cycles in the traditional SLJ to 148312 in the novel SLJ, which corresponds to 197.32% increase. The number of pins did not change the maximum failure load noticeably while the strain at failure and energy absorption was sensitive to the number of the pins. A good agreement was achieved between the experimental joint strength and the joint strength predicted by the numerical model using the cohesive zone model (CZM) for the adhesive layer. An important observation of FEA results is that the adhesive layer at the interface of both adherends probably fails before the adhesive on the metallic pins.

5.4. Welded-bonded

Another advanced hybrid joining method is weld-bonding [187] which is commonly used for combining multiple materials in many products due to their lower cost and reduced weight advantages [188]–[190]. Weld-bonding composes of four steps as follows: (1) spreading adhesive layer on the two metallic sheets, (2) assembling, (3) spot welding and (4) curing [191]. This method was used to prevent vibration and to reduce noise emission in automobile transmissions, railways carriage and aircraft due to their superior static and fatigue properties which result in lightweight structures [192]–[195]. In addition, weld-bonded joints avoid inner-surface corrosion of spot-welded joints and increase the durability of adhesive-bonded joints [196]. The combination of the adhesive bonding with the spot-welding could be a promising solution for designers who wants to have the benefit of potential weight reduction of the adhesive bonding joint and the peel resistance of the spot welding.

Darwish [196] proposed a finite element approach to study the process of spot welding of dissimilar joints. Two scenarios of spot-welded and weld-bonded models having identical adherends (steel-steel) and dissimilar adherends (steel-brass, steel-aluminium, brass-aluminium) were analysed. Asymmetrical stress distribution was observed at the far ends of the weld nugget for the spot-welded dissimilar joint with the higher peak value of the stresses towards lower stiffer adherend. The combination of adhesive layer with spot welding led to not only a stronger joint but also balanced stresses and elimination of stress concentrations in dissimilar adherends joints. Liu et al. [197][198] investigated weldability of magnesium alloy to aluminium alloy, including microstructure characteristics and mechanical properties in laser weld bonded (LWB) joints. Welding dissimilar metal in the presence of the adhesive layer raises two fundamental issues which are not encountered when these methods were used individually: if it is feasible to weld two metals in the presence of the adhesive layer and what would be the influence of the adhesive layer to the microstructure characteristics of the welds in LWB joints. Their experiment results showed the possibility of using LWB for joining Mg to Al with a failure zone about 0.3 mm distance away the weld edge which is caused by oxidisation and carbonisation of the adhesive layer during the laser welding process. The failure load capacity of the LWB joints is significantly higher than welded joints and bonded joints, which shows that the failure zone had little influence on the load-bearing capability of joints.

Wang et al. [199][200] studied the effect of adhesive layer on the Al fusion zone in the LWB Mg-Al process in comparison to the laser welding process. The existence of the adhesive layer in LWB joints changed the surface temperature and the surface state of the Al alloy. The laser welding penetration depth increased nearly 1.5 times in the Al alloy interface with the adhesive coating in comparison to only laser welding joints. This lead to a lower tendency of micro-cracks forming in the laser welding in LWB joints in comparison to only laser welding joints. The tensile strength of LWB Mg-AL joints was nearly 85% higher than only laser-welded Mg-Al joints. Wang et al. [201] also studied the effect of a nickel (Ni) interlayer on the fusion zone, strengthened with an additional adhesive layer. According to the analysis of the thermodynamic behaviour, the adhesive and Ni interlayer restrain the reaction between the Al and Mg, which leads to the improvement of the property of the Al-Mg welded joint. Chowdhury et al. [202] studied the durability of the friction stir spot welding (FSSW) of the dissimilar Al/Mg and Mg/Al with an additional adhesive layer under cyclic loading. FSSW was performed on top adherend at the centre of the overlapped area. Three different types of dissimilar single-lap joints were manufactured, i.e., (top) Al/Mg (bottom), (top) Al/Mg (bottom) with adhesive, and (top) Mg/Al (bottom) alloys with adhesive. The maximum failure load of the Mg/Al adhesive weld joints was higher than that of the Al/Mg adhesive weld joints (Figure 18(a)). In addition, both of the Mg/Al and Al/Mg adhesive welding joints had longer fatigue life (S-N curve) significantly in comparison to the dissimilar weld joints without adhesive, especially at higher cyclic load levels (Figure 18(b)).

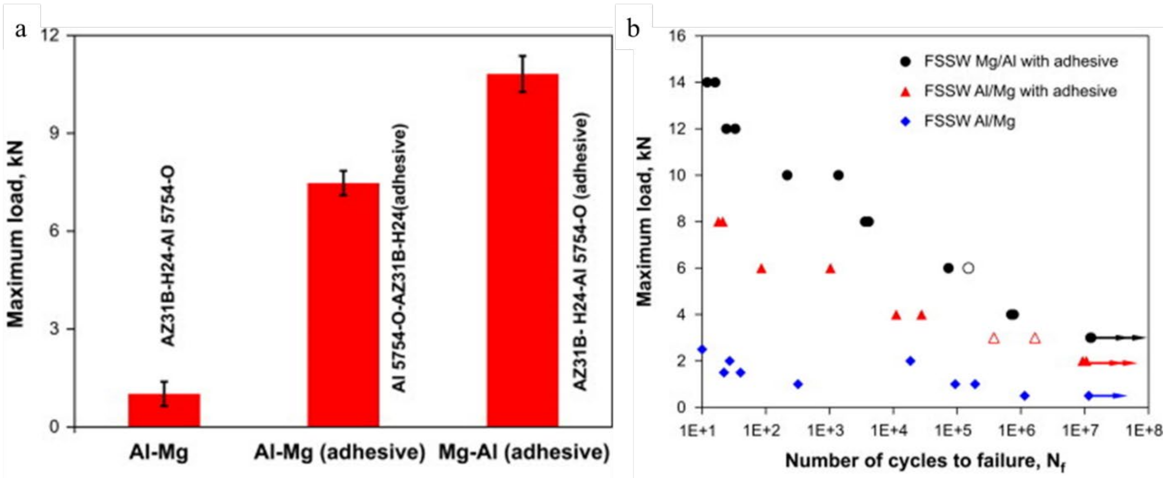

Figure 18: (a) Maximum failure load, and (b) S–N curves of the dissimilar Al/Mg weld, Al/Mg adhesive weld and Mg/Al adhesive weld. Solid symbols indicate the nugget pull-out failure and empty symbols indicates the failure perpendicular to the loading direction [201].

Xu et al. [203] investigated the microstructure and mechanical properties of similar joints of the welded bonded (WB) Mg/Mg and the dissimilar joint of WB Mg/Steel and the resistance spot welded (RSW) Mg/Steel. The impact of the Ford Accelerated Cyclic Corrosion (Test L-467) on the spot joining of dissimilar Al-steel joints by friction bit joining (FBJ) was studied by Lim et al. [204] for the case with the adhesive layer (weld-bonding joints) and without the adhesive layer (FBJ only joints). The strength of the FBJ only specimen decreased significantly with larger corrosion cycles while the FBJ joint with the adhesive layer maintained nearly 80% of its original strength. In addition, the FBJ without adhesive layer had a 93% interfacial failure rate (28 samples out of 30 samples) in comparison to 40% for FBJ with adhesive layer due to the corrosion between the joining bit and the steel sheet in only FBJ specimen while the presence of the adhesive layer closes the gap between the Al and steel sheets.

5.5. Multi-layers reinforcement

The use of reinforcement through-thickness is another effective hybrid joining method showing positive results [205], which relies on the local reinforcement of the composite laminate with high-strength metal layers.

Santos et al. [206] investigated the advantage of the strengthening of the CFRP by titanium (Ti) laminate with and without using adhesive layers (Adh) in the interfaces between the titanium and the composite with different lay-up configurations. An improvement in the strength of Ti-Adh-CFRP-Adh-Ti joints was observed in comparison to those of CFRP only configurations. Morgado et al. [207] showed that delamination in composite laminate could not be avoided by reinforcing it with metal through-thickness, though it can be delayed which leads to an increase of the strength and energy absorption of the hybrid joints. Camanho et al. [208] introduced a novel metallic insert with tapered ends to increase the efficiency of composite single-lap bolted joints and showed that the metallic insert provides new regions for load transfer, which leads to a higher maximum load and a joint efficiency.

6. Conclusion

This review paper focused on dissimilar bonded joints with the aim of providing a better understanding of the current joining methods. First, the mechanical behaviour of the dissimilar bonded joints under various loading conditions was discussed by considering the effect of various design parameters on the performance of joints. Then, the available methods for geometrical and material optimisations of dissimilar bonded joints were analysed. In addition, the durability of dissimilar bonded joints under aggressive environmental conditions was considered. Finally, the advantages and disadvantages of available hybrid joining methods were assessed for dissimilar bonded joints. The conclusions are summarised as follow:

- One of the disadvantages associated with dissimilar bonded joints is asymmetric stress distribution a higher stress concentration at the one end of overlap occurs due to the existence of lower stiffness adherend. This may cause interface failure in dissimilar joint especially for brittle adhesives which are sensitive to the high peeling stresses due to small plasticisation allowance. Therefore, the failure can initiate suddenly under relatively low mechanical or thermal service loads. However, the ductile adhesive could potentially provide better performance in comparison to brittle adhesive. The larger plastic deformation capacity of a ductile adhesive, which can redistribute the load uniformly and make use of the less stressed parts of the overlap
- The most studies used a single layer of the cohesive element to simulate the interaction between adherends and adhesive which is accurate enough for identical adherend joint. However, the method cannot describe the failure process for the hybrid joint and estimate the strength of the joint accurately. Since the change in the material of the adherends affects the interaction between adhesive and adherends, the roughness on various surfaces and change of joining schemes such as hybrid connection etc; more research should be conducted in this area to improve the available methods for dissimilar adhesively bonded joints.
- Despite the fact that many studies have been conducted by using a geometrical and material modification to improve the load-carrying capacity of the adhesively bonded joints with similar adherends, there are only a limited number of studies focusing on the performance of dissimilar joints. A need is clear for a study of different joint configuration to provide comparative information about both stress distribution and strength of each design to nominate the optimum geometry of joints. Moreover, novel geometrical or material modifications (e.g. tapers, holes,

fillets, round corners, notches and mixed-adhesive) are necessary to decrease high peak stresses in dissimilar bonded joint, which can reduce asymmetric stress distribution and improved performance.

- The use of adhesive bonding in combined with different joining methods (bolting, riveting, Z-pinning and welding) could be a potential solution for engineers to design dissimilar hybrid joints having better load-carrying performance. The existence of fasteners could guarantee the functioning of the joints, even if the failure occurs in the adhesive layer due to higher stress concentration at the edges of the bond-line. The main disadvantage of mechanical fasteners with metal and composite adherends is the damage to the fibres of the laminate, which occurs during the expensive pre-treatment before joining. Z-pinning, in combination with an adhesive layer, would suggest a possible increase in the strength of bonded joints. Hybrid joining method requires multi-layer reinforcement, which can be used to reinforce the interfacial stiffness of composite with metal and to increase the bond strength in the dissimilar bonded joint. Multi-layer reinforcement scheme could be used to reduce the through-the-thickness interfacial peak stresses to smooth their stress distribution along the bond-line.

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