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# **Bonded flush repairs for aerospace composite structures: a review on modelling strategies and application to repairs optimization, reliability and durability**

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**Abstract** – Bonded repairs for aerospace composite structures are very promising thanks to the high strength recovery rate they can achieve while keeping a good strength to mass ratio. Flush repairs, i.e. scarf and stepped repairs, are the most suitable for repairing load-carrying structures as they provide maximum repairs efficiency while keeping a smooth aerodynamic surface. Design of composite bonded repairs is challenging because of their complex failure behaviour. This paper reviews existing work on flush repair design. It includes a synthesis of experimental results on static failure behaviour, and of modelling approaches by analytical, semi-analytical and finite element techniques. Recent investigations on flush repairs are pointed towards optimization, durability and reliability purposes: many innovative repair designs were identified, that could allow reducing greatly flush repairs size while keeping constant strength. Beyond static behaviour, recent works were reported on damage tolerant design for bonded repairs, along with fatigue and impact behaviour, that could raise the level of confidence that is given to composite bonded repairs.

**Keywords:** *CFRP; scarf repair; stepped-lap repair; adhesive bonding; FEM; strength prediction, cohesive zone modelling;*

## 1. Introduction

Composite materials are widely used in aerospace structures due to their high specific strength and fatigue performance [1]. During the past decades, their use increased [2] to such extent that aircrafts including significant proportions of Carbon Fibre Reinforced Polymer (CFRP) in their structures, like the Airbus A350XWB or the Boeing 787 Dreamliner, were released. Along with their performances, composite materials come with their own weaknesses and may experience damage during the aircraft service life. Bird strike [3], lightning strike [4-5], along with impacts due to ground collision or tool drop during maintenance can be cited as common sources of damage to aircrafts composite structures. Compared to metallic materials, they are vulnerable to impacts because of the brittle behaviour of the matrix and fibres, and the lack of through-the-thickness reinforcement. It can lead to a substantial damage and decrease of the compressive, tensile and shear strength [6-7]. In order to restore its strength, the damaged part may be replaced or repaired, depending on the feasibility and the cost-effectiveness of each option.

Repairs to composites laminates can be mechanically fastened, adhesively bonded, or both (hybrid repair). The lack of non-destructive inspection technique to detect weak bonds makes the certification of bonded repairs difficult, so that the area is under investigation [8-9]. Thus, bolted repairs are the current standard for primary bearing load structures because it is simple to ensure that the attachment is compliant to the regulation. However, adhesively bonded repairs offer many advantages: they avoid adding mass to the structure, creating stress concentration around the bolts, and provide increased repair efficiency [10].

Bonded repair types can be classified as follows [11]: (i) cosmetic repairs by resin injection; (ii) doubler repairs (semi-structural); (iii) flush repairs (structural). Doubler repairs are performed by bonding patches to one or both sides of the structure depending on accessibility. They are suitable for relatively thin laminates, but flush repairs become preferable for thick laminates. Flush repairs require removing pristine laminate in a scarf or stepped shape and

bonding patch with a complementary shape to material that has been removed, they offer better joint efficiency and allow keeping a smooth external aerodynamic surface at the cost of a more complex repair procedure. In the recent years, several reviews [12-19] and books [20-22] were published on the topic of composite bonded joints and repairs.

This paper focuses on flush repairs to composite laminates, i.e. scarf and stepped repairs, as they are a very attractive way to restore damaged laminate strength and require advanced design and modelling techniques. Its goal is to synthesize knowledge on flush repairs failure behaviour brought by experimental work and to review and discuss modelling techniques that are used to predict flush repairs strength. Then, recent work on flush repairs optimization and new and original repair designs will be highlighted, and studies on reliability and durability of flush repairs will be reviewed.

## **2. Experimental work on static failure behaviour**

### *2.1. Specimens typology*

Flush repairs are performed by removing pristine material around the damage area in a scarf or stepped shape (Figure 1). This denomination relies on the parent laminate shape: scarf repair refers to parent laminate with a smooth shape, whereas stepped repair shape refers to machined steps that can be one or a few plies thick. A patch with complementary shape to the removed material is then bonded onto the parent laminate. It can be either pre-cured patch that is bonded to the parent laminate with adhesive, known as *hard patch* [23], or stacked prepreg or wet plies cured directly onto the parent laminate, known as *soft patch* [24].

It has to be noted that for a scarf repair with a soft patch, the parent laminate has a smooth surface, but the patch is applied in a stepped shape, it can be denominated as *stepped-scarf* to be distinguished from *tapered-scarf* where both parent and patch are smoothly machined. This difference does not exist for stepped repairs because the soft or hard nature of the patch does

not change the final repair geometry. Literature can sometimes be confusing because stepped-scarf is employed to describe stepped repairs as well. [12, 25-26].

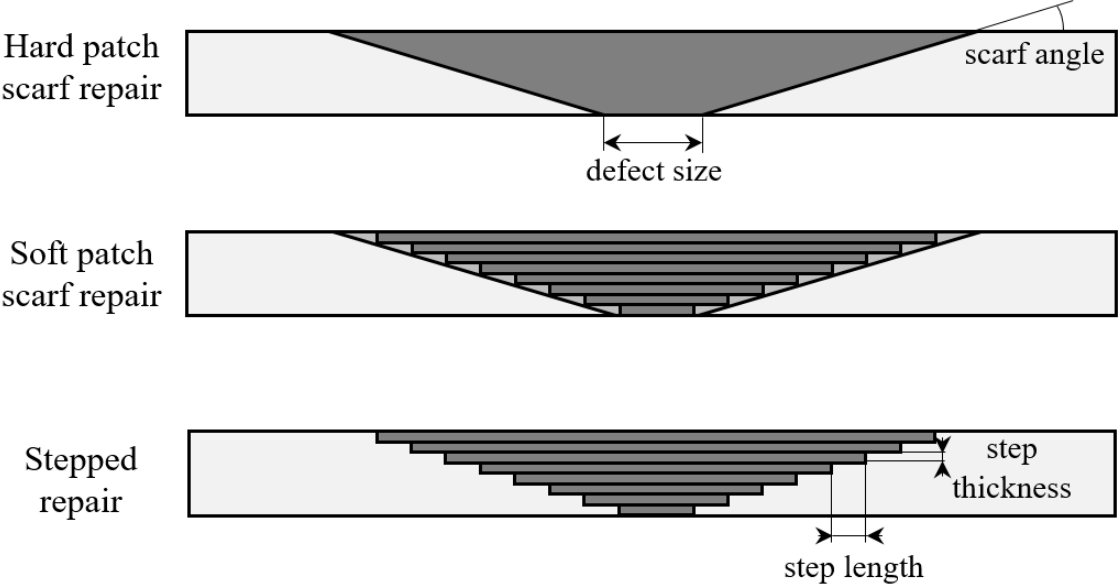


Figure 1: Flush repair types

Studies on composite repairs address three different types of specimens (Figure 2). Flush joints are made of two pristine laminates, scarfed or stepped, and directly bonded together leading to a parent / parent configuration. Those specimens allow studying the scarf or stepped bonded joint, but do not account for the presence of the repair patch. Flush repaired coupons include the repair patch. They are made of two laminates, stepped or scarfed, and bonded together with a hard patch or a soft patch, leading to a parent / patch / parent configuration. Coupons usually have a width of 20 to 30 mm that allows producing many specimens with a limited amount of material. The last type of specimen is the flush repaired panel, which means to be representative for a real repair. It is a laminate panel with a hole that stands for damaged material that has been removed, which is then scarfed or stepped, often in a circular shape, and repaired with a patch.

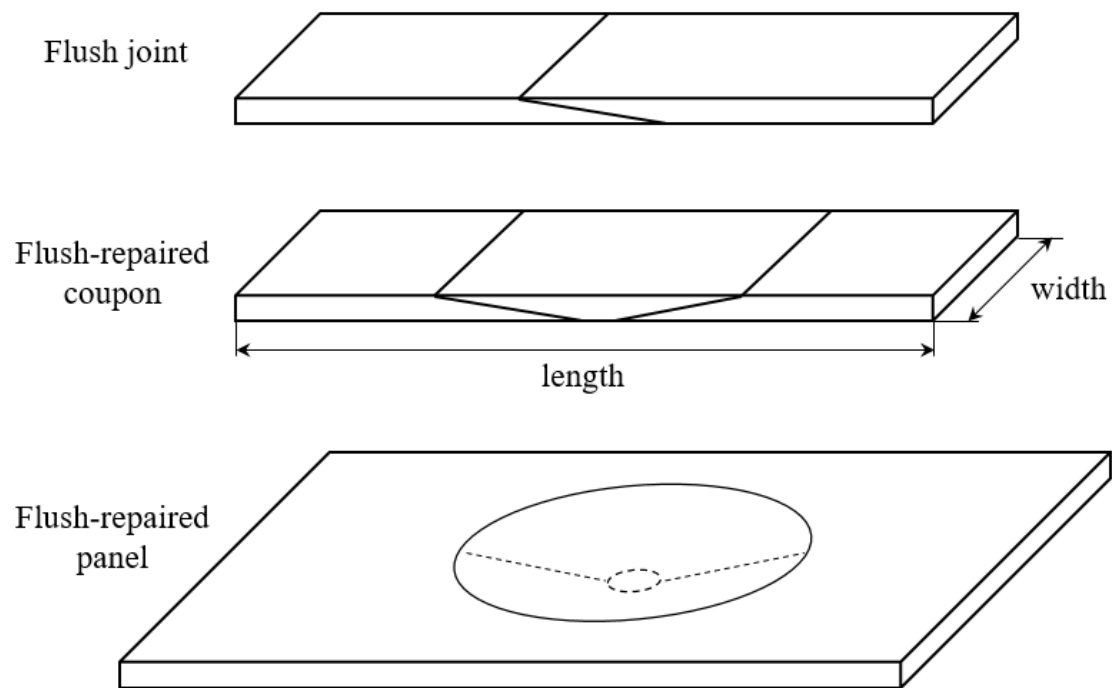


Figure 2: Specimen configurations used in flush repairs studies

## 2.2. Failure modes

When a composite bonded joint is loaded in tension, several failure mechanisms may occur along the bondline [14]: failure within the adhesive layer (cohesive failure), failure at the interface between adhesive and adherend (adhesive failure), matrix failure (intralaminar and interlaminar) or fibre failure of the laminates. Besides failure of the bondline, a bonded repair can also fail by rupture of the adherends themselves. When dealing with composite flush repairs, the failure mode may be a combination of these mechanisms.

Experimental static tension tests on scarf joints [27-31] and scarf repaired coupons [32-33] made of unidirectional (UD) CFRP has been carried, and distinct modes of failure have been observed depending on the scarf angle (Figure 3). For steep scarf angles, the repair fails by cohesive failure of the bondline. For shallower angles, the bondline fails by mixed cohesive failure plus intralaminar and interlaminar failure. Cohesive failure occurs near  $0^\circ$  plies whereas

matrix cracking initiate near  $90^\circ$  plies first and appears near  $45^\circ$  plies when the load approaches the ultimate load of the specimen. With a  $0^\circ$  unidirectional layup [34-35] this mode does not occur. The more the angle is shallow, the more the failure dominated by composite failure. Lastly, for very shallow angles, the failure occurs by parent laminate or repair patch tensile fracture, with a crack path that can be completely outside of the bondline, or that goes through parent, patch and a part of the bondline. Marques et al. [36] conducted tensile tests on scarf-repaired coupons and reported failure in the parent laminate region for scarf angle of  $1.09^\circ$  and failure in the repaired region for angles from  $1.45^\circ$  to  $2.42^\circ$ . Thus, the weakest part of a scarf repair is not always the repaired region. In some shallow configurations [37], failure occurred by simultaneous debonding of the repair and fracture of the parent laminate near tabs. In the field of composite joints and repairs, CFRP woven fabric laminates adherends have been less studied than UD CFRP adherends. Experimental work on scarf repaired coupons [38] and scarf joints [39] made of woven fabric CFRP exhibited the same failure modes as those know for UD CFRP scarf joints.

Beyond tension loading, which is the most studied load case, failure modes of scarf joints under compression loading have also been addressed [40-43]. For steep angles, cohesive failure occurs in the same as it is for tension test. For shallow angles, when Euler buckling of the specimen is not prevented, mixed cohesive and matrix failure occurs, when it is prevented using long end tabs, local buckling of the composite occurs with no debonding.

Studies presenting experimental work on stepped joints and stepped repaired coupons have also been carried [26, 35, 44-45] but the stepped configuration seems to have drawn less attention than the scarf configuration. Failure modes of stepped joints and repairs are essentially the same as the ones of scarf joints, including debonding of the patch and rupture of the laminates. Instead of the repair angle, the step ratio (ratio between length and the thickness of one step) is more convenient to describe stepped repairs. Wang et al. [26] studied the influence of the number of

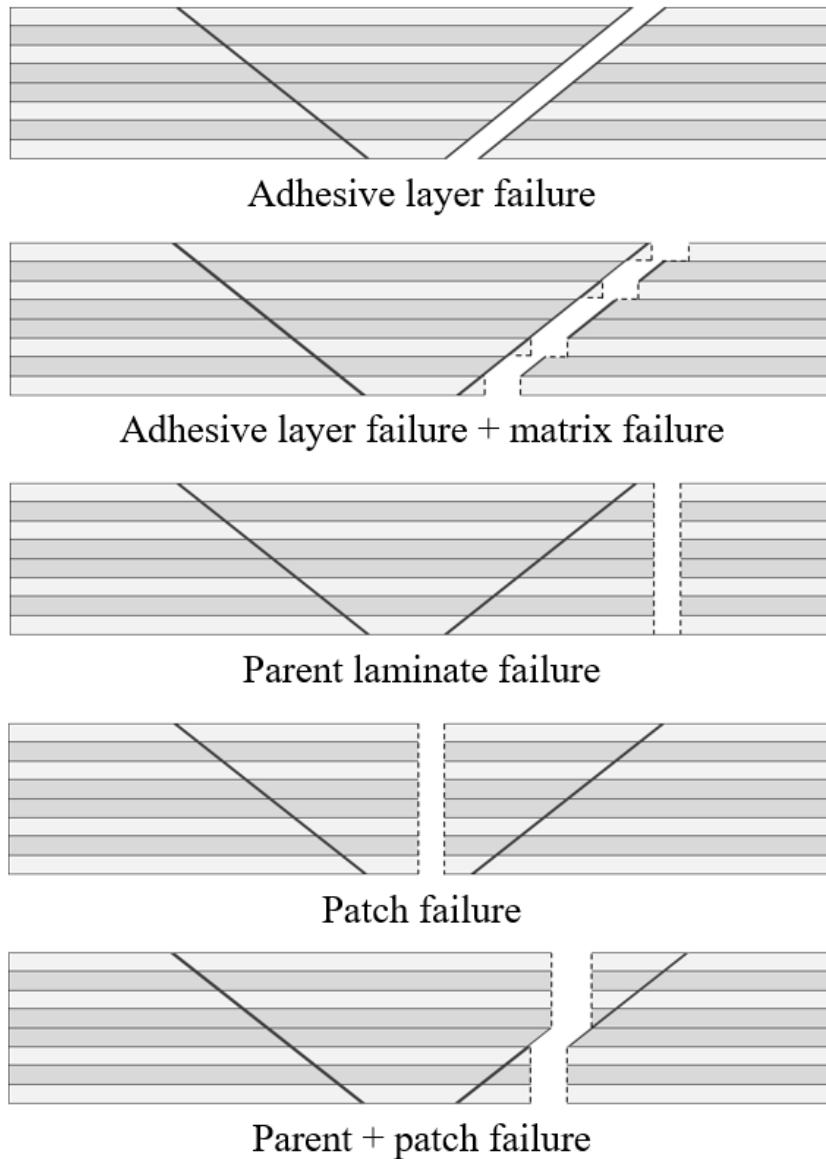


Figure 3: Typical tensile failure modes of flush repairs

steps for given ratio of 1:20. Failure mode was debonding of the patch for low number of steps and repair patch fracture or main plate fracture for high number of steps. It was observed that as the number of steps increased, the strength of the repair increased. Collombet et al. [46] presented results showing stepped joints with a specific layup only made of  $\pm 45^\circ$  plies failing by laminate fracture with no debonding at all. They concluded that the stepped joint was not always the weakest part of the assembly. Three different step ratios of 1:23, 1:30 and 1:50 were tested and the same failure mode and strength was obtained.



Few studies presenting scarf-repaired panels were reported, such large specimens are expensive and require a large applied load to reach failure. Xiaoquan et al. and Breitzman et al. [47-48] both conducted uniaxial tension tests on scarf repaired panels with initial hole through the whole thickness of the panel and repaired with a scarf angle of  $6^\circ$ . In both studies, panels failed by debonding of the patch leading to fracture of the main plate in the smallest area section on both sides of the scarfed area while the patch remained bonded to one of the halves of the panel. Baig et al. [49] compared scarf repaired panels tensile strength between  $6^\circ$  and  $10^\circ$  with prepreg or pre-formed patch. The plates also failed by debonding of the patch, but it was reported that the difference in strength between these two angles was not obvious. Chong et al. and Darwish et al. [50-51] worked on scarf repaired panels with angles of  $0.6^\circ$  and  $2^\circ$  respectively. In both cases, failure occurred by brittle fracture of the main plate and the patch with no debonding of the patch and they achieved strength restoration of 90% and 95% respectively. According to Chong et al., fracture initiated in the area near the end of the repair, at the tip of  $0^\circ$  plies and then propagated very quickly.

The two identified failure modes for flush repaired plates match with the ones observed for flush joints and repaired coupons. However, mentioned studies on flush repaired panels only presented one failure type each, making it difficult to assess properly how the transition between failure modes happens as the repair angle varies, and to what extent the comparison between flush joints and flush repairs is valid. Further experimental work on flush repaired panels could provide such pieces of information and allow investigating bi-axial loading for instance. However, those large specimens can be expensive, which could explain why they are less studied.

Beyond the influence of scarf angle and step ratio, which are the most studied parameters in papers with experimental static tests on flush repairs, other conception parameters may influence the strength or failure mode of a flush repair. Initial defect size influence was studied

by static tensile tests of scarf-repaired coupons [33] and scarf repaired panels [47]. Doubling defect size length or diameter causes a variation of repair strength between -1% and 5%. One could say there is no clear influence of defect size on repair strength, and it could be explained saying that defect size has no influence on the load carrying part of the flush repair. Bonding parameters such as surface preparation, adhesive type, thickness, curing cycle are known to be important to perform a bonded joint with maximum strength [12]. However, all studies that propose experimental testing of flush repaired specimens use a set of bonding parameters and stick to it. Moreover, most papers use the same types of ductile adhesives, like FM300-2K or Araldite 2015, with the same thickness of about 0.2mm. Thus, it is not possible to assess properly the influence of those bonding parameters on the strength or failure modes of flush repairs with the data currently available in the literature.

### **3. Flush repairs modelling**

The multiplicity of failure mechanisms involved in scarf and stepped joints failure makes them complex to model. Two general approaches to analyse bonded repairs have been developed, the first one is the use of failure criteria to predict the strength of the repair, and the second one is to model repair failure with initiation and propagation of damage. Analytical models for bonded joints were already reviewed [15, 52-55]. Comprehensive reviews of static strength prediction methods for bonded joints [56-58], including numerical models and damage modelling were proposed. Therefore, this section aims to highlight the specific aspects of scarf and stepped repairs modelling, and to discuss the representativeness of a flush joint model to study a flush repair.

#### *3.1. Analytical and semi-analytical models*

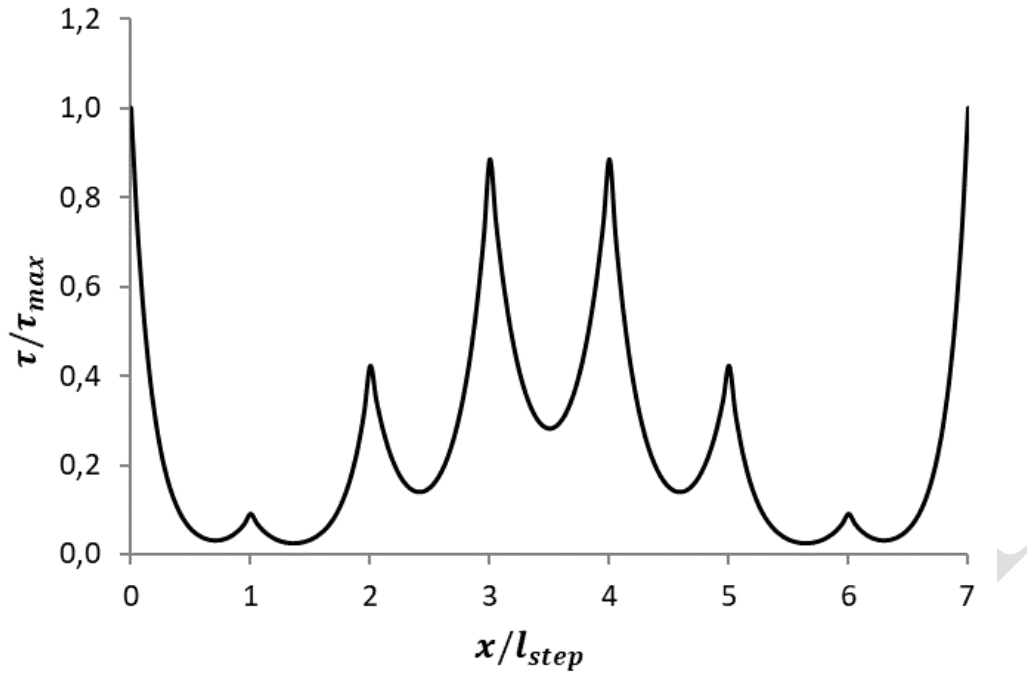


Figure 4 : Normalized shear stress distribution along composite stepped joint bondline

Analytical models for bonded joints are often described as two-dimensional. However, the simplest ones are one-dimensional, meaning that they depend on only one variable of space even though they can allow displacements in two directions. Arnovljevic [59] can be cited as the first occurrence of an analytical for single lap bonded joints. Erdogan and Ratwani [60] provided an analytical model for flush joints by adapting Volkersen [61] shear-lag model with adherends modelled as bars and adhesive as a layer of shear springs, to stepped (Figure 4) and scarf geometries. Hart Smith [62] then introduced adhesive plasticity in bonded joints equations for single lap, stepped and scarf joints. The main limitation of these classical models for scarf and stepped joints are: (i) neglecting bending of the adherends, (ii) neglecting transverse shear strain in the adherends, and (iii) not taking in account the varying stiffness of plies along the bondline of tapered scarf joints due to the different orientations of plies. This last effect makes scarf repair more challenging to treat analytically than stepped repairs which remain a succession of single lap joints.

Semi-analytical models for flush repairs were also reported. Equations are solved by numerical integration instead of obtaining a closed form solution. Ahn and Springer [63] used a stepped repair model for scarf repaired coupons with soft patch. They used elastic-plastic behaviour for the adhesive coupled with a maximum strain criterion for the adhesive layer and the laminates. Mortensen and Thomsen [64] introduced cylindrical bending of the adherends in scarf and stepped joints in a semi-analytical model. Equations were solved numerically because of the boundary conditions. This kind of semi-analytical approaches allows overcoming some of the previously mentioned limitations while saving a lot of computation time compared to finite elements (FE) analysis. A three-dimensional semi-analytical model for stepped-repaired coupons was release by Li et al. [65]. Their model is based on mesh-free formulations of Hamilton canonical equation for laminated plates and adhesive and gives account of transverse shear deformation plus bending of the structure. Harman and Wang [66] proposed a semi-analytical model base on Erdogan and Ratwani's equations for scarf joints, to model variable scarf angle along the bondline. They confronted their analytical model to the stress distribution obtained by FE analysis, which shown that their model did not give accurate prediction the shear stress peaks in the adhesive near  $0^\circ$  plies where most of the load is transferred through the joint. This is because adherends were still treated as homogeneous with properties derived from classical laminate theory. Liu et al [67] modified Harman and Wang's model by modelling the stiffness of each ply of the composite adherends separately. According to comparison with FE analysis, their solution is indeed more accurate than the previous one. They obtained secondary shear stress peaks near  $0^\circ$  plies that were missing with the precedent model but still has a 10% error in term of shear stress peaks by comparison with FE solution.

There is still some attention in the recent years towards analytical and semi-analytical models for scarf and stepped repair because they remain a cheap solution to predict repair strength. This is what makes them attractive to be used towards optimization purposes or to be implemented

in simple toolboxes or spreadsheets destined to repair design in the industry. Wang et al. [26] followed Ahn's equations and added linear assumption for shear deformation of the adherends, which was first proposed by Tsai [68], to improve it. They developed a computerized tool to predict stepped-repaired coupon failure that gave result in good agreement with experimental results. Other semi-analytical models dedicated to bonded joints could be applied to scarf and stepped joints such as the macro-element (ME) technique proposed by Paroissien et al [69]. Scarf and stepped joint involve a variation of material and geometrical properties along the overlap, which can be supported by the ME technique through a meshing, or a dedicated formulation based on Taylor expansion series. Moreover, the boundary conditions and loadings are not restricted, and the progressive failure of specimen can be described using suitable nonlinear material laws. Ramalho et al. [70,71] developed a meshless method for single lap joints strength prediction. It relies on the implementation of Exponent Drucker-Prager yielding criterion for adhesive into a Natural Neighbor Radial Point Interpolation Method. It was demonstrated to be suitable for elastic plastic analysis of single lap joints with isotropic or anisotropic adherends, and to be suitable to model the behavior of very ductile adhesives. It is able to predict joint strength and stresses within adhesive layer. Implementation of this kind of method for flush joints or repairs would enlarge the field of semi-analytical methods for flush repairs design.

Analytical and semi-analytical models for flush joints remain limited to scarf and stepped coupons geometries, thus not allowing directly modeling a flush-repaired plate, which is currently only achieved with finite element analysis.

### *3.2. Finite elements analysis*

#### *3.2.1. Current practices on FE modelling*

FE method allows dealing with some of the analytical methods limitations, at the cost the increased implementation and computation time. Finite element models for flush repairs are developed under the same geometric simplifications than the ones made for analytical models: perfect tapered scarf repair or perfect stepped repair. It suits well scarf repairs with hard patch and stepped repairs respectively. Soft-patch scarf repairs do not fall right into one of the two previous hypotheses (section 2.1) because of the interface between smooth machined parent panel surface and repair plies applied in a stepped shape. This configuration is frequently studied in literature and is usually modelled as a tapered scarf repair. Ridha et al. [72] can be mentioned as an exception because they developed a stepped model based on previous experimental work [48, 73] where panels were smoothly scarfed and repaired with soft patch. To the authors' knowledge, no research work proposed a more refined geometry for soft patch scarf repair to address resin rich pockets along the bondline for instance.

Several modelling strategies have been employed to model flush joints and repair coupons. Purely 2D plane strain models under plane strain hypothesis were used in first place [32, 74]. With the increase of computing power, researchers modelled flush joints or repaired coupons in 3D with their full width [33, 67] freeing themselves from plane strain hypothesis at the cost of heavy meshes even in simple cases like a scarf joint. Eventually, whole flush-repaired panels can now be modelled thanks to FE modelling. In some studies, for implementation purposes linked to widely used Abaqus software, three-dimensional models with only one element in width and bounded displacement in the width direction, leading to a plane strain state, [75-76] were used. FE method allowed to model full flush repaired panels in 3D, and different meshing strategies were identified: (i) 1 layer of shell elements for the whole plate with varying properties along the steps (for stepped repairs)[25, 72]; (ii) 1 shell element per ply to model plies individually while saving computation time [77]; (iii) 1 brick element per ply [30]; (iv) 4 brick elements per ply [78-79]. In most of the models, the adhesive layer is often meshed with

4 elements in the thickness with elastic or elastic-plastic behaviour when it not treated by cohesive zone modelling. Each study generally focuses on only one meshing strategy for a flush repair, thus it is difficult to compare them and assess the benefits and drawback of each one. Three meshes of increasing complexity were realised by the authors in order to illustrate different FE modelling strategies for flush repairs (Figure 5).

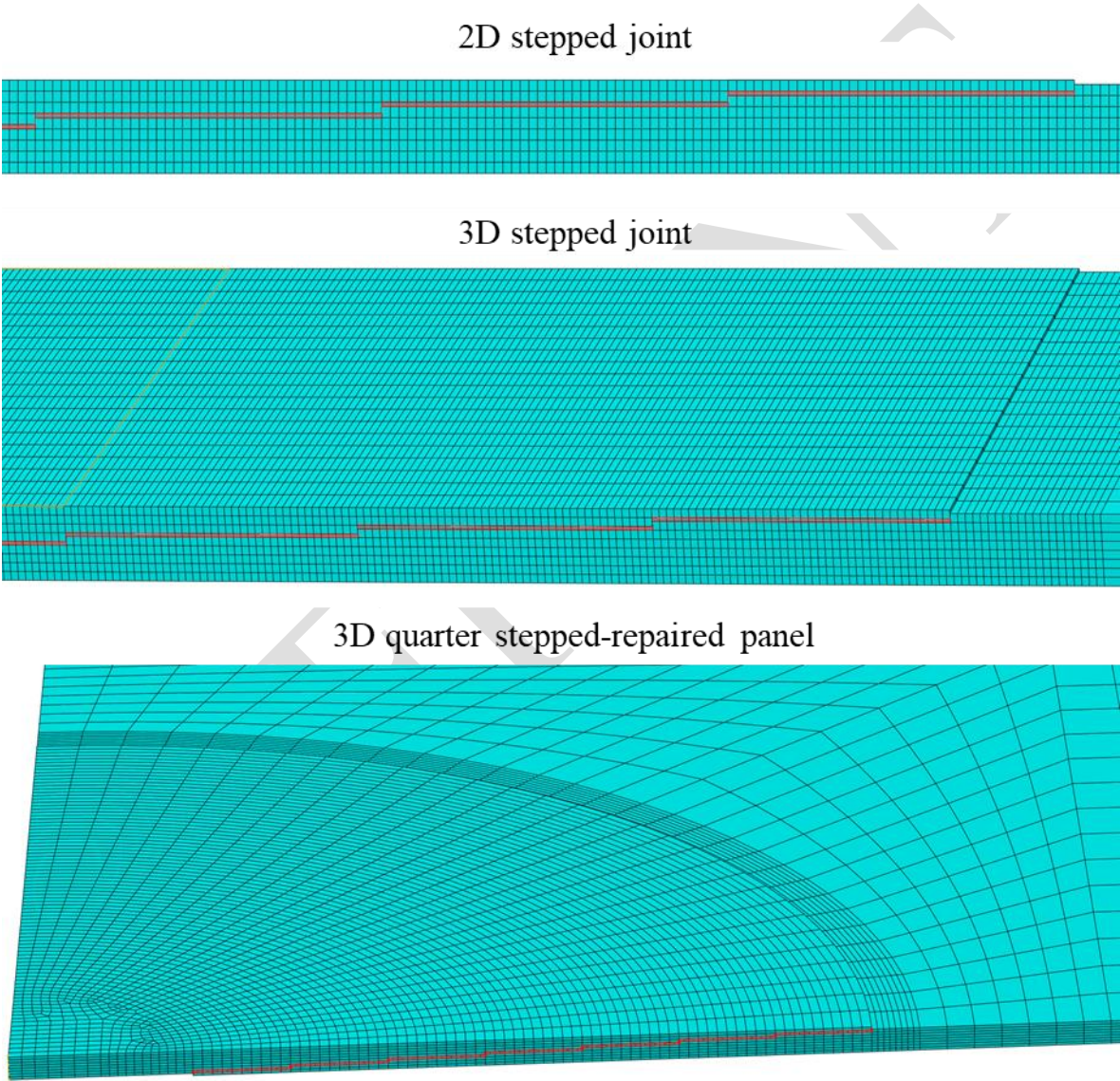


Figure 5 : Different types of meshes to model flush repairs

3.2.2. Failure prediction by criterion approach

Chapter 2 of Wang and Duong's book [21] is dedicated to failure criteria for bonded repairs. Stress and strain criteria can be expressed either in terms of maximum value, or value at a given distance of a stress peak or averaged over a zone. Energetic criteria can be used when considering an initial crack in the repair [80], i.e. fracture mechanics, or using corner singularities at the tip of the adherends in the repair. For composite adherends, classical stress criteria are Tsai-Hill [81], Tsai-Wu [82] and Hashin [83].

One could cite Odi and Friend [84] as they developed an early 2D plane stress FE model for composite scarf joints with discrete modelling of each ply of adherends by one layer of elements and elastic behaviour of adherends and adhesive. This improvement allowed to obtain the stress peaks at the tip of  $0^\circ$  plies that were missing with previous FE models where adherends were treated as homogenous with properties derived from classical laminate theory. Average stress over joint length criterion was used for adhesive and a comparison between maximum stress criterion and Tsai-Wu for laminates was proposed. Wang and Gunnion [85] proposed a strain-based approach for the design of scarf joints and repairs. They modelled the adherends as elastic and the adhesive as elastic-plastic. They identified stress concentrations factors near  $0^\circ$  plies tip and proposed to use Von Mises strain as failure criterion for adherends and to evaluate it at a characteristic distance from the plies tip equal to one ply thickness, meanwhile maximum shear stress was used to predict adhesive failure. Stress concentration factors were then used to predict failure with a first order analytical model. Critical failure volume (CFV) criterion [86] was used to address stress concentration in some studies on flush repairs [48, 87]. It is a criterion of statistic nature, based on finding the sub-volume which has the highest probability of local failure. Truong [33] employed the damage zone method to predict the strength of scarf repaired coupons. An experimental test was chosen as reference to determine the critical damage zone at failure load, according to Tsai-Hill criterion for laminates and maximum shear stress for



adhesive. Recently, Doitrand et al. [88] recently introduced a novel coupled stress and energy criterion that was used successfully for scarf joint analysis [89].

3.2.3 Failure prediction by damage modelling

With the latest developments of FE modelling, it has become possible to include damage initiation and propagation in the simulation without the including an initial defect in the model. This has led to the damage modelling approach, which drawn a lot of attention in the past years. In the context of bonded repairs, Cohesive Zone Modelling (CZM) [90-91] and Continuum Damage Mechanics (CDM) [92] are commonly employed.

CZM is used to simulate crack propagation along predefine paths with traction-separation behaviour of the interface. Bilinear (Figure 6), trapezoidal and exponential law shapes are the most common. It is well suited for bonded joints because the crack path is already known as it is the bonded joint itself. Moreover, CZM is also popular to model delamination between composites plies. Both CZM global approach, i.e., including the stiffness of the joint in the traction separation law, and local approach, i.e., meshing the adhesive with classical elements and adding very high stiffness traction separation law for interfaces between adhesive and

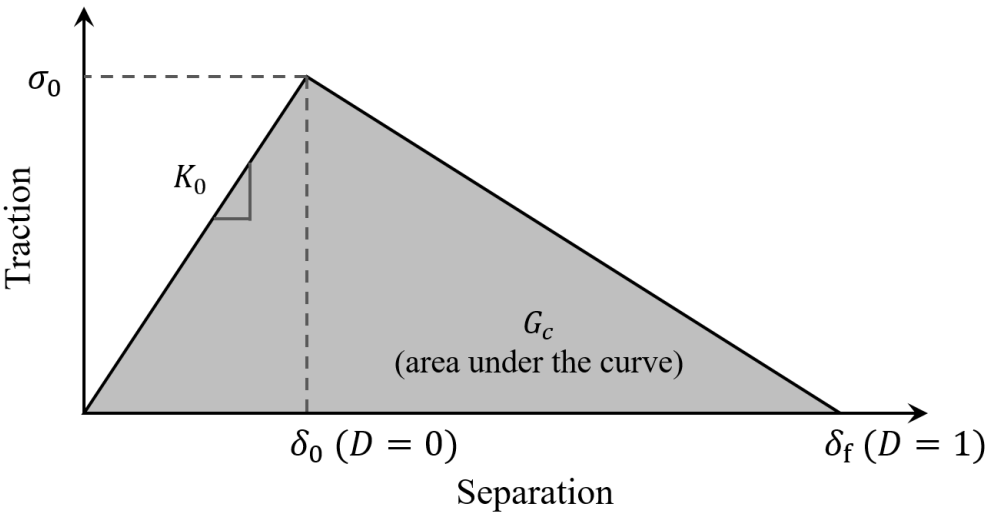


Figure 6: Bilinear traction-separation law

adherends, are suitable model bonded joints in repairs. Different traction separation law shapes can be used for the adhesive like bilinear (Figure 5), trapezoidal or exponential. They have different sensitivity to adhesive strength and toughness and the law shape influences the simulated strength of the repair [70].

CDM consists in progressive material softening when a failure criterion is reached during the analysis, thus it does not require predefining a crack path. Softening can be achieved step by step, in that case the FE analysis is solve with a progressive damage loop (Figure 7), or it can be continuous and based on material toughness using softening material laws directly implemented in the FE code.

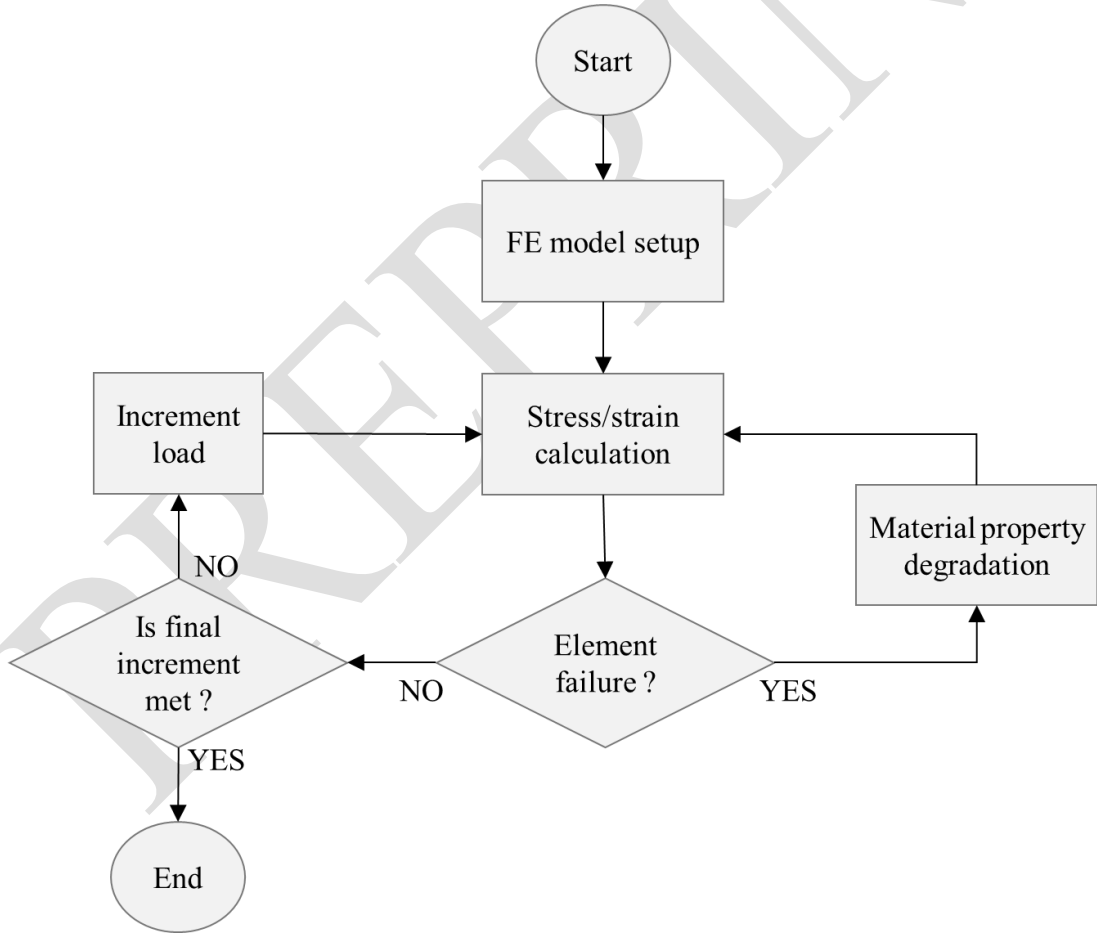


Figure 7: Analysis with step-by-step progressive material degradation flow chart

One can choose to use CZM for adhesive, matrix failure and fibre failure [32], or to use CDM for adhesive and laminates properties degradation [47], or to use CZM for the adhesive and CDM for laminates, this being now common for flush repairs models [67, 92-95]. Damage modelling allowed providing better understanding of the failure mechanisms involved in flush joints by reproducing accurately the failure mechanisms observed experimentally, including mixed cohesive plus matrix failure (section 2.2.) [32, 67]. CZM and CDM brings high nonlinearities to FE models, it led to the use of explicit dynamic analysis for flush repairs quasi-static tensile strength [75, 79, 96]. Moreover, it may avoid convergence difficulties for the post-failure part of the simulation in case of brittle failure that can be encountered with static implicit methods. FE with damage modelling allowed to treat more complex loadings than tension, for instance buckling [42] or 3 points bending [97-98].

Table 1 is proposed to overview the deviations between experimentally measured strength and predicted strength of flush repairs in various studies. It does not treat studies including impacts in order to stay focused on damage mechanisms inherent to the bonded repairs. As data was not directly available in many cited studies, but rather presented in form of graphs, it was manually extracted from those graphs by using WetPlotDigitalizer tool. Average, minimum and maximum deviations between experiments and prediction were then computed. These indicators do not give precise account of the trend of discrepancies between experiments and models, but they allow highlighting the robustness of models to modifications of the repair configuration.

From this data, it can be said that few studies presented strength prediction for stepped repairs. In terms of accuracy, a 10% deviation can be considered as satisfying regarding what was achieved in different studies. Well calibrated semi-analytical model [63] can provide the same accuracy in strength prediction than recent 3D FE with damage modelling. It shows that the discussion does not rely on determining which approach is the most precise, but which approach

is the most robust or reliable. Models that require parameter calibration that are not based on material behaviour are likely to be less robust. This is the case of methods requiring characteristic distance calibration, like point strain. The same could be said about material softening laws based on pre-set values that are not based on measure of material strain toughness measurement. When it comes to CZM, experimental tests for toughness measurement are quite standard, namely double cantilever beam, end-notched flexure and mixed-mode bending. However, there is no standard procedure for parameters identification. It can be directly based on measurements [99-103], or indirectly identified by calibrating a FE model to match to experimental tests. The same is true for the maximum stress parameter  $\sigma_0$ , which is often extracted from other tests like thick-adherend shear test (TAST) or butt joint but could be also extracted from crack propagation tests. Even though CZM allows to predict very well the behaviour of a structure including crack propagation, it remains a kind a of global approach because the stresses in the process zone are not directly measured. The measure of stress in a small area including the process zone is possible though [104].

Table 1: Deviations between predicted and experimental strength of composite bonded flush repairs. The number of configurations presented for each study only includes configurations for which experimental/modelling comparison were presented. The same is true for parameters studied. (ScJ: Scarf joint, ScRC: Scarf-repaired coupon, ScRP: scarf-repaired panel, StJ: stepped joint CZM: Cohesive zone modelling, CDM: Continuum damage modelling, VCCT: Virtual crack closure technique, CFV: Critical failure volume, DZM: Damage zone method).

Study	Specimen type	Loading	Config. tested	Parameters studied	Model type	Approach for bondline failure	Approach for laminate failure	Deviation between experimental and predicted strength		
								Avg.	Min.	Max.
Ahn 1998b [38]	ScRC	Tension	12	Scarf angle, overplies, hotwet (HW) aging	Semi-Analytical	Max. shear strain	Max. strain	6% 20% (HW)	3% 10% (HW)	11% 34% (HW)
Odi and Friend 2004 [84]	ScJ	Tension	5	Scarf angle	FE 2D	Avg. shear stress	Max. stress	36%	23%	59%
Kumar 2006 [34]	ScJ	Tension	6	Scarf angle	FE 2D	CDM	Hashin-Lee	8%	5%	12%
Wang 2008 [85]	ScJ	Tension	5	Scarf angle	Analytical + FE	Max. shear strain	Point strain	15%	4%	48%
Campilho 2009 [32]	ScRC	Tension	7	Scarf angle	FE 2D	CZM	CZM	8%	1%	20%
Campilho 2009 [42]	ScRC	Buckling	7	Scarf angle	FE 2D	CZM	CZM	2%	1,5%	5%
Breitzman 2009 [48]	ScRP	Tension	2	Panel scarfed / repaired	FE 3D	CDM	CFV [Iarve 2007]	9%	8%	10%
Xiaoquan 2013 [47]	ScRP	Tension	4	Defect size, layup	FE 3D	CDM	CDM	11%	2%	20%

Goh 2013 [80]	ScJ	Tension	4	Initial flaw length	FE 3D	VCCT	Not modelled	1%	0,5%	3%
Liu 2016 [67]	ScJ	Tension	1		FE 3D Semi-Analytical	CZM Max. shear stress	CDM Not modelled	9%		27%
Truong 2016 [33]	ScRC	Tension	5	Scarf angle, overplies, defect size	FE 3D	Max. shear stress	DZM Tsai-Hill DZM Tsai-Wu	8%	0,5%	16%
Truong 2019 [97]	ScJ	3 Pts Bending	6	Scarf angle, lower pins distance	FE 3D	CZM	CZM (delamination)	5%	1%	10%
Han 2019 [44]	StJ	Tension	1		FE 3D	CZM	Not modelled	1%		
Collombet 2019 [46]	StJ	Tension	1		FE 3D	Avg. shear stress	Tsai-Hill	0%		
Feng 2019 [30]	ScJ	Tension	4	Laminates thickness	FE 3D	CZM	CDM	3%	1%	5%
Wang 2019 [45]	ScRC	Tension	5	Steps number, overplies	Semi-analytical	Max. shear strain	Max. strain	9%	2%	23%
Sonat 2020 [39]	ScJ	Tension	3	Scarf angle	FE 3D	CZM	CDM	7%	5%	9%
Sun 2020 [29]	ScJ	Tension	6	Scarf angle	FE 3D	CZM	CDM + CZM	5%	1%	9%
Moreira 2020 [105]	ScRC	3 Pts bending	1		FE 2D	CZM	Not modelled	4%		
Hayes-Griss 2020 [75]	ScJ	Tension	11	Layup, flaw length, flaw position, sandwich support	FE 3D plane strain	CZM	CDM + CZM	8%	1%	35%

### 3.3. *Representativeness of the equivalent joint*

Many studies addressing composite flush repairs focus on the equivalent joint, i.e., two-dimensional joint with the same geometric parameters than the repair, rather than the actual repair. It allows saving modelling and computation time. This approach is based on the assumption that, under uniaxial load, the stresses along the bondline of a scarf or stepped joint are almost identical to the stresses in a radial slice of the repaired-panel aligned with the direction of the load. Under this assumption, designing a flush repair based on the equivalent joint should give conservative result because the equivalent joint represents the most loaded part of the repair, but precise understanding of the consequences of this hypothesis is needed to avoid overly conservative design.

This approach is a matter of discussion in the literature. Soutis and Hu [106] exhibited a 40% gap between the strength of a scarf-repaired panel analysed by linear FE and the equivalent scarf joint analysed by a semi-empirical method. Later, Gunnion and Hertzberg [107] presented a FE parametric study of scarf joint and scarf repair with linear elastic behaviour of laminates and adhesive. A 25% average stress reduction was found by comparing the scarf joint and scarf repaired panel models, it was attributed to load bypass around the repair. Wang and Gunnion [84] showed by FE analysis that adherends experience a similar level of strain concentration near 0° plies in a scarf repair and in a scarf joint, comforting the legitimacy of the equivalent joint assumption and disputing Soutis and Hu conclusions. Moreover, they suggested that in case of equal bi-axial loading, the difference between scarf joint and scarf repair strength might be smaller than under uniaxial loading. Pierce & Falzon [79] studied by FE with CZM both full repairs and equivalent joints with scarf or stepped configurations in a study on fibre-oriented design. Their simulations showed that the strength of the repair and the equivalent joint is similar for 8° and 5° angles, and that the strength of the repair becomes substantially greater

than the equivalent joint strength one for  $3^\circ$  and  $2^\circ$  angles. Tashi and Abedian [75] very recently released a comprehensive numerical study comparing stress in the bondline in 2D and 3D models for scarf joints and scarf repaired panels. They pointed that stating a general rule about the difference between stresses in scarf joints and scarf repair would not be reasonable as it depends on the repair angle and stacking sequence and material properties. Their computed shear stresses for scarf-repaired plates were lower than the ones in scarf joints, but with a small discrepancy. Very little experimental data comparing repairs and equivalent joints is available, Chong et al. [50] conducted experimental tension test on scarf joints, scarf repaired coupons and scarf repaired panels. An increase of 10% in tensile strength between the scarf repaired coupon and scarf repaired panel was found. This difference was attributed to the strength redistribution around the repair when the first yield of the adhesive occurs in the load direction. It would indicate that the strength of repair is likely to be higher than the equivalent joint. Further experimental and numerical work, including damage modelling simulations, is needed to provide an understanding of the differences between failure behaviour of a flush repair and its equivalent joint, and to what extent the equivalent joints hypothesis is valid. This could help saving computation time in strength prediction simulations because even for small coupons, detailed FE models can reach more than 500.000 degrees of freedom [46].

#### **4. Optimization**

As flush repairs require very shallow scarf angles, a lot of pristine material needs to be removed and the spatial extension of the repair increases with the thickness of the laminate that is repaired. Reducing flush repairs dimension is a major concern because space available in the reparation area is often limited on aircraft structure due to the presence of other structural elements, like frames or stiffeners. Thus, repair optimization is a matter of interest as it leads to



increased repair strength at equal repair dimension, or reduced repair dimensions at equal strength.

A distinction can be made between two types of works that can be done towards flush repair optimization purposes. On the one hand, one can carry a sensitivity analysis, to assess the influence of a change in a design parameter within a chosen range, or to assess the benefits of a new repair shape. This type of work could be described as exploratory as it does not provide the best configuration possible but brings information on most sensible parameters and innovative repair shapes. On the other hand, one can achieve an optimization loop analysis, using an optimization algorithm to find the best possible configuration based on the chosen criterion to be optimized.

#### *4.1. Influence of design parameters*

Main design parameters of flush repairs are repair angle or ratio, adhesive thickness, plies thickness, laminates stacking sequence and overplies configuration. The sensitivity of stress distribution in the bondline to those parameters was addressed by numerical parametric studies [107-110]. Shallower repair angles, thicker plies and thinner adhesive layer tend to reduce the peak shear and peel stresses along the bondline, but addition of overplies, i.e. additional plies added over the repair patch, is the parameter that most dramatically decreases peak shear and peel stresses.

Scarf angle or ratio is the most studied parameter in flush repairs studies as it drives the failure mode of the repair (see section 2.2.). Strength of scarf repaired coupons and scarf repair plates increases when the scarf angle decreases and can reach up to 95% of the undamaged laminate strength [50]. Maximum strength of the repair is achieved when it fails by parent laminate fracture only and the optimum angle of a repair can be defined as the steepest angle that leads to this failure mode. It would not be reasonable to give a general rule regarding the optimum

scarf angle, as repair strength depends not only on the angle but also on material properties. Research papers tend to show that the strength of a repair coupon can rise until  $2^\circ$  (1:28) [32] or  $1^\circ$  (1:57) [36] and aircraft manufacturers recommend 1:60 (Airbus) and 1:45 (Boeing) [46]. Stacking sequences of composite adherents influence joints and repairs strength. Experimental test [84] showed that scarf joints with  $0^\circ$  surface plies have a lower strength than scarf joints with  $90^\circ$  plies. This was attributed to higher stress concentration at the tip of  $0^\circ$  when they were positioned at the external surface of laminates, confirming previous numerical results that show the increase in peak peel stress when  $0^\circ$  plies were on the outer surfaces [107-108]. Regarding stacking sequence of repair patch, the common practice is to match ply-by-ply the stacking sequence of the parent laminate with the patch plies to restore the original structure stiffness. Breitzman et al. [48], investigated the idea to offset the patch stacking sequence by one ply, leading to a configuration where each repair ply overlaps a parent ply of same orientation (Figure 8). It was shown by FE analysis that the patch overlapping stacking sequence reduces shear stress peaks in the bondline of scarf repairs. Moreover, an optimization study on patch stacking sequence was performed to determine the one that would minimize the von Mises stresses in the adhesive. Nidernhuber et al. [111] studied those ply-matching and overlapping configurations experimentally by tensile test on stepped joints with 1:50 ratio. The overlapping configuration was found to provide an 11% increase in tensile strength comparing to the ply-matching configuration confirming its benefits.

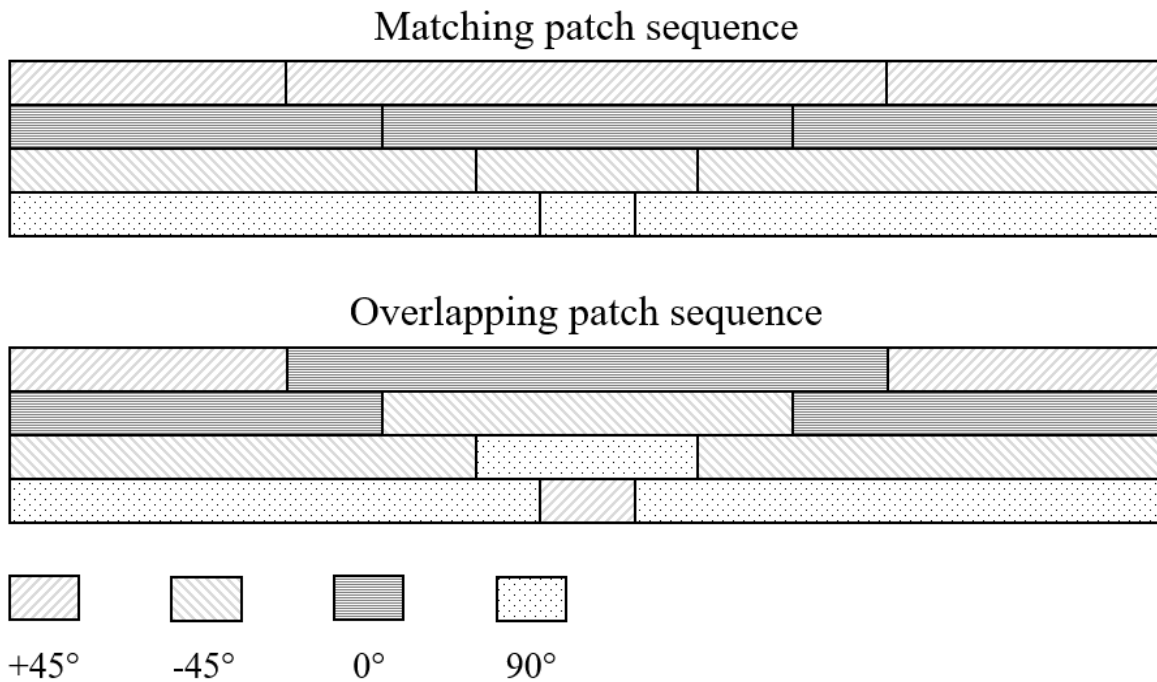


Figure 8: Matching and overlapping patches for stepped repairs

Regarding overplies, i.e., additional plies added on top of the flush repair (Figure 9), it was shown experimentally that they increase the repair strength [38]. FE modelling [48] confirmed that overplies reduced the stress in the bondline and increased the repair strength [78]. Overplies size and orientation were investigated numerically [108], and it was found that overplies orientation had little influence on peel and shear stress reduction in the repair. A critical overlap length of 5 mm was identified as no significant improvement was obtained with longer overplies, but the 0-5mm range was not explored. Experimental results on scarf-repaired coupons [37] showed different failure mode depending on the overplies length: short overplies disbonded and longer ones did not. Overplies were not made of the same material than the laminates: CFRP woven fabric were used for overplies and UD CFRP for laminates.

The choice between a scarf and a stepped repair can be considered as a design parameter. However, there is little data available directly comparing scarf and stepped repairs as each paper focuses on one choice. Numerical studies highlighted that stress concentrations were higher in stepped joints compared to scarf joints of equivalent angle [95, 108] but that careful choice of

design parameters in order to reduce peak stress can make them compete with tapered scarf repairs. These comparisons were conducted between stepped and perfect tapered scarf models, but tapered scarf remains an idealization of a wet-layup scarf repair. Therefore, real scarf repairs may experience higher stress concentration than predicted with these models due to non-perfectly smooth bondline.

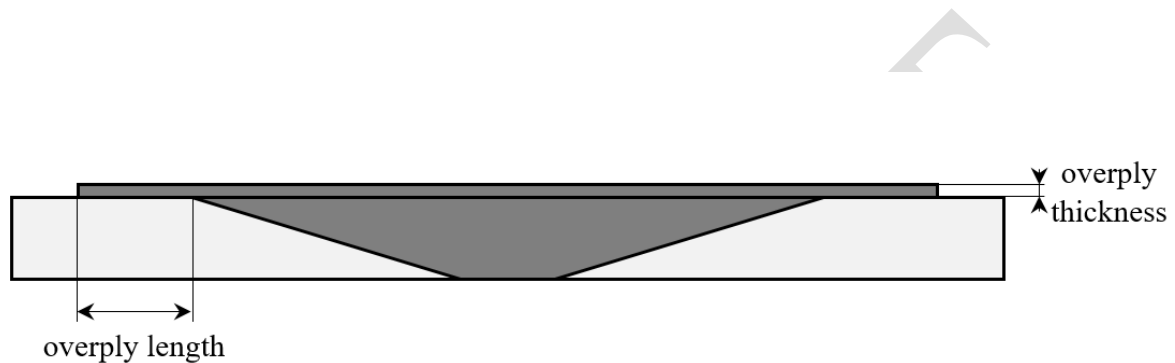


Figure 9: Flush repair with overply

#### 4.2. Innovative designs

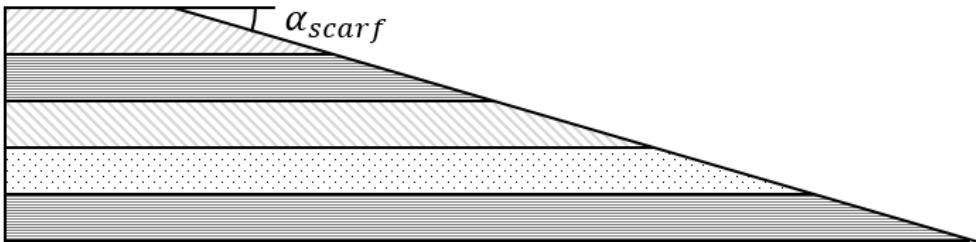
In order to optimize flush repairs, some studies went beyond the traditional design parameters and tested new repairs shapes. Wang and Gunnion [112-113] worked on patch shape optimization for scarf repairs under bi-axial loading. They showed that under non equi-biaxial stress, the circular shape is not optimal and leads to removing more pristine material than what is needed. Innovative patch shapes were proposed by varying the scarf angle to vary all around the repair, while remaining constant in each radial slice. An optimization technique was developed, and an elliptical shape was proposed to reduce the repair size under bi-axial loading. In case of damage with a high aspect ratio, i.e. very elongated, a hybrid square-ellipse profile was proposed. Other patch shapes such as octagonal patches were investigated in the field of double lap repairs [114] and could be extended to flush repairs. Nidernhuber et al. [111] proposed a fibre-oriented repair design for stepped repairs. As under uniaxial loading, most of the load is transferred by the plies aligned with its direction, their idea was to increase the overlap length for the plies aligned in the direction of the load, where stresses are the highest,

or to reduce it for the others. Tension tests were conducted to compare constantly 16 UD plies stepped joints of 1:50 ratio and fibre-oriented step joints with ratios of 1:50 for  $0^\circ$  plies, 1:35 for  $45^\circ$  plies and 0 for  $90^\circ$ . It was shown that fibre-oriented design reduced the repair length by nearly 40% while keeping the same tensile strength. Pitanga et al. [115] proposed a new design for scarf repairs with variable scarf angle (Figure 10). Their idea is also to reduce the repair length by using two different scarf angles, a 1:20 or 1:30 ratio for  $0^\circ$  plies and 1:2 ratio for  $45^\circ$  and  $90^\circ$  plies. Specimens were machined precisely using a CNC router. Tensile strength of optimized specimens and standard 1:20 straight scarf joints were compared. The 1:30/1:2 configuration achieved 64% of the strength of standard 1:20 straight scarf joints at only 40% the size and was further improved by the addition of two  $0^\circ$  cover plies to reach 75% of the initial 1:20 joint. Pierce and Falzon [79] used 3D FE analysis including damage modelling to compare the strength of fibre-oriented scarf or stepped repaired plates. Their simulations did not show benefits for stepped repair with fibre-oriented design, but it did for scarf repairs with a 40% area reduction at equal strength. These results were attributed to the higher stress concentration that exists in stepped joints compared to scarf joints, which could initiate failure of the repair earlier even with an optimized design. They discussed Nidernhuber's conclusions, assessing that experimental testing with steeper angles would be required to properly assess the benefits of fibre-oriented design for stepped repairs. Damghani et al. [96] proposed a variable length stepped repair design. The idea is similar to fibre-oriented design by Nierdnerhuber et al. [111] (Figure 11). Experimental testing was conducted on twelve woven plies stepped repaired coupons. The initial damage that was considered was not going through all the thickness of the coupon, leaving six pristine plies at the bottom. The repair consisted of two steps each being three-ply-thick. Four configurations were tested with different ratios for  $0/90^\circ$  and  $+45/-45^\circ$  plies. The optimized repair scheme restored 64% of the pristine laminate strength compared to 77% obtained with classic repair of high 1:60 ratio. Sun et al. [116]

conducted experimental testing of stitched scarf repairs panels. Holes were drilled into the parent laminate to perform a hand-made stitching of the repair with carbon fibre threads, which were then infused with resin and cured to be bonded to the parent laminate. For panels with a 1:10 scarf ratio, the stitching improved the strength of the panels by 27% compared to non-stitched ones.

Several new repairs designs were proposed with promising results. However, given the discussions highlighted between some studies, further investigations are needed to assess what size reduction or strength increase is conceivable.

### Constantly-scarfed laminate



### Variably-scarfed laminate

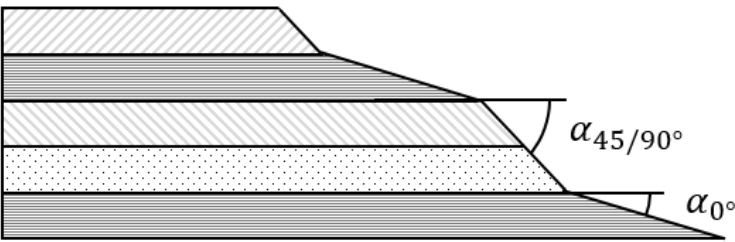


Figure 10: Schematic visualization of variable scarf angle introduced by [115]

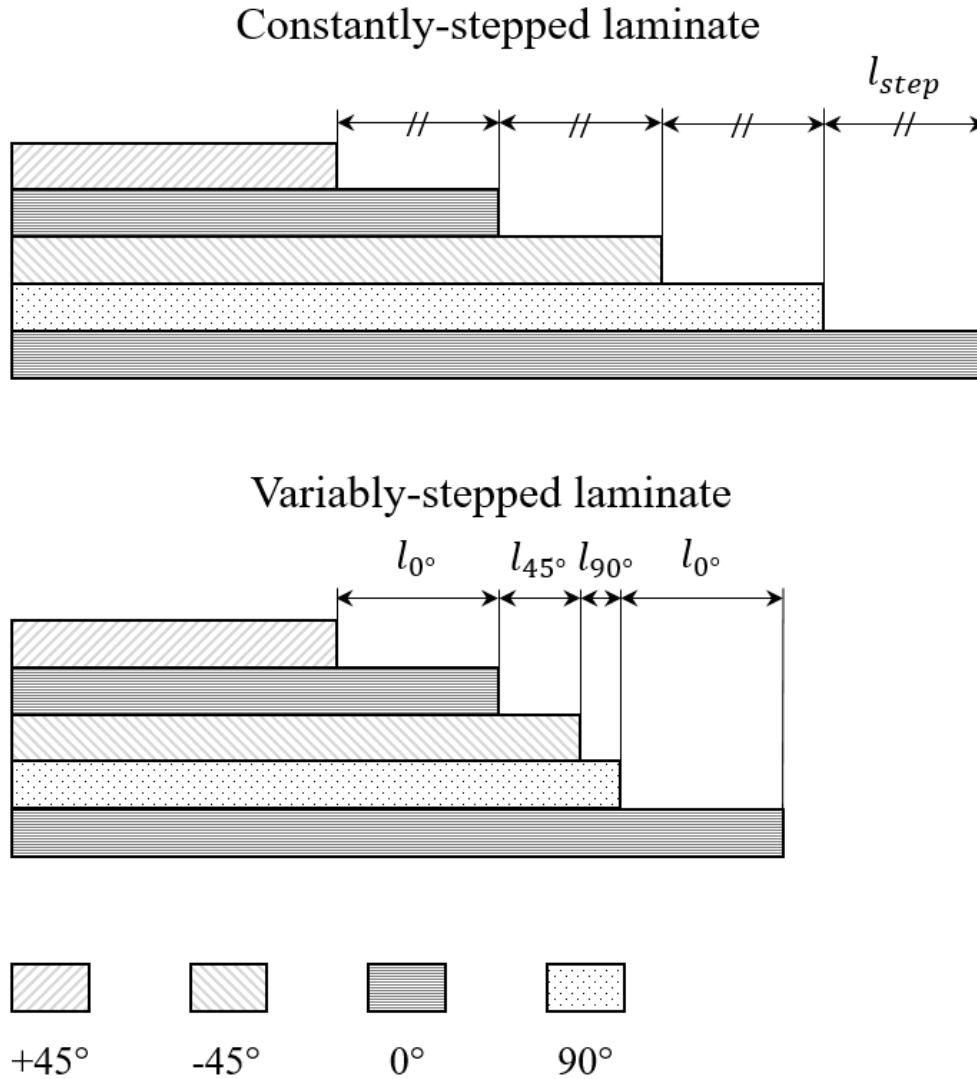


Figure 11: Schematic visualization of variably-stepped laminates design introduced by [96,111]

## 5. Reliability and durability

*Reliability analysis aims to compute the probability of failure considering uncertainties or to calculate the safety values at a given confidence and reliability level. In the recent years, reliability of bonded composite joints and uncertainties in those structures elaboration were reviewed [117,118]. Limited work was done on probabilistic assessment of flush repairs strength [119,120,121]. Simple methodologies were provided in order to take in account stochastic variations for the material and geometrical properties as well as the external*

*loading. It was shown that the peak bondline stress is very sensible to variation of scarf angle and adhesive thickness [121].”*

Mechanical durability of flush repairs is a major concern. Beyond static loads, they may experience impacts and fatigue during their service life. This is why providing an understanding of flush repairs impacts and fatigue behavior is of interest. Environmental durability is also a major problem of flush repaired plates. Budhe et al. [17] reviewed bonded repairs environmental issues, such as moisture and temperature aging. Briefly, the most important factors are moisture and temperature. Their individual effects on the properties of composite material and adhesive is understood, but limited work was done on their combined effect on bonded repairs. Many factors such as curing cycle, test temperature or glass transition temperature may influence the fracture toughness of the adhesive and repair patch. Moisture can significantly decrease the strength of bonded joints. Pre-bond moisture and post-bond moisture are both to be considered, and pre-bond moisture is to be avoided as much as possible. FE Analysis with CZM allows to predict the behavior of bonded joints in hydrothermal conditions. Data obtained by experimental aging tests can be incorporated to traction-separation laws by degrading cohesive zone parameters. However, accurate prediction of the behavior of bonded joints submitted to heavy environmental conditions remains challenging as conventional aging is very time consuming. Accelerated aging tests may offer opportunities to improve the environmental durability analysis.

### *5.1. Damage tolerance*

Airworthiness regulations require bonded repairs to match the design ultimate load in presence of disbonds [95, 132-133]. Thus, several papers proposed analysis of flush joints and repairs strength in presence of an initial defect in the bondline (Figure 12). This approach can be described as “damage tolerant design” of flush repairs.





Figure 12: Scarf repair with bondline flaw

Goh et al. [80] investigated the strength of scarf joints with initial flaws of different lengths starting at one end of the joint. Experimental tension tests showed that the strength of the joints decreases when the size of the flaw increases and depends on the orientation of the flaw next to the crack tip and on the flaw size. A loss of 25% of the bond provoked a loss of 50% of the joint strength. Kosmann et al. [134] studied experimentally and numerically scarf joints with flaws and reached the conclusion that the presence of a flaw can dramatically reduce the joint strength. Wu et al. [135] compared the damage tolerance of scarf and stepped joints by FE modelling. An extensive parametric study including flaw length, flaw width, flaw location, number of steps, adherend stacking sequence and overplies was proposed. It was shown that stepped joints with a lower number of steps are more damage tolerant than those with a high number of steps or than scarf joints. Hayes-Griss et al. [94] carried out experimental testing of scarf joints with flaws at room temperature and addressed the influence of temperature and moisture on specimen strength. Full width-flaws of 10%, 20% and 40% of the total bondline length were tested. They concluded that under hot-wet conditions, scarf joints are less sensitive to bondline flaws than under room temperature or cold dry conditions. Fracture along the bondline systematically happened by interfacial failure that initiated at the tip of the flaw and jumped to the bondline on the opposite side. Feng et al. [30] proposed a numerical investigation of the influence of 3D defects in the bondline of composite scarf joints, with round, square or triangular shapes and representing from 5% to 25% of the bonded area. Defect shape had no influence on the strength loss for small defects, but for large defects the triangular shape led to a higher strength loss than the others. Sonat et al. [39] encountered unexpectedly high levels

of porosity, in a range of 0.1-0.5mm estimated porosity rate of 10%, in the bondlines of their first batch of composite scarf joints specimens. They successfully produced a second batch of specimens without porosities and concluded that the first batch had a 13% strength loss compared to the porosity-free one. Numerical investigation was carried out with a 3D finite element (FE) model of a scarf joint and two defects scenarios: (i) evenly distributed round shaped voids of 1mm diameter in the bonding surface to replicate levels of porosity between 4% and 14%, (ii) one round shaped void of diameter between 2.5mm and 10mm. A good agreement between experimental data and the 10% porosity rate simulation was found. Hayes-Griss et al. [75] proposed an improved numerical methodology to predict failure of scarf joints with initial flaws, using FE with CZM and CDM. They brought improved understanding of the failure behaviour of flawed scarf joints. With the 3° scarf angle, damage would initiate by matrix tension in 45°/90°plies in pristine joints. In presence of a flaw, damage would initiate at the tip of the flaw, then would provoke delamination in the adjacent 45°/90° plies and finally reach the bondline and interface failure would progress all along it. They concluded that both composite and adhesive damage assessment should be carried out to propose a damage tolerant design of a scarf joint.

Reported studies address mainly smooth scarf joints, further numerical or experimental work on the stepped geometry and on whole flush-repaired panels could provide an understanding of the effect of flaw position relative to the loading axis for instance.

## 5.2. *Impact behaviour*

Repaired areas of composites structures may suffer impact damage as well as the rest of the rest of structure. Regarding the choice between repairs shapes, it was shown by FE analysis that the scarf shape is more effective than single lap joint to reduce stress concentration in bonded joints under impact loads [122]. Kumari et al. [123] assessed the effect of impact position on scarf

repaired panels by dynamic FE analysis. The most vulnerable location to impacts was the patch edge. The same type of numerical analysis was carried [124] to study multi-impact load case on scarf-repaired panel. Patch stacking sequence effect on impact damage was investigated by experimentally and by FE analysis [125]. It was concluded that stiffer patches improved the impact performance of scarf-repaired panels. Patch misalignment with the parent structure was also explored, it had a greater effect than patch stacking sequence on impact damage.

Compression after impact (CAI) is a critical type of solicitation of composite structures. Wang et al. [95-2015] showed by experimental and numerical testing that pristine laminates and stepped-lap joints had similar levels of compressive strength reduction when subject to the same impact damage. This trend would be very favourable for flush repairs to be used for primary bearing load structures because the repair would not be more vulnerable than the pristine structure. Shufeng et al. [126] conducted experimental CAI tests on scarf-repaired panels. Impact position influence was investigated, and it was shown that the edge of the patch was the location where impacts degraded the most the compressive strength of specimens, which is consistent with numerical results of Kumari et al. [123]. A FE model including CDM was developed and gave results in good agreements with experiments. Tension after impact (TAI) was investigated as well on composite flush repairs [127-128]. Shallow scarf angle demonstrated a higher tensile strength recovery rate after impact than steeper angles. [129]. Liu et al. [130] studied residual tensile strength after impact of stepped-joints specimens of 1:17 ratio. A dramatic decrease of 50% in residual tensile strength of tested specimens was observed at an impact energy threshold of 4J. The same type on study was conducted on 5° scarf joint specimens [131], it was stated that impact damage in the adhesive joint would occur with high enough impact energy and have significant effect on the tensile strength of scarf joints. Given the small number of studies dealing with impacts on bonded repairs, there is room for more investigation.

### 5.3. *Fatigue*

Composites materials are known for their fatigue performances, but a bonded repaired structure could be more vulnerable to fatigue than pristine laminates. Fatigue of bonded stepped and scarf joints in general is therefore a field of investigation [136, 137]. A few papers dealing with fatigue of composite bonded repairs were released. Yoo et al. [37] carried experimental fatigue tests of scarf-repaired coupons loaded in tension with scarf ratios of 1:20 and 1:30.  $10^6$  fatigue cycles were reached by pristine specimens with an applied stress equal to 60% of their static strength, compared to 30% for repaired specimens, showing that they are more vulnerable to fatigue than pristine ones. Shallower scarf angles provided better strength recovery rate. Observed fatigue failure modes were similar to static failure modes with mixed intralaminar and cohesive failure of the bondline. Moreira et al. [104] proposed 3 points bending fatigue study of scarf-repaired coupons of  $10^\circ$  angle. A 2D FE model was proposed and was able to predict the fatigue life in agreement with experiments. The model was then employed to assess the influence of scarf angle on the fatigue life of scarf repaired coupons. It showed important gains with the decrease of the scarf angle. Guan et al. [138] carried out experimental work on fatigue of full scarf-repaired panels. Fatigue cycles with a load amplitude between 5% and 0.5% of static strength were applied. Specimens reached  $10^6$  with no damage revealed by C-scan. Static test then showed that those fatigue cycles did not have any impact on the static strength and failure behaviour of the repaired panels. Wong et al. [139] carried out fatigue test on composite stepped joints. Distributed optical fibre sensors were used to monitor the onset and then propagation of fatigue damage. Specimens failed along the bondline. Moreira et al. [140] release a numerical study on 3 points bending fatigue of different composite joint types. CZM and modified Paris law were used to model crack propagation in the bondline, and single lap,

double lap, scarf and stepped joints were compared. Scarf repairs appeared to be the most efficient choice in terms of fatigue life.

From studies that were presented, it appears that modelling techniques for bonded joints and composites are now mature enough to produce behaviour and strength prediction of composite flush repair subjected to impact, to presence of flaws. There is room to pursue those studies in order to assess the effect of various parameters there are not yet explored, such as flaw position in a 3D repair for instance. These reliability and durability approaches could be applied to innovative designs to identify any other advantages or drawbacks they bring. As there are few studies on fatigue of composite bonded repairs, more work is required to understand and to predict their fatigue behaviour.

## **6. Conclusions**

In this paper, design of those repairs was reviewed, and the following points were identified. Static tensile failure behaviour of flush joints and flush repairs is well understood. The repair angle or ratio drives the failure mode. Several studies showed that, with a shallow enough angle, the adhesive is not the weak link of a flush repair anymore. However, there is a lack of experimental data available on flush-repaired panels failure. Other load cases as compression and bending drawn less attention from researchers.

Various approaches to model flush repairs were identified. Beyond classical analytical models, there are recent developments of semi-analytical models and finite elements models. Those last models tend to be computational-heavy due to damage modelling with cohesive zone modelling and continuum damage mechanics. A comparison of discrepancies between experimental and predicted strength of repairs in various studies was proposed, and it shown that many models can achieve satisfying prediction of flush repairs strength. The discussion relies then on the robustness of each method, i.e., how they are sensitive to uncertainties in material parameters

measurement, and to what extent a given parameter calibration remains valid when repair configuration changes from the initially studied case.

The equivalent joint approach, stating that a flush repair can be design by studying the equivalent two-dimensional joint to the repair is a matter of discussion in the literature. Further work is required to provide a deeper understanding of the representativeness of the equivalent joint.

Numerous studies on repairs design parameters were identified. No general rule can be stated about the optimal repair angle or ratio, but very shallow angles are required to achieve maximum strength. The addition of overplies can be mentioned as a critical parameter allowing to increase repairs strength. Most of papers are focused on scarf repairs and there is little data available comparing scarf and stepped repairs designs.

Many innovative repairs designs were reported, with new patch shapes, varying steps length, or varying scarf angle. These are promising ways to optimize flush repairs size. It may open the field towards performing flush repairs on aerospace structures when only small areas are available for the repair.

Reliability and durability of flush repairs, including impacts, damage tolerance and fatigue, is a matter of interest. Current modelling techniques are able to accurately predict the behaviour of flawed or impacted composite repairs. The capability to design bonded repairs less sensitive to initial flaws, or to damage that could occur during their life might be a promising way to reach bonded repair certification for primary bearing structures.

#### **Declaration of conflicting interests**

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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PREPRINT

## References

- [1] Konur O, Matthews FL. Effect of the properties of the constituents on the fatigue performance of composites: a review. *Composites* 1989;20:317–328.  
<https://doi.org/https://doi.org/10.1016/0010-4361%2889%2990657-5>.
- [2] Marsh G. Composites consolidate in commercial aviation. *Reinf Plast* 2016;60(5):302–305.  
<https://doi.org/10.1016/j.repl.2016.08.002>
- [3] Georgiadis S, Gunnion AJ, Thomson RS, Cartwright, BK. Bird-strike simulation for certification of the Boeing 787 composite moveable trailing edge. *Compos Struct* 2008;86(1-3):258-268.  
<https://doi.org/10.1016/j.compstruct.2008.03.025>.
- [4] Kumar V, Yokozeki T, Karch C, Hassen AA, Hershey CJ, Kim S, Lindahl JM, Barnes A, Bandari YK, Kunc V. Factors affecting direct lightning strike damage to fiber reinforced composites: A review. *Composites Part B* 2020;183:107688.  
<https://doi.org/10.1016/j.compositesb.2019.107688>.
- [5] Kawakami H, Feraboli P. Lightning strike damage resistance and tolerance of scarf-repaired mesh-protected carbon fiber composites. *Composites Part A* 2011;42(9):1247–1262.  
<https://doi.org/10.1016/j.compositesa.2011.05.007>
- [6] Davies GAO, Zhang X. Impact damage prediction in carbon composite structures. *Int J Impact Eng* 1995;16(1):149–170.  
[https://doi.org/10.1016/0734-743X\(94\)00039-Y](https://doi.org/10.1016/0734-743X(94)00039-Y).
- [7] Shyr T-W, Pan Y-H. Impact resistance and damage characteristics of composite laminates. *Compos Struct* 2003;62(2):193–203.  
[https://doi.org/10.1016/S0263-8223\(03\)00114-4](https://doi.org/10.1016/S0263-8223(03)00114-4).
- [8] Baker A, Gunnion AJ, Wang CH. On the certification of Bonded Repairs to Primary Composite Aircraft Components. *J Adhes* 2015;91(1-2):4–38.  
<https://doi.org/10.1080/00218464.2014.883315>.
- [9] Zhou W, Ji X-l, Yang S, Liu J, Ma L-H. Review on the performance improvements and non-destructive testing of patches repaired composites. *Compos Struct* 2021;263:113659.  
<https://doi.org/10.1016/j.compstruct.2021.113659>.
- [10] Baker AA, Rose LRF, Jones R. *Advances in the Bonded Composite Repair of Metallic Aircraft Structure - Volume 1*. Elsevier; 2002.
- [11] Heslehurst RB. *Engineered Repairs of Composite Structures*. CRC Press; 2019.



<https://doi.org/10.1201/9780429198656>.

[12] Katnam KB, da Silva LFM, Young TM. Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities. *Prog Aerosp Sci* 2013;61:26–42.

<https://doi.org/10.1016/j.paerosci.2013.03.003>.

[13] Katnam KB, Comer AJ, Roy D, da Silva LFM, Young TM. Composite Repair in Wind Turbine Blades: An Overview. *J Adhes* 2014;91(1-2):113–139.

<https://doi.org/10.1080/00218464.2014.900449>.

[14] Banea MD, da Silva LFM. Adhesively bonded joints in composite materials: An overview. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2009;223(1):1–18.

<https://doi.org/10.1243/14644207jmda219>.

[15] Budhe S, Banea MD, de Barros S, da Silva LFM. An updated review of adhesively bonded joints in composite materials. *Int J Adhes Adhes* 2017;72:30–42.

<https://doi.org/10.1016/j.ijadhadh.2016.10.010>.

[16] Kupski J, Teixeira de Freitas S. Design of adhesively bonded lap joints with laminated CFRP adherends: Review, challenges and new opportunities for aerospace structures. *Compos Struct* 2021;268:113923.

<https://doi.org/10.1016/j.compstruct.2021.113923>.

[17] Budhe S, Banea MD, de Barros S. Bonded repair of composite structures in aerospace application: a review on environmental issues. *Appl Adhes Sci* 2018;6.

<https://doi.org/10.1186/s40563-018-0104-5>.

[18] Zhou W, Ji X-l, Yang S, Liu J, Ma L-h. Review on the performance improvements and non-destructive testing of patches repaired composites. *Compos Struct* 2021;263:113659.

<https://doi.org/10.1016/j.compstruct.2021.113659>.

[19] Paroissien E, Lachaud F, Schwartz S. Modelling load transfer in single-lap adhesively bonded and hybrid (bolted / bonded) joints. *Progress in Aerospace Sciences* 2022;130:100811.

<https://doi.org/10.1016/j.paerosci.2022.100811>

[20] Duong CN, Wang CH. *Composite Repair*. Elsevier; 2007.

<https://doi.org/10.1016/b978-0-08-045146-6.x5000-0>.

[21] Duong CN, Wang CH. *Bonded Joints and Repairs to Composite Airframe Structures*. Elsevier; 2015.

<https://doi.org/10.1016/C2013-0-00565-8>.

[22] L.F.M. da Silva, A. Öschner, R.D. Adams, RD (Editors), *Handbook of Adhesion Technology* (2 volumes) 2nd edition. 2018 Springer, Heidelberg (DE).

<https://doi.org/10.1007/978-3-319-55411-2>.

[23] Baker AA. Development of a hard-patch approach for scarf repair of composite structure. Defence Science and Technology Organisation Report TR-1892; 2006. p. 19.

[24] Whittingham B, Baker AA, Harman A, Bitton D. Micrographic studies on adhesively bonded scarf repairs to thick composite aircraft structure. *Composites Part A* 2009;40(9):1419–1432.

<https://doi.org/10.1016/j.compositesa.2008.12.011>.

[25] Psarras S, Loutas T, Papanoum M, Triantopoulos OK, Kostopoulos V. Investigating the effect of stepped scarf repair ratio in repair CFRP laminates under compressive loading. *J Compos Sci* 2020;4:153.

<https://doi.org/10.3390/jcs4040153>.

[26] Wang S, Xie Z, Li X. On adhesively bonded stepped-scarf joint: an analytical model and its validation. *Mech Adv Mater Struct* 2019;28:938–951.

<https://doi.org/10.1080/15376494.2019.1614699>.

[27] Pipes RB, Adkins DW. Strength and mechanics of bonded scarf joints for repair of composite materials. 1982 (Final Report, June 1981–May 1982)

[28] Adin H. The investigation of the effect of angle on the failure load and strength of scarf lap joints. *Int J Mech Sci* 2012;61(1):24–31.

<https://doi.org/10.1016/j.ijmecsci.2012.04.010>.

[29] Sun L, Tie Y, Hou Y, Lu X, Li C. Prediction of failure behavior of adhesively bonded CFRP scarf joints using a cohesive zone model. *Eng Fract Mech* 2020;228:106897.

<https://doi.org/10.1016/j.engfracmech.2020.106897>.

[30] Feng W, Xu F, Yuan J, Zang Y, Zhang X. Focusing on in-service repair to composite laminates of different thicknesses via scarf-repaired method. *Compos Struct* 2019;207:826–835.

<https://doi.org/10.1016/j.compstruct.2018.09.096>.

[31] Roy R, Kweon J-H, Nam Y. Tensile strength of multi-angle composite laminate scarf joints with FEM. *IOP Conference Series: Materials Science and Engineering* 2020;784:12007.

<https://doi.org/10.1088/1757-899X/784/1/012007>.

[32] Campilho RDSG, de Moura MFSF, Pinto AMG, Morais JLL, Domingues JJMS. Modelling the tensile fracture behaviour of CFRP scarf repairs. *Composites Part B* 2009;40:149–157.

<https://doi.org/10.1016/j.compositesb.2008.10.008>.

- [33] Truong V-H, Yoo J-S, Kim C-H, Park M-Y, Choi J-H, Kweon J-H. Failure load prediction of laminates repaired with a scarf-bonded patch using the damage zone method. *Adv Compos Mater* 2016;26:115–133.  
<https://doi.org/10.1080/09243046.2016.1232008>.
- [34] Kumar SB, Sridhar I, Sivashanker S, Osiyemi SO, Bag A. Tensile failure of adhesively bonded CFRP composite scarf joints. *Mater Sci Eng, B* 2006;132:113–120.  
<https://doi.org/10.1016/j.mseb.2006.02.046>.
- [35] Matta S, Ramji M. Prediction of mechanical behaviour of adhesively bonded CFRP scarf jointed specimen under tensile loading using localised DIC and CZM. *Int J Adhes Adhes* 2019;89:88–108.  
<https://doi.org/10.1016/j.ijadhadh.2018.12.002>.
- [36] Marques TPZ, Mayer S, Cândido GM, Rezende MC. Fractographic analysis of scarf repaired carbon/epoxy laminates submitted to tensile strength. *Eng Fail Anal* 2021;124:105374.  
<https://doi.org/10.1016/j.engfailanal.2021.105374>.
- [37] Yoo J-S, Truong V-H, Park M-Y, Choi J-H, Kweon J-H. Parametric study on static and fatigue strength recovery of scarf-patch-repaired composite laminates. *Compos Struct* 2016;140:417–432.  
<https://doi.org/10.1016/j.compstruct.2015.12.041>.
- [38] Ahn S-H, Springer GS. Repair of composite laminates-I : test results. *J Compos Mater* 1998;32(11):1036-1039.  
<https://doi.org/10.1177/002199839803201102>.
- [39] Sonat E, Özerinç S. Failure behavior of scarf-bonded woven fabric CFRP laminates. *Compos Struct* 2021;258:113205.  
<https://doi.org/10.1016/j.compstruct.2020.113205>.
- [40] Kwon YW, Slaff R, Bartlett S, Greene T. Enhancement of composite scarf joint interface strength through carbon nanotube reinforcement. *J Mater Sci* 2008;43(20):6695–6703.  
<https://doi.org/10.1007/s10853-008-2689-8>.
- [41] Kwon YW, Marrón A. Scarf Joints of Composite Materials: Testing and Analysis. *Appl Compos Mater* 2009;16(6):365–378.  
<https://doi.org/10.1007/s10443-009-9104-8>.
- [42] Campilho RDSG, de Moura MFSF, Ramantani DA, Morais JJJ, Domingues JJMS. Buckling Behaviour of Carbon–Epoxy Adhesively-Bonded Scarf Repairs. *J Adhes Sci Technol* 2009;23(10-11):1496–1513.  
<https://doi.org/10.1163/156856109x433045>.

- [43] Kumar SB, Sivashanker S, Bag A, Sridhar I. Failure of aerospace composite scarf-joints subjected to uniaxial compression. *Mater Sci Eng A* 2005;412:117–122.  
<https://doi.org/10.1016/j.msea.2005.08.033>.
- [44] Mollenhauer D, Fredrickson B, Schoepner G, Iarve E, Palazotto A. Analysis and measurement of scarf-lap and step-lap joint repair in composite laminates. In *Proceedings of the 16th International Conference on Composite Materials, Kyoto, Japan, 2 July 2007*.
- [45] Han Q, Liu B, Xie W. The tension failure mechanisms of composite stepped bonding repairs and joints for the aircraft primary load-bearing structures. *J Adhes Sci Technol* 2019;33:675–690.  
<https://doi.org/10.1080/01694243.2018.1558477>.
- [46] Collombet F, Davila Y, Avila S, Morales A, Crouzeix L, Grunevald Y-H, Hernandez H, Rocher N, Cénac F. Proof of a composite repair concept for aeronautical structures: a simplified method. *Mechanics & Industry* 2019;20(8):812.  
<https://doi.org/10.1051/meca/2020056>.
- [47] Xiaoquan C, Baig Y, Renwei H, Yujian G, Jikui Z. Study of tensile failure mechanisms in scarf repaired CFRP laminates. *Int J Adhes Adhes* 2013;41:177–185.  
<https://doi.org/10.1016/j.ijadhadh.2012.10.015>.
- [48] Breitzman TD, Iarve EV, Cook BM, Schoepner GA, Lipton RP. Optimization of a composite scarf repair patch under tensile loading. *Composites Part A* 2009;40(12):1921–1930.  
<https://doi.org/10.1016/j.compositesa.2009.04.033>.
- [49] Baig Y, Cheng X, Hasham HJ, Abbas M, Khan WA. Failure mechanisms of scarf-repaired composite laminates under tensile load. *J Braz Soc Mech Sci Eng* 2015;38(7):2069–2075.  
<https://doi.org/10.1007/s40430-015-0460-z>.
- [50] Chong HM, Liu SL, Subramanian AS, Ng SP, Tay SW, Wang SQ, Feih S. Out-of-autoclave scarf repair of interlayer toughened carbon fibre composites using double vacuum debulking of patch. *Composites Part A* 2018;107:224–234.  
<https://doi.org/10.1016/j.compositesa.2018.01.001>.
- [51] Darwish FH, Shivakumar KN. Experimental and Analytical Modeling of Scarf Repaired Composite Panels. *Mech Adv Mater Struct* 2013;21(3):207–212.  
<https://doi.org/10.1080/15376494.2013.834096>.
- [52] van Ingen JW, Vlot, A. Stress analysis of adhesively bonded single lap joints. (Report LR-740). Delft University of Technology 1993.

- [53] da Silva LFM, das Neves PJC, Adams RD, Spelt JK. Analytical models of adhesively bonded joints—Part I: Literature survey. *Int J Adhes Adhes* 2009;29:319–330.  
<https://doi.org/10.1016/j.ijadhadh.2008.06.005>.
- [54] da Silva LFM, das Neves PJC, Adams RD, Wang A, Spelt JK. Analytical models of adhesively bonded joints—Part II: Comparative study. *International Journal of Adhesion and Adhesives* 2009;29:331–341.  
<https://doi.org/10.1016/j.ijadhadh.2008.06.007>.
- [55] Wong EH, Liu J. Interface and interconnection stresses in electronic assemblies – A critical review of analytical solutions. *Microelectron Reliab* 2017;79:206–220.  
<https://doi.org/10.1016/j.microrel.2017.03.010>.
- [56] He X. A review of finite element analysis of adhesively bonded joints. *Int J Adhes Adhes* 2011;31(4):248–264.  
<https://doi.org/10.1016/j.ijadhadh.2011.01.006>.
- [57] Ramalho LDC, Campilho RDSG, Belinha J, da Silva LFM. Static strength prediction of adhesive joints: A review. *Int J Adhes Adhes* 2020;96:102451.  
<https://doi.org/10.1016/j.ijadhadh.2019.102451>.
- [58] Tserpes K, Barroso-Caro A, Carraro PA, Beber VC, Floros I, Gamon W, Kozłowski M, Santandrea F, Shahverdi M, Skejić D, Bedon C, Rajčić V. A review on failure theories and simulation models for adhesive joints. *J Adhes* 2021:1–61.  
<https://doi.org/10.1080/00218464.2021.1941903>.
- [59] Arnovljevic I, 1909. Das Verteilungsgesetz der Tiefspannungen in axial beanspruchten Verbundstaben. *Z.F. Archund-Ing-Wesen*, 55, 415-418.
- [60] Erdogan F, Ratwani M. Stress Distribution in Bonded Joints. *J Compos Mater* 1971;5:378–393.  
<https://doi.org/10.1177/002199837100500308>.
- [61] Volkersen O. Die Nietkraftverteilung in zugbeanspruchten Nietverbindungen mit konstanten Laschenquerschnitten. *Lufsfahrtforschung* 1938:15:41-47.
- [62] Hart-Smith, LJ. Adhesive-bonded scarf and stepped-lap joints. Douglas Aircraft Co., NASA Langley report CR-112237, 1974.  
<https://ntrs.nasa.gov/citations/19740005084>
- [63] Ahn S-H, Springer G. Repair of Composite Laminates-II: Models. *J Compos Mater* 1998;32(11):1076–1114.  
<https://doi.org/10.1177/002199839803201103>.

- [64] Mortensen F, Thomsen OT. Simplified linear and non-linear analysis of stepped and scarfed adhesive-bonded lap-joints between composite laminates. *Compos Struct* 1997;38:281–294.  
[https://doi.org/10.1016/S0263-8223\(97\)00063-9](https://doi.org/10.1016/S0263-8223(97)00063-9).
- [65] Li D, Qing G, Liu Y. A three-dimensional semi-analytical model for the composite laminated plates with a stepped lap repair. *Compos Struct* 2011;93(7):1673–1682.  
<https://doi.org/doi:10.1016/j.compstruct.2011.01.013>.
- [66] Harman AB, Wang CH. Improved design methods for scarf repairs to highly strained composite aircraft structure. *Compos Struct* 2006;75(1-4):132–144.  
<https://doi.org/doi:10.1016/j.compstruct.2006.04.091>.
- [67] Liu B, Xu F, Feng W, Yan R, Xie W. Experiment and design methods of composite scarf repair for primary-load bearing structures. *Composites Part A* 2016;88:27–38.  
<https://doi.org/10.1016/j.compositesa.2016.05.011>.
- [68] Tsai MY, Oplinger DW, Morton J. Improved theoretical solutions for adhesive lap joints. *Int J Solids Struct* 1998;35(12):1163–1185.  
[https://doi.org/10.1016/S0020-7683\(97\)00097-8](https://doi.org/10.1016/S0020-7683(97)00097-8).
- [69] Ordonneau B, Paroissien E, Salaün M, Benitez-Martin A, Schwartz S, Malrieu J, Guigue A. A simplified modal analysis of a single lap bonded joint using the macro-element technique. *Int J Solids Struct* 2022:111631. In press.  
<https://doi.org/10.1016/j.ijsolstr.2022.111631>.
- [70] Sánchez-Arce IJ, Ramalho LDC, Campilho RDSG, Blinha J. Material non-linearity in the numerical analysis of SLJ bonded with ductile adhesives: A meshless approach. *Int J Adhes Adhes*, 2021;104:102716.  
<https://doi.org/10.1015/J.ijadhadh.2020.102716>
- [71] Ramalho LDC, Sánchez-Arce IJ, Campilho RSDG, Belinha J. Strength prediction of composite single lap joints using the radial point interpolation method. *Compos Struct* 2021;259:113228  
<https://doi.org/10.1016/j.compstruct.2020.113228>
- [72] Ridha M, Tan VBC, Tay TE. Traction–separation laws for progressive failure of bonded scarf repair of composite panel. *Compos Struct* 2011;93(4):1239–1245.  
<https://doi.org/10.1016/j.compstruct.2010.10.015>.
- [73] Breitzman TD, Cook BM, Schoeppner GA, Iarve EV. Composite Scarf Repair Patch Optimization Under Uniaxial Loading Conditions. Volume 3: Design and Manufacturing, ASMECD; 2007.

<https://doi.org/10.1115/IMECE2007-43588>.

[74] Odi RA, Friend CM. A Comparative Study of Finite Element Models for the Bonded Repair of Composite Structures. *J Reinf Plast Compos* 2002;21:311–332.

<https://doi.org/10.1177/0731684402021004257>.

[75] Hayes-Griss JM, Orifici AC, Khatibi AA. An improved progressive failure modelling and damage tolerant design methodology for composite scarf joints with bondline flaws. *Composites Part A* 2020;131:105776.

<https://doi.org/10.1016/j.compositesa.2020.105776>.

[76] Tashi S, Abedian A. A comprehensive 2 Dimensional and 3 Dimensional FEM study of scarf repair for a variety of common composite laminates under in-plane uniaxial and equibiaxial loadings. *Int J Adhes Adhes* 2022;114:103092.

<https://doi.org/10.1016/j.ijadhadh.2022.103092>.

[77] Riccio A, Ricchiuto R, Di Caprio F, Sellitto A, Raimondo A. Numerical investigation of constitutive material models on bonded joints in scarf repaired composite laminates. *Eng Fract Mech* 2017;173:91–106.

<https://doi.org/10.1016/j.engfracmech.2017.01.003>.

[78] Pinto AMG, Campilho RDSG, de Moura MFSF, Mendes IR. Numerical evaluation of three-dimensional scarf repairs in carbon-epoxy structures. *Int J Adhes Adhes* 2010;30(5):329–337.

<https://doi.org/doi:10.1016/j.ijadhadh.2009.11.001>.

[79] Pierce RS, Falzon BG. Modelling the size and strength benefits of optimised step/scarf joints and repairs in composite structures. *Composites Part B* 2019;173:107020.

<https://doi.org/10.1016/j.compositesb.2019.107020>.

[80] Goh J Y, Georgiadis S, Orifici A C, Wang C H. Effects of bondline flaws on the damage tolerance of composite scarf joints. *Composites Part A* 2013;55:110–119.

<https://doi.org/10.1016/j.compositesa.2013.07.017>.

[81] Hill R. A theory of the yielding and plastic flow of anisotropic metals. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 1948;193:281–297.

<https://doi.org/10.1098/rspa.1948.0045>.

[82] Tsai SW, Wu EM. A General Theory of Strength for Anisotropic Materials. *J Compos Mater* 1971;5(1):58–80.

<https://doi.org/10.1177/002199837100500106>.



- [83] Hashin Z. Failure Criteria for Unidirectional Fiber Composites. *J Appl Mech* 1980;47(2):329–334.  
<https://doi.org/10.1115/1.3153664>.
- [84] Odi RA, Friend CM. An improved 2D model for bonded composite joints. *Int J Adhes Adhes* 2004;24(5):389–405.  
<https://doi.org/10.1016/J.IJADHADH.2001.06.001>.
- [85] Wang CH, Gunnion AJ. On the design methodology of scarf repairs to composite laminates. *Compos Sci Technol* 2008;68(1):34–46.  
<https://doi.org/10.1016/J.COMPSCITECH.2007.05.045>.
- [86] Iarve E V, Kim R, Mollenhauer D. Three-dimensional stress analysis and Weibull statistics based strength prediction in open hole composites. *Composites Part A* 2007;38(1):174–185.  
<https://doi.org/h10.1016/j.compositesa.2006.01.004>.
- [87] Iarve E., Breitzman TD, Cook BM, Schoeppner GA and Mollenhauer DH, Tensile failure prediction and measurement in composite scarf repair”, In: *Proceedings of the 16th International Conference on Composite Materials Kyoto, 2007*.
- [88] Doitrand A, Fagiano C, Carrère N, Chiaruttini V, Hirsekorn M. Damage onset modeling in woven composites based on a coupled stress and energy criterion. *Eng Fract Mech* 2017;169:189–200.  
<https://doi.org/10.1016/j.engfracmech.2016.11.021>.
- [89] Doitrand A, Leguillon D. Comparison between 2D and 3D applications of the coupled criterion to crack initiation prediction in scarf adhesive joints. *Int J Adhes Adhes* 2018;85:69–76.  
<https://doi.org/https://doi.org/10.1016/j.ijadhadh.2018.05.022>.
- [90] Elices M, Guinea G V, Gómez J, Planas J. The cohesive zone model: advantages, limitations and challenges. *Eng Fract Mech* 2002;69(2):137–163.  
[https://doi.org/10.1016/S0013-7944\(01\)00083-2](https://doi.org/10.1016/S0013-7944(01)00083-2).
- [91] Campilho RDSG, Banea MD, Neto, JA, Silva LD. Modelling adhesive joints with cohesive zone models: effect of the cohesive law shape of the adhesive layer. *Int J Adhes Adhes*, 2013;44:48-56.  
<https://doi.org/10.1016/j.ijadhadh.2013.02.006>
- [92] Liu P, Zheng J. Progressive failure analysis of carbon fiber/epoxy composite laminates using continuum damage mechanics. *Mater Sci Eng A* 2008;485(1-2):711-717.  
<https://doi.org/10.1016/j.msea.2008.02.023>



- [93] Psarras S, Loutas T, Galanopoulos G, Karamadoukis G, Sotiriadis G, Kostopoulos V. Evaluating experimentally and numerically different scarf-repair methodologies of composite structures. *Int J Adhes Adhes* 2020;97:102495.  
<https://doi.org/https://doi.org/10.1016/j.ijadhadh.2019.102495>.
- [94] Hayes-Griss JM, Gunnion AJ, Khatibi AA. Damage tolerance investigation of high-performance scarf joints with bondline flaws under various environmental, geometrical and support conditions. *Composites Part A* 2016;84:246–255.  
<https://doi.org/10.1016/j.compositesa.2016.02.005>.
- [95] Wang C H, Venugopal V, Peng L. Stepped Flush Repairs for Primary Composite Structures. *J Adhes* 2015;91:95–112.  
<https://doi.org/10.1080/00218464.2014.896212>.
- [96] Damghani M, Bolanos S, Chahar A, Matthews J, Atkinson GA, Murphy A, Edwards T. Design, novel quality check and experimental test of an original variable length stepped scarf repair scheme. *Composites Part B* 2022;230:109542.  
<https://doi.org/10.1016/j.compositesb.2021.109542>.
- [97] Truong V-H, Kwak B-S, Roy R, Kweon J-H. Cohesive zone method for failure analysis of scarf patch-repaired composite laminates under bending load. *Compos Struct* 2019;222:110895.  
<https://doi.org/10.1016/j.compstruct.2019.110895>.
- [98] Campilho RDSG, de Moura MFSF, Pinto AMG, Ramantani DA, Morais JLL, Domingues JJMS. Strength Prediction of Adhesively-Bonded Scarf Repairs in Composite Structures under Bending. *MSF* 2010;636–637:233–8.  
<https://doi.org/10.4028/www.scientific.net/MSF.636-637.233>.
- [99] Rice JR. A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks. *J Appl Mech* 1968;35(2):379–386.  
<https://doi.org/10.1115/1.3601206>.
- [100] de Moura MFSF. Application of Cohesive Zone Modeling to Composite Bonded Repairs. *J Adhes* 2015;91(1-2):71–94.  
<https://doi.org/10.1080/00218464.2014.901912>.
- [101] Silva DFO, Campilho RDSG, Silva FJG, Carvalho UTF. Application a direct/cohesive zone method for the evaluation of scarf adhesive joints. *Appl Adhes Sci* 2018;6:13.  
<https://doi.org/10.1186/s40563-018-0115-2>

- [102] Jaillon A, Jumel J, Lachaud F, Paroissien E. Mode I cohesive zone model parameters identification and comparison of measurement techniques based on uncertainty estimation. *Int J Solids Struct* 2020;191-192:577–587.  
<https://doi.org/10.1016/j.ijsolstr.2019.12.014>.
- [103] Lélías G, Paroissien E, Lachaud F, Morlier J. Experimental characterization of cohesive zone models for thin adhesive layers loaded in mode I, mode II, and mixed-mode I/II by the use of a direct method. *Int J Solids Struct* 2019;158:90-115.  
<https://doi.org/10.1016/j.ijsolstr.2018.09.005>
- [104] Huo X, Luo Q, Li Q, Zheng G, Sun G. On characterization of cohesive zone model (CZM) based upon digital image correlation (DIC) method. *Int J Mech Sci* 2022;215:106921.  
<https://doi.org/10.1016/j.ijmecsci.2021.106921>.
- [105] Moreira RDF, de Moura MFSF, Silva FGA, Reis JP. High-cycle fatigue analysis of adhesively bonded composite scarf repairs. *Composites Part B* 2020;190:107900.  
<https://doi.org/10.1016/j.compositesb.2020.107900>.
- [106] Soutis C, Hu FZ. Failure Analysis of Scarf-Patch-Repaired Carbon Fiber/Epoxy Laminates Under Compression. *AIAA J* 2000;38(4):737–740.  
<https://doi.org/https://doi.org/10.2514/2.1027>.
- [107] Gunnion AJ, Herszberg I. Parametric study of scarf joints in composite structures. *Compos Struct* 2006;75(1):364–376.  
<https://doi.org/10.1016/j.compstruct.2006.04.053>.
- [108] Bendemra H, Compston P, Crothers PJ. Optimisation study of tapered scarf and stepped-lap joints in composite repair patches. *Compos Struct* 2015;130:1–8.  
<https://doi.org/10.1016/j.compstruct.2015.04.016>.
- [109] Liu B, Xu F, Yan R, Ji Z, Li W. Parameters sensitivity and optimization for composite scarf repair. *J Reinf* 2014;33(23):2164-2173.  
<https://doi.org/0.1177/0731684414555744>
- [110] Damghani M, Bakunowicz J, Murphy A. Understanding the influence of laminate stacking sequence on strain/stress concentrations in thin laminates at repair holes with large scarf angles. *J Compos Mater* 2019;53(28-30):4273-4284.  
<https://doi.org/10.1177/0021998319855772>
- [111] Niedernhuber M, Holtmannspötter J, Ehrlich I. Fiber-oriented repair geometries for composite materials. *Composites Part B* 2016;94:327–337.  
<https://doi.org/10.1016/j.compositesb.2016.03.027>.

- [112] Wang CH, Gunnion AJ. Optimum shapes for minimising bond stress in scarf repairs. *Aust J Mech Eng* 2008;6(2):153–158.  
<https://doi.org/10.1080/14484846.2008.11464570>.
- [113] Wang CH, Gunnion AJ. Optimum shapes of scarf repairs. *Composites Part A* 2009;40(9):1407–1418.  
<https://doi.org/10.1016/j.compositesa.2009.02.009>.
- [114] Kashfuddoja M, Ramji M. Design of optimum patch shape and size for bonded repair on damaged Carbon fibre reinforced polymer panels. *Mater Design* 2014;54:174–183.  
<https://doi.org/https://doi.org/10.1016/j.matdes.2013.08.043>.
- [115] Pitanga MY, Cioffi MOH, Voorwald HJC, Wang CH. Reducing repair dimension with variable scarf angles. *Int J Adhes Adhes* 2021;104:102752.  
<https://doi.org/10.1016/j.ijadhadh.2020.102752>.
- [116] Sun C, Zhao W, Zhou J, Altenaiji M, Cantwell WJ, Wang Q Y, Guan ZW. Mechanical behaviour of composite laminates repaired with a stitched scarf patch. *Compos Struct* 2021;255:112928.  
<https://doi.org/10.1016/j.compstruct.2020.112928>.
- [117] Crane R, Dillinham G, Oakley B. Progress in the Reliability of Bonded Composite Structures. *Appl Compos Mater* 2017;24:221-223.  
<https://doi.org/10.1007/s10443-016-9523-2>
- [118] Omalrey, Jayasree N, Mihalis K. Defects and uncertainties of adhesively bonded composite joints. *SN Appl Sci* 2021;3:769.  
<https://doi.org/10.1007/s42452-021-04753-8>
- [119] Diaz J, Pereira F, Romera L, Hernandez S. Probabilistic assessment of the structural failure of single-lap bonded joints. *Int J Adhes Adhes* 2012;37:70-78.  
<https://doi.org/10.1016/j.ijadhadh.2012.01.020>
- [120] Feng W, Xu F, Xie W, Zhang M. Fatigue performances and reliability analysis of fatigue life for scarf-repaired composite laminates. *J Adhes* 2020;98(4):367-389.  
<https://doi.org/10.1080/00218464.2020.1834389>
- [121] Kimiaiefar A, Toft H, Lund E, Thomsen OT, Sørensen JD. Reliability analysis of adhesive bonded scarf joints. *Eng Struct* 2012;35:281–287.  
<https://doi.org/10.1016/j.engstruct.2011.11.013>.
- [122] Sato C, Ikegami K. Dynamic deformation of lap joints and scarf joints under impact loads. *Int J Adhes Adhes* 2000;20(1):17–25.  
[https://doi.org/10.1016/S0143-7496\(99\)00010-X](https://doi.org/10.1016/S0143-7496(99)00010-X).

- [123] Kumari P, Alam A, Saahil. Influence of the impact position on scarf repair composite under low velocity impact: FEA investigation. *Mater Today: Proc* 2021;38:3005–3013.  
<https://doi.org/10.1016/j.matpr.2020.09.323>.
- [124] Kumari P, Alam A, Saahil. Multi-impact on scarf repaired composite laminates: FE investigation. *Mater Today: Proc* 2021;46:645–650.  
<https://doi.org/10.1016/j.matpr.2020.11.584>.
- [125] Cheng X, Du X, Zhang J, Zhang J, Guo X, Bao J. Effects of stacking sequence and rotation angle of patch on low velocity impact performance of scarf repaired laminates. *Composites Part B* 2018;133:78–85.  
<https://doi.org/10.1016/j.compositesb.2017.09.020>.
- [126] Shufeng L, Xiaoquan C, Yunyan X, Jianwen B, Xin G. Study on impact performances of scarf-repaired carbon fiber reinforced polymer laminates. *J Reinf* 2015;34(1):60-71.  
<https://doi.org/10.1177/0731684414562465>
- [127] Kumari P, Wang J, Saahil. Residual Tensile Strength of the Multi-Impacted Scarf-Repaired Glass Fiber-Reinforced Polymer (GFRP) Composites. *Materials* 2018;11(12):2351.  
<https://doi.org/10.3390/ma11122351>.
- [128] Kumari P, Wang J, Saahil. Tensile After Impact Test of Scarf-Repaired Composite Laminates. *Arab J Sci Eng* 2019;44:7677–7697.  
<https://doi.org/10.1007/s13369-019-03857-z>
- [129] Hoshi H, Nakano K, Iwahori Y. Study on repair of CFRP laminates for aircraft structures. In: *Proceedings of the 16th International Conference on Composite Materials Kyoto, 2007*.  
[http://www.iccm-central.org/Proceedings/ICCM16proceedings/contents/pdf/ThuI/ThIA2-01ge\\_hoshih226587p.pdf](http://www.iccm-central.org/Proceedings/ICCM16proceedings/contents/pdf/ThuI/ThIA2-01ge_hoshih226587p.pdf)
- [130] Liu B, Han Q, Zhong X, Lu Z. The impact damage and residual load capacity of composite stepped bonding repairs and joints. *Composites Part B* 2019;158:339–351.  
<https://doi.org/10.1016/j.compositesb.2018.09.096>.
- [131] Liu B, Xu F, Qin J, Lu Z. Study on impact damage mechanisms and TAI capacity for the composite scarf repair of the primary load-bearing level. *Compos Struct* 2017;181:183–193.  
<https://doi.org/10.1016/j.compstruct.2017.08.087>.
- [132] FAA Federal Aviation Regulations (FARS) Part 23, Section 573-Damage Tolerance and Fatigue Evaluation of Structure (Federal Aviation Administration, Washington, DC, 2005).
- [133] FAA, Composite Aircraft Structure: Advisory Circular (AC) 20-107B, Change 1 2010.

- [134] Kosmann JD, Holzhüter D, Gunnion AJ, Hühne C. Experimental and Finite Elements Analysis of Bondline Flaw Criticality in Composite Scarf Joints. In : Proceedings of the 16th European Conference on Composite Materials, Seville, 22-26 June 2007.
- [135] Wu C, Chen C, He L, Yan W. Comparison on damage tolerance of scarf and stepped-lap bonded composite joints under quasi-static loading. *Composites Part B* 2018;155:19–30.  
<https://doi.org/10.1016/j.compositesb.2018.08.031>.
- [136] Jen Y-M. Fatigue life evaluation of adhesively bonded scarf joints. *Int J Fatigue* 2012;36(1):30–39.  
<https://doi.org/10.1016/j.ijfatigue.2011.08.018>.
- [137] Stape T H S, Tulkki O, Salim I A, Jamal K N, Mutluay M M, Tezvergil-Mutluay A. Composite repair: On the fatigue strength of universal adhesives. *Dent Mater* 2022;38(2):231–241.  
<https://doi.org/10.1016/j.dental.2021.12.003>.
- [138] Guan W, Su Y, Tong G. Static and Fatigue Properties of Scarf Patch Repaired Composite Laminates: An Experimental Study. *IOP Conf. Ser.: Mater. Sci. Eng.* 2019;677(2):022010  
<https://doi.org/10.1088/1757-899X/677/2/02201>
- [139] Wong L, Chowdhury N, Wang J, Chiu W K, Kodikara J. Fatigue Damage Monitoring of a Composite Step Lap Joint Using Distributed Optical Fibre Sensors. *Materials* 2016;9(5):374.  
<https://doi.org/10.3390/ma9050374>.
- [140] Moreira R D F, de Moura M F S F, Silva F G A, Ramírez F M G, Silva F D R. Numerical comparison of several composite bonded repairs under fatigue loading. *Compos Struct* 2020;243:112250.  
<https://doi.org/10.1016/j.compstruct.2020.112250>.

## Figure captions

Figure 1: Flush repair types

Figure 2: Specimen configurations used in flush repair studies

Figure 3: Typical tensile failure modes of flush repairs

Figure 10 : Normalized shear stress distribution along composite stepped joint bondline

Figure 11 : Different types of meshes to model flush repairs

Figure 6: Bilinear traction-separation law

Figure 7: Analysis with step-by-step progressive material degradation flow chart

Figure 8: Matching and overlapping patches for stepped repairs

Figure 9: Flush repair with overply

Figure 10: Schematic visualization of variable scarf angle introduced by [115]

Figure 11: Schematic visualization of variably-stepped laminates design introduced by [96,111]

Figure 12: Scarf repair with bondline flaw