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Review

A Literature Review on Crack Arrest Features for Composite Materials and Composite Joints with a Focus on Aerospace Applications

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Abstract: Crack propagation within composite materials or along the interface of composite joints is a phenomenon that might result in catastrophic failure of a structure. When the factor of safety is involved in the integrity of a structure, fail-safe design becomes crucial by embedding failure-confining features. This article reviews the research work that has been carried out on such crack-arresting features (CAFs) for composite laminates, composite-to-composite joints and composite-to-metal joints. The methodology of descriptive–narrative systematic literature review was employed in order to present the state of the research in the field. Crack stopping along adhesively joined interfaces was the most common subject encountered in the literature, while other types of secondary bonding such as thermoplastic welding were quite limited. The types of the CAFs were mainly categorized by means of their integration into the structure, namely "production" and "post-production". For each method reviewed, the common aspects of the CAFs in question are discussed as well as the outcome of the work.

Keywords: crack arrest features; adhesive joints; composite materials; damage tolerance

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1. Introduction

The integration of composite materials in the aerospace industry has been proven critical for weight reduction and the load-bearing capability of the structures [1]. Thermoset composite materials have been in the foreground of research for the past decades, while thermoplastic materials are also being investigated as a sustainable alternative for use in the aerospace industry [2]. The integration of composites in such critical structures, however, has arisen concerns about their resistance to damage. The major cause of catastrophic failures found in such materials is the growth of interlaminar cracking, gradually propagating through the entire component [3]. Consequently, the need of confining this phenomenon has led many researchers to the development and investigation of mechanisms able to stop or retard the composites' interlaminar crack propagation.

Another major concern for these materials is the method of joining when used in load-carrying parts. Mechanical fastening, such as bolting and pinning, requires drilling procedures resulting in stress concentration at the affected area, while the inserted metallic fasteners increase the overall weight of the structure, thus mitigating the advantages of the composite materials.

Dustless joining techniques, including adhesive bonding and thermoplastic welding, are very promising methods to replace mechanical fastening, offering more uniform stress distribution without the integration of considerable extra weight [4–7]. However, adhesive bonding cannot be used as a standalone joining method in primary parts of aircrafts. The strict rules imposed by international airworthiness organizations define that joints within the primary structural elements of the aircraft must be fail-safely designed, usually by the integration of crack-confining features. As a matter of fact, according to the European Union Aviation Safety Agency's (EASA) AMC 20-29 regulations report, adhesive joints in primary structures must comply with the following [8,9]: "For any bonded joint, the failure of which would result in catastrophic loss of the aeroplane, the limit load capacity must be substantiated by one of the following methods:

1. The maximum disbond of each bonded joint consistent with the capability to withstand the required loads must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features; or
2. Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint; or
3. Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint."

Similar regulatory measures are advised by other worldwide organizations such as the Federal Aviation Agency (FAA), stating that "Arrested growth may occur due to design features such as a geometry change, reinforcement, thickness change, or a structural joint".

Even though the requirement is limited to adhesively bonded structures, it can be desirable to also apply the requirement to thermoplastic welded joints. The integration of crack arrest features (CAFs) seems to be the most viable technique for the compliance of dustless joining and their usage in critical, load-bearing parts.

Various types of such crack-stopping mechanisms have been under research, focusing mainly on the adhesive bonding of thermoset composite materials. The findings in the literature for thermoplastic welding crack stoppers or other joining techniques are very limited [10]. Thus, the vast majority of the findings in the review were focused on adhesively bonded joints. The technologies featured in such joints, however, could be potentially transferrable to any type of interface. In general, very common is the use of pinning combined with adhesively bonded joints as a through-the-thickness reinforcement, creating a crack-stopping point. Similarly, bolts and other types of fasteners have been investigated as crack arresters. Other features that can be found in the literature are architecture-based stoppers, with their integration into the bond's production phase.

The present review [11,12] aims to provide an overall presentation of the research that has been conducted on these crack arrest features and set the ground for further development on the topic. Each feature was categorized based on its means of installation (production installation–postproduction installation). Every literature finding was sorted based on the research methodology applied, namely experimental or numerical modeling, as well (Table 1).

2. Research Methodology

2.1. Inclusion Criterion

The included studies were focused on crack arrest features applied in both thermoset and thermoplastic matrix composites, with composite joints and hybrid joints (composite-to-metal). Both production-inserted and postproduction-inserted crack-stopping methods fell under the inclusion criterion of the review. Only research works written in the English language were considered.

2.2. Literature Identification

Literature searching was conducted based on keywords such as "Crack arrest Feature", "Crack stopper" and "Crack arrestment". Works that are included in the review were retrieved from reputable publishers and scientific databases. The main sources were "Multidisciplinary Digital Publishing Institute", "Science Direct", "Springer", "Taylor and Francis". The "Google Scholar" scientific database was also considered mainly for the retrieval of conference proceedings articles.

2.3. Quality and Eligibility Assessment

The quality of the scientific sources included in the present review was initially ensured by selecting peer-reviewed articles published by well-respected journals in the field of composite materials and composite joints. Furthermore, a thorough study of each work was followed in order to ascertain the fulfillment of the given eligibility criteria.

2.4. Screening for Inclusion

Each candidate research paper and work to be included in this review was evaluated based on relevance to the topic under study. Firstly, the title and the abstract of all relevant articles were examined, and articles not meeting the inclusion criterion were rejected. After the full evaluation of the articles, forward and backward searching was utilized through the references. This procedure continued iteratively until no other relevant works could be retrieved. Finally, the total number of literature findings that met the established criterion was 81, justifying the relatively short length of the present review.

3. Crack Arrest Features for Composite Joints

3.1. Production-Based Crack Arrest Features

The research work reported in this chapter focuses on experimental testing and modeling of crack arrest features that are integrated into the joint through the design phase of the joining. Such a feature is found in the work of Löbel et al. [13,14], where they studied the impact of a hybrid bondline (Figure 1). Specifically, a ductile thermoplastic inlay was embedded in the brittle epoxy bond, and the crack-arresting capability was tested experimentally through double cantilever beam (DCB) and single-lap shear (SLS) tests. The results of the DCB test proved that the crack-stopping capability of the specific CAF increased the necessary load for debonding, although the SLS tests showed only a minor impact on the results in relation to the specimen without CAFs. The authors also noted that the effectiveness of the studied arrestor was crack-path-dependent, as deflection from the bondline and subsequent intralaminar damage would render the feature useless. Thus, the joint design, the CAF's placement and the laminates' ply sequence should be selected with care.

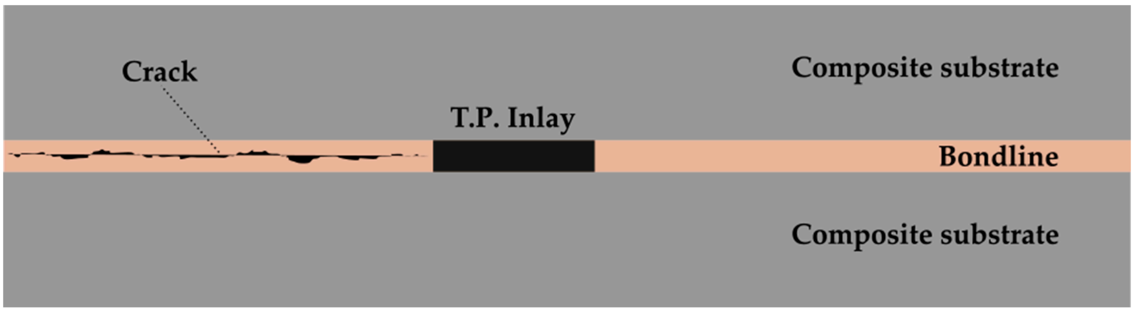

Figure 1. The hybrid bondline concept with embedded thermoplastic inlays.

A similar study was conducted by Malkin et al. [15], where they used a commercially available rubber particulate toughness modifier in carbon-reinforced epoxy matrix laminates. They studied experimentally and analytically the impact of low-to-high and high-to-low toughness steps in the bond on the crack-front propagation under peeling mode. The work included testing of the toughness transition using two designs, namely a discrete straight-line step and a "zig-zag" bio-inspired transition area. The results showed the ability of the low-to-high toughness step to act as a CAF, while the opposite configuration resulted in unstable crack growth due to the lack of excess residual strain energy along the interface. This instability, however, was able to be inhibited via the staggered bio-inspired transition region (Figure 2).

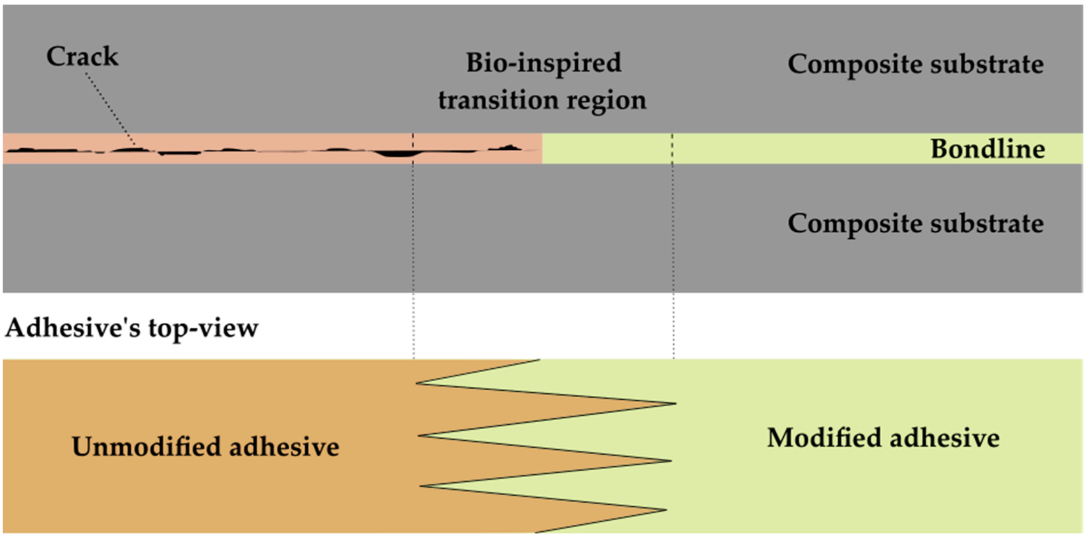

Figure 2. The modified adhesive transition concept with bio-inspired staggered region.

Other researchers have also conducted studies on delamination arrest in adhesively bonded thermoset composite materials by means of a soft interlayer insertion [16–19]. Yudahnto et al. [13] studied 3D-printed, wavy nylon inserts within the adhesive bondline as a fracture toughness enhancement. As shown in Mode-I testing, the thermoplastic insert managed to retard crack propagation by "strand" bridging, which is the extrinsic toughening mechanism present in the configuration.

Tao et al. [20] incorporated adhesive ligaments in thermoset composite joints as a bridging triggering technique by alternatively patterning the top and bottom interfaces (Figure 3). The authors employed the use of two-dimensional finite element analyses to study crack propagation under Mode-I loading. Different geometries and interface properties were examined, and the results showed that the energy dissipation can be improved as much as twice from the neat bond, mainly through proper interface property optimization.

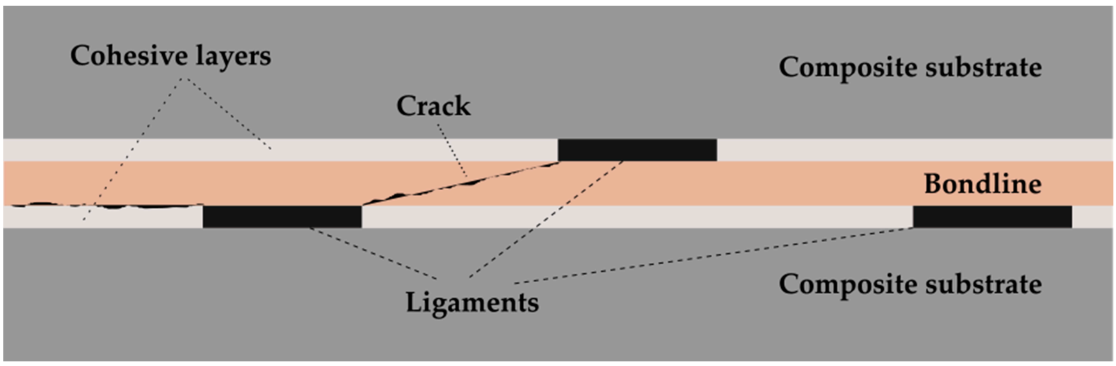

Figure 3. The double interface concept with integrated adhesive ligaments to trigger crack bridging.

The investigation of such softening modifications along the crack path is not only limited to adhesive bonding, as similar works can be found studying the interlaminar damage suppression in a similar manner [16,19]. Yasaee et al. [18] have investigated the effect of interleaves' embedment into a laminated E-glass/epoxy composite material. The interleaving materials studied were thermoplastic film, thermoplastic particles, chopped E-glass and aramid fibers, E-glass/epoxy prepreg orthogonally aligned, thermoset adhesive film and thermoset adhesive particles. The experimental campaign included Mode-I loading of the enriched specimens in order to determine the crack-stopping capabilities of the various materials inserted in the failure-propagating interface. Apparently, the thermoplastic polyimide film insert presented the highest increase in the critical propagation fracture toughness, while the nylon particles and thermoset foam resulted in a value decline.

Hishada et al. [21] examined the introduction of an interlocking fiber-based crack arrester at a T-joint numerically and experimentally. The study revealed that it is crucial that this particular CAF is located near the deltoid, while crack propagation arrestment depends on the type of the arrester configuration. Research work by Mincakuchi & Takeda [22,23] examined the influence of a fiber-based x-type crack stopper (Figure 4) in a crack lap shear joint under fatigue loading conditions as well as under quasistatic peeling mode. It was concluded both from testing and numerical investigations that the mechanism stopping the crack growth was the suppression of crack opening and secondary bending.

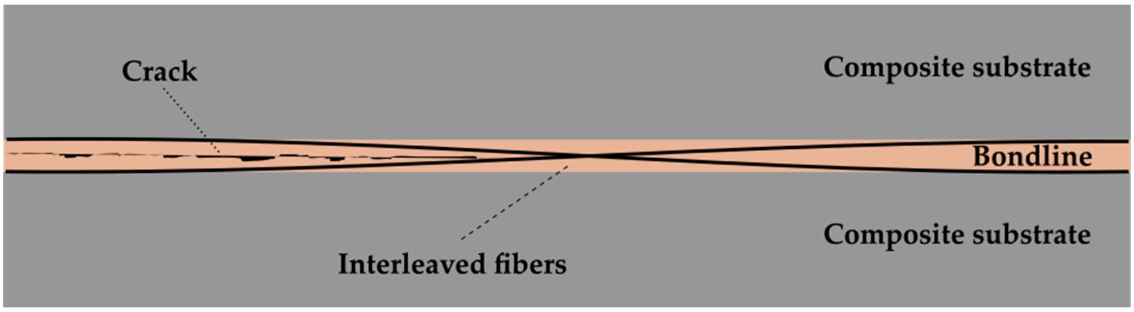

Figure 4. The interleaved fibers' concept as a crack arrester.

Another material-morphology-induced CAF examined by Tserpes et al. [24,25] is the introduction of corrugation at the joint overlap (Figure 5). The existence of corrugation was investigated experimentally through double cantilever beam and crack lap shear tests. The authors concluded that "For the DCB specimen, both the experimental and numerical results showed that the corrugation managed to stop the crack growth in the adhesive. On the contrary, in the CLS specimen, the corrugation did not manage to stop crack growth as the specimen was fully disbonded". Furthermore, a sensitivity analysis on the diameter and the height of the corrugation through finite element software was performed, resulting in no major deviation from the reference geometry. The CAF in question under tensile loading, however, was found to result in high stress concentration around the feature, which may end up in rapid substrates' fracture.

Figure 5. Corrugation formed into a thermoset matrix woven composite laminate [24].

Another toughening strategy followed by Maloney & Fleck [26] was the introduction of periodic stop holes along an epoxy bondline. Mode-I loading was chosen for testing the crack arrest feature's effectiveness, resulting in the conclusion that the toughening was influenced by the stop hole diameter in relation to the crack's tip plastic zone size. Furthermore, the authors included in the study the integration of copper mesh wire in the joint, showing that toughening can be achieved by crack bridging.

Precuring z-pinning was studied by Chang et al. [27], where fiber pins were used as crack stoppers (Figure 6). The authors conducted experiments on single-lap shear configurations with thermoset composite materials for different pin diameters. The joint benefited from up to a 40% increase in static strength and fatigue strength. The mechanisms of crack propagation were evaluated systematically through fractographic analysis. The final failure was caused by pullout and shearing of the fibers for lower z-pin contents. However, the increment in the density of the inserted pins resulted in the differentiation of the failure type from cohesive failure to substrates' fracture due to damage to the in-plane fibers. Similarly, Koh et al. [28] conducted tests on composite single-lap joints and T-joints subjected to pulloff loading. The joint was reinforced with fiber pins in the through-the-thickness direction of the joint before curing. Pinning proved to be of major importance for peeling mode tests, suppressing crack propagation by the traction bridging force generated by the pins.

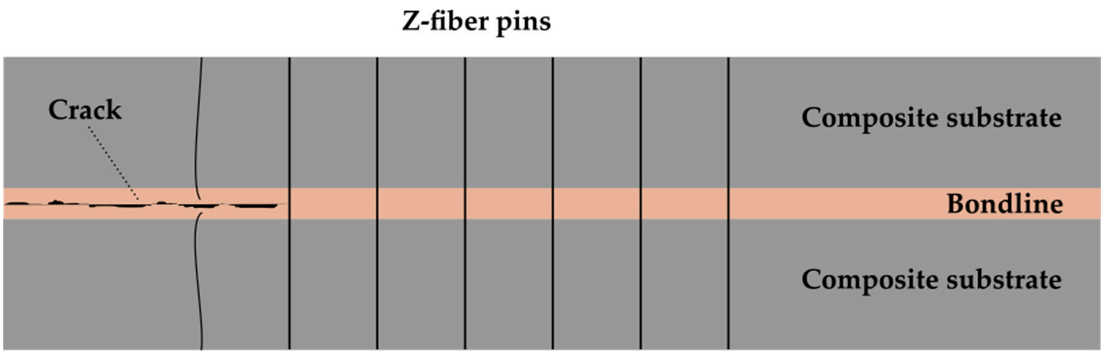

Figure 6. The concept of z-fiber pinning along the bondline.

Byrd and Birman [29] also worked on the determination of the crack arrest capability of through-the-thickness co-consolidated carbon and titanium pins on double cantilever beam coupons subjected to fatigue. The work included an analytical/numerical study of the pin volume in the bondline and investigation of the crack length at the free-end of the DCB coupon. Three different substrates' configurations were taken into consideration including E-glass/epoxy, carbon/epoxy and ceramic matrix composite laminates. Full crack arrestment was achieved under certain circumstances, even with a low volume fraction of the embedded pins for low applied loads. Although the article was limited in the examination of short crack lengths, it was proven that the use of such CAFs can ultimately be beneficial in terms of the fatigue life of the joint.

The process of cold metal transfer (CMT) [30] could stand as a means of increasing the load bearing of hybrid composite–metallic joints by the treatment of the metallic surfaces. Smith [31] experimentally studied the effect of the Comeld™ surface treatment on the load-bearing capability of hybrid composite–metallic joints. This technique introduces protrusions (proggles) onto the metallic surface to act as mechanical interlocks (Figure 7). In this study, the substrate materials were sandblasted (control) and Comeld™-treated stainless steel plates and an E-glass-reinforced woven composite, which was directly molded on the metallic material. The experimental campaign included quasi statically loaded comb-joints. A higher load-carrying capability with double the absorbed energy was measured for the Comeld™-treated specimens in comparison to the control joints, while the failure sequence was also proven to be less abrupt. In a similar principle, Ucsnik et al. [32,33] experimentally examined the effectiveness of different protrusion geometries on hybrid metallic–composite double-lap shear joints. They tested two different proggle patterns embedded on the stainless steel substrates' surfaces, comparing them to reference untreated specimens. The protrusions studied were a) cylinder pins and b) ball-head pins. In both cases, the results indicated an increment in the ultimate load and energy absorption prior to failure, with the ball-head pin geometry achieving more than a 50% benefit in terms of ultimate load bearing in comparison to the control samples.

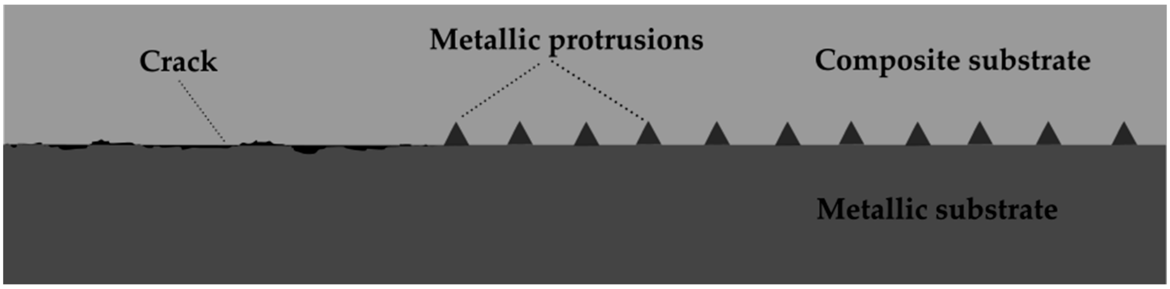

Figure 7. The concept of through-the-thickness metallic protrusions for hybrid metallic–composite joints.

Many other researchers have also investigated the damage tolerance improvement for hybrid metallic–composite joints via the modification of metallic surfaces [34–44]. The mechanical interlocking by the protrusions has been proven to offer great advantages to the quasistatic load-bearing ability of the joints, the fatigue life performance and the impact response of the joints. Among the most critical challenges of this technology is the viability of the manufacturing of such joints. Feistauer et al. [45], Sarantinos et al. [46] and Shang et al. [47] synthesized reviews of the various assembly techniques available in the industry and academia for the formation of hybrid metal–polymer joints with through-the-thickness reinforcements. They emphasized the importance of selecting the structuring process based on the initial capital investment, production cycles, joint geometry, complexity and mechanical requirements. Moreover, they stated that there is still a lack of knowledge in the field regarding critical engineering aspects of the subject, mentioning parameters such as reinforcement density, distribution, geometry and materials.

Another strategy adopted by many scientists to improve the damage tolerance of aerospace and other engineering structures is the toughening of the adhesives used for the fusion of composite and metallic substrates [48–57]. Carbon nanotubes (CNTs) and carbon nanofibers (CNFs) have been in the foreground of research in the last two decades, aiming for the improvement of fracture toughness properties for commercially used adhesives. Gude et al. [58] experimentally examined the effect of these nanoreinforcements on bonded thermoset-based matrix composites. They examined the differentiation of the Mode-I fracture toughness values for a baseline epoxy in comparison to the nanoparticle-modified ones, also taking into consideration the effect of grit-blasted and plasma surface treatments. It was concluded that the modifiers induced the activation of mechanisms within the adhesive for higher energy dissipation, resulting in the toughening of the resulting joint.

Wagih et al. [59] worked on a mechanical investigation for toughening a commonly used Araldite 420 A/B two-component epoxy adhesive via bondline microstructure modification according to a bio-inspired concept. They introduced artificial voids into the bonded surface of a composite T-joint to mimic the microstructure of the *Mytilus californianus* proteinic adhesion system, which encapsulates low-adhesion regions. The authors stated that considerable improvements in strength and toughness were realized, reaching 3.27 times and 18.9 times those of conventional T-joints, respectively.

3.2. Postproduction-Based Crack Arrest Features

Works that could be found in the literature regarding the implementation of crack stoppers on composite material joints in a secondary phase are presented in this chapter. A very extensively studied postproduction CAF is the use of through-the-thickness pinning and riveting. Rao et al. [10] examined the influence of a self-spreading leg rivet as a crack arrester. They conducted quasistatic tests on single-lap shear specimens fabricated from carbon-fiber-reinforced thermoplastic matrix nylon-PA6 composite material. The riveting process was modeled through thermomechanical finite element modeling for the optimization of the rivet geometry (length and pip height). Through optimal process parameters, the results showed joint strength increment.

Kadlec et al. [60] investigated the effect of metallic pins on the strength of crack lap shear specimens with different pinning patterns subjected to quasistatic and fatigue loading. The experiments resulted in crack deceleration for the pinned specimen compared to the unpinned ones. Moreover, an investigation of the underlying crack-confining mechanisms of the pins was conducted, resulting in the following conclusions: "Two crack arrest mechanisms associated with the use of Z-pins were identified. (1) The Z-pins hold the fracture faces together, increasing friction and decreasing deformation along the crack front. (2) The Z-pins cause bearing damage, which initiates fibre tow splitting and narrow delamination of the adherent first ply". The authors also suggested a structural health monitoring (SHM) method for identifying damage through the measurement of the electrical resistance of the pins.

In the framework of a European aerospace research program abbreviated as "BOPACS", work conducted by Kruse et al. [61,62] was focused on the study of lockbolts and through-the-thickness reinforcement as crack arrestors, as well as the investigation of plasma and laser treatment effectiveness on the surfaces prior to bonding in order to increase the adhesive strength. The researchers experimentally and numerically investigated the aforementioned features in cracked lap shear (CLS) specimens under static and fatigue conditions. A parametric study on the lockbolts revealed definitive arrestment results in all configurations, while the laser-processed bonded surface presented a considerable increment in the ultimate bond strength. The authors also mentioned that the through-the-thickness reinforcement via the surface layer of knitted fabric, stripped using laser in order to free up fibers, showed crack-retarding capability as well.

Floros and Tserpes [63] conducted a numerical study on the performance of bolts as crack stoppers in adhesively bonded composite joints. They performed both quasistatic and fatigue finite element analyses to investigate the crack growth behavior in cracked lap shear (CLS) and wide single-lap shear (WSLS) configurated joints. A parametric study of bolts' placement along the bondline as well as initial interfacial damage scenarios induced by impact was conducted in this work. The results indicated that the presence of bolts in fatigue loading conditions remarkably retarded crack propagation in contrast to the load-bearing capability increment in quasistatic loading conditions, where their effect was much less prominent. The distance of the initial defects to the bolts also affected the outcome of the crack deceleration, as a shorter length led to an increase in the CAF's effectiveness.

Staple-like pins (Figure 8) as crack propagation inhibitors were proposed by Löbel et al. [64] and were studied experimentally on composite materials' double-lap joints. The effectiveness of precuring and postcuring staple insertions was examined. The staple type, number and diameter were parameters under study as well. Overall, the joint strength was able to be increased by 28% over conventional riveting. The staple diameter was proven as a critical design parameter with direct correlation to the joint damage tolerance.

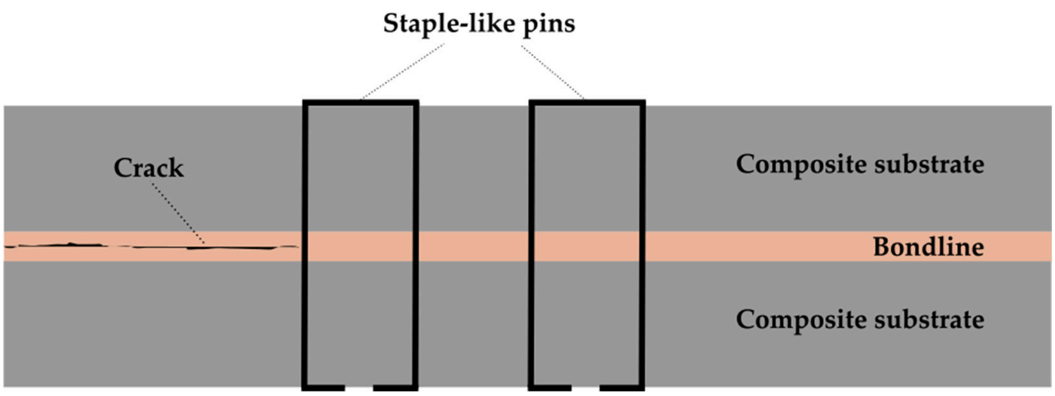

Figure 8. The concept of staple-like pins installed at the bonded substrates.

Metallic fasteners as crack stoppers in split beams subjected to Mode-I and Mode-II can be found in the work of Cheung et al. [65]. Numerical modeling as well as the development of analytical/mathematical practice was followed by the authors to study the effect of the fastener on the crack onset. Furthermore, a quantification test of the delamination-arresting ability of the fasteners under sliding loading conditions was performed. The impact of the fasteners' preload and the hole-fastener clearance on the crack-arresting effectiveness was investigated experimentally. As stated by the authors, "It is shown that the fastener effectively eliminates G_I by restricting the opening displacement behind the crack tip, at the same time forcing the crack to propagate in pure Mode II". Richard & Lin [66,67] used titanium bolts in series in double cantilever beam peel-loaded specimens to act as crack stoppers. It was found that, under fatigue loading, the results were sensitive to the drilled hole clearance and the torque applied to the bolt's nut. In a similar principle, a technical paper authored by Action & Engelstad [68] describes their experimental and numerical campaign to investigate the crack arrestment ability of fasteners on double cantilever beam (Mode-I), double shear (Mode-II) and DCB-like pi-joint specimens. Retardation of the damage was observed in all three cases as the bondline failure required a higher load level.

Bruun et al. [69], in a technical paper, presented a parametric experimental investigation of mixed-mode cocured cracked lap shear (CLS) specimens containing lockbolts as CAFs. The authors conducted quasistatic tests on three different quasi-isotropic layup configurations of composite laminates with the bolted CAF installed at various torque values. The crack propagated unstably between the crack tip and the inserted CAF following a deceleration until the total failure of the joint. The coupons with the longest distance between the crack tip and the bolt exhibited the highest load-bearing capability prior to the total interfacial damage. Moreover, it was shown that the torque values did not considerably affect the bolt's ability to confine the damage.

Another postproduction crack arrest feature is the implementation of rivetless nut plate joints, which can be found in the article of Sachse et al. [70]. The researchers worked experimentally to study the crack-stopping efficiency of the nut in a hybrid bonded-fastened crack lap shear specimen subjected to fatigue loading. It was found that the debonding growth was reduced by a factor of 100, while the numerical models used confirmed the experimental results. Lopez-Cruz et al. [71] presented a parametrical experimental study on a single-lap shear specimen with a hybrid adhesive-bolted joint (Figure 9). Parameters under consideration were the type and application of adhesive, type of bolt-washer used and the bolt-hole clearance. The adherent thickness and the adhesive type proved to be the most sensitive variables for the joint strength, while the washer size did not affect the results by much.

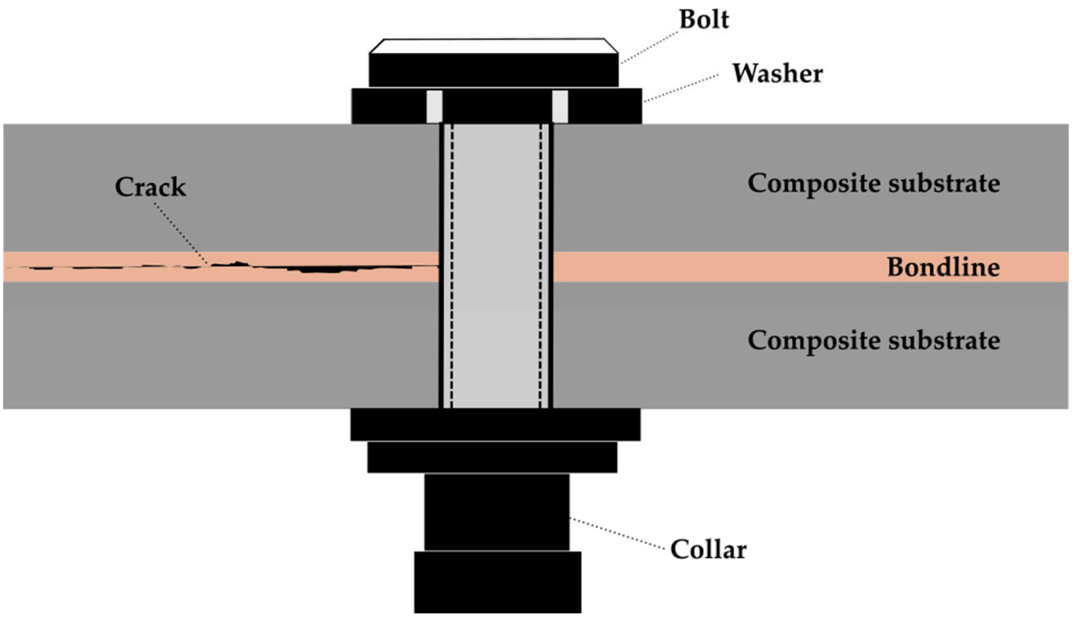

Figure 9. Lockbolt installed in the bonded substrates.

Fatigue life and damage propagation of hybrid bolted-bonded joints were investigated by Kelly [72]. This work focused on both experimental and numerical results of joints with brittle (epoxy) and ductile (polyurethane) adhesives containing bolts as crack arrest features. The epoxy-based hybrid bond did not show significant strength and fatigue life improvement in comparison to the unbolted adhesive joint because only a small fraction of the load was transferred by the bolt, as revealed by the finite element analysis. On the contrary, the more ductile polyurethane adhesive in combination with the bolt showed an increase of up to 22% to the adhesive-bonded joint, with significant load transferred by the fastener. The author concludes that hybrid joining offers potential improvements in strength and fatigue life, but the right combination of material and joint design must be implemented for the load to be appropriately distributed between the adhesive and the bolt.

The authors of [73] experimentally and numerically evaluated the performance of refill friction stir spot welding (RFSSW) as a CAF on co-consolidated thermoplastic matrix laminates. RFSSW constitutes a newly developed joining technology for metallic and thermoplastic composites, while the aforementioned study focused on its potential application as a crack stopper. Quasistatic loading tests were conducted on mixed-mode crack lap shear specimens (Figure 10), accompanied by the development of a simulation methodology via the finite elements method (FEM). It was concluded that the feature could not fully arrest the development of interfacial failure, although the ultimate strength of the joint was increased and the performance could potentially be improved further through installation topology optimization of the CAF.

Figure 10. The RFFSW feature installed as CAF on crack lap shear specimens.

Other researchers have also covered the joining of hybrid metal–plastic structures in their works. Proença et al. [74] studied the influence of the tool rotational speed experimentally on the joint performance at aluminum–PA6 bonding. They found that the process parameter of rotational velocity has a direct relation with the rivet anchoring and tensile strength. Goushegir et al. [75–77] extensively studied the performance and microstructure of friction spot joints between aluminum and carbon-reinforced polypropylene-sulfide (PPS). They performed mechanical tests as well as thermal and other monitoring techniques to evaluate the joint's formation.

4. Crack Arrest Features for Composite Materials

Chu [16] experimentally studied the effect of replacing the central 0^0 layers of 16-ply AS/3501-6 graphite-epoxy laminates with E-glass, Kevlar and S-glass softening strips in order to investigate their effectiveness in increasing the integrity of the material. The author studied the impact of the features by initially fatigue loading the coupons, introducing initial damage and finally subjecting the specimens to quasistatic tensile loading until failure. Furthermore, moisture effects on the crack-arresting ability of the features were examined as well, comparing the "dry" to the "wet" specimens. Overall, it was concluded that the S-glass strip functioned superiorly to the Kevlar and E-glass, while moisture did have a significant negative effect on the crack confinement of the strips.

An analytical and experimental investigation of a semicylindrical crack arrester produced either from resin or CFRP material (Figure 11a) was conducted by Hirose et al. [78] for foam-core sandwich panels. The feature was intended for delamination suppression at the interface between the foam core and the surface skin. The concept presented was able to suppress crack propagation at the studied geometry and even affect the damage at a larger distance from the actual feature. The main outcome of the work in question was that crack arrester radius as well as material modulus are expected to have the most prominent role in interfacial failure suppression. In another article published by the authors [79], the effect of a splice-type CAF manufactured by CFRP fabric prepreg and introduced into a foam-core sandwich panel was studied (Figure 11b). The CAF studied was placed at a 30^0 angle within the foam core and was merged in a tapered butt-joint configuration of the outer CFRP surface skins. Its damage suppression capability was proven by Mode-I fracture toughness testing.

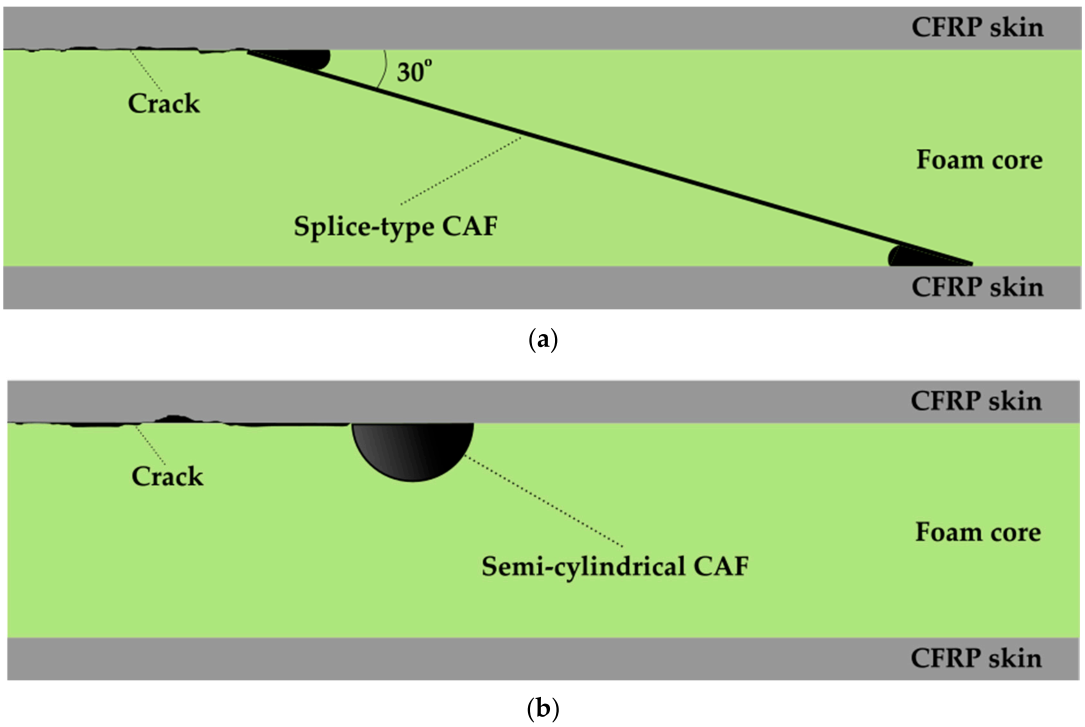

Figure 11. The concept of (**a**) splice-type CAF in foam-core sandwich panels; (**b**) semicylindrical CAF in foam-core panels.

McKinley [80] conducted an experimental study on the crack-stopping effect of metallic and composite straps bonded on the outer boron/epoxy facesheets of metallic honeycomb sandwiched panels (Figure 12). The tests were held in a four-point-bending quasistatic loading configuration until total failure. The results proved the crack-arresting capability of the straps and an improvement in laminates' residual strength capacity as well. Overall, the S-glass composite strap offered the most superior crack-arresting performance. Norman and Sun [81] have also proposed adhesive strips embedded into composite laminates acting as crack stoppers. In their analytical/experimental article, they concluded that the strips were able to arrest the damage in graphite/epoxy material, induced by quasistatic and low-velocity impact loading.

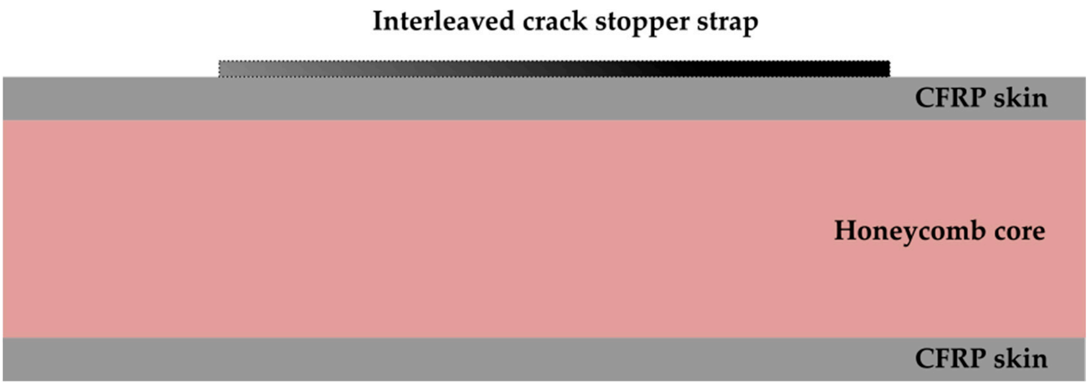

Figure 12. The Interleaved Crack Stopper Strap in honeycomb sandwich panel concept.

Kumar and Babu [82,83] numerically investigated the effect of z-fiber pinning in a curved stiffened composite panel. They focused on the suppression of the damage at the connection points between the composite panel and the stiffening beams, where they introduced through-the-thickness reinforcements. The finite elements investigation revealed the ability of the z-fiber pins to suppress failure, mainly due to triggering the fiber-bridging phenomenon. The pins' diameter was proven as an effective crack-confining parameter, and the authors stated that smaller-diameter pins were able to transfer higher amounts of loading. Moreover, the pins' spacing impacted the damage propagation as well, as larger spacing resulted in an increase in the structure's integrity.

Richard and Lin [84] presented the effect of titanium fasteners acting as crack arresters in their numerical and experimental work. They studied their impact on carbon/epoxy laminates subjected to quasistatic and fatigue loading. The fastener's clearance to the laminate was also considered. The fasteners' joint stiffness and the frictional load transfer were the main crack-confining mechanisms. Furthermore, it was also shown that the fasteners' spacing was mode-mixity- and testing-configuration-dependent.

Psihoyos et al. [85] developed a finite element model, studying the delamination-arresting ability of transversely installed butt-joined elements to a skin-stiffener structure (Figure 13). The results were compared to previously conducted experiments, including both quasistatic and cyclic loading of the skin-stiffener assembly along its longitudinal axis. Both the numerical analysis and testing proved the ability of the crack-arresting components to deflect and stop failure along the skin laminate of the structure.

Finally, Yasaee et al. [86] worked on studying the effect of embedded strips in E-glass-reinforced epoxy composites for interlaminar crack propagation stopping (Figure 14). The strips examined in the article were thermoplastic film, thermoplastic particles, chopped fibers, glass/epoxy prepregs, thermoset adhesive film and thermoset adhesive particles. The performance of the aforementioned interleaves was benchmarked through Mode-II fracture toughness testing. Apparently, a polyimide thermoplastic film insert was proven as the most efficient way to increase the opening mode fracture toughness. Ultimately, the authors stated that "maintaining the mechanical linkage between the interfaces via the use of inserted fibres or films was seen to be the most effective way of increasing the mode I fracture toughness for a laminated GFRP".

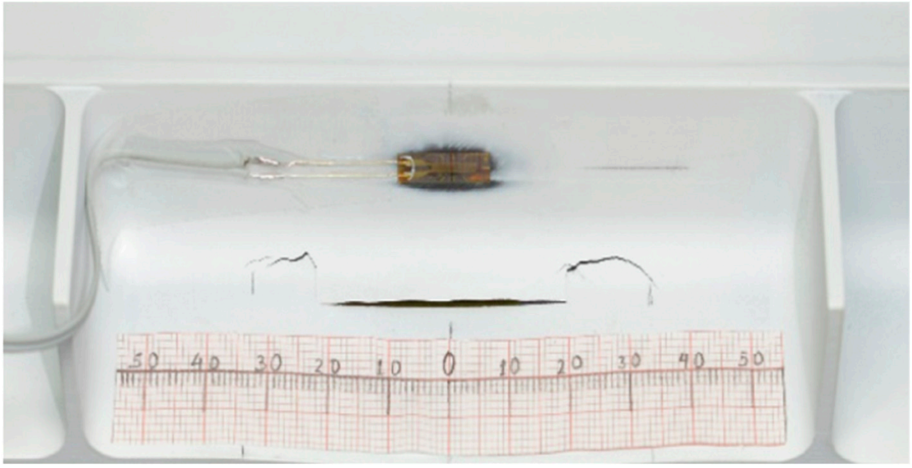

Figure 13. Transverse butt-joined elements as CAF in skin-stiffener structure [85].

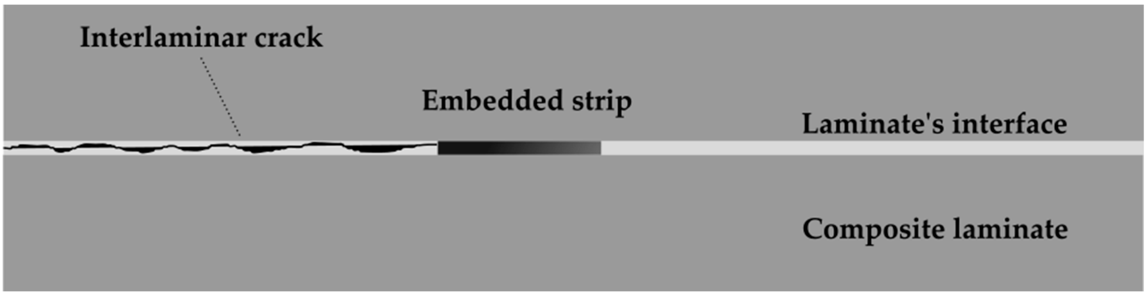

Figure 14. The embedded strip CAF concept.

Table 1. List of literature findings based on the type of study, CAF and substrates' material.

Authors	Experimental	Simulation	Type of CAF	Substrates'/Parent Material
T. Löbel et al. [13]	•		Hybrid bondline	IM7/8552
Z. Rao et al. [10]	•	•	Pins with spreading legs	CF/PA6
Chi Ho E. Cheung et al. [65]		•	Metal fasteners	AS4/3501-6
N. Jeevan Kumar et al. [83]		•	z-fiber pins	Carbon/epoxy and Glass/epoxy
L. Richard et al. [66,67]	•	•	Bolts	T800/3900-2
T. Kruse et al. [61,62]	•		Lockbolts and z-reinforcement	Thermoset matrix composite
M. Kadlec et al. [60]	•		z-pins	IM7/8552
R. Malkin et al. [15]	•		Interface modification	IM7/8552
C. S. Chu [16]	•		Softening strips	AS/3501-6 graphite-epoxy
J. E. Action et al. [68]	•	•	Bolts	-
K. Tserpes et al. [24]	•	•	Corrugation	R-367-2/T2TE2
S. Hisada et al. [21]	•	•	Interlocking fibers	T700SC/2592
A. Yudhanto et al. [17]	•		Hybrid bondline	T700/M21
R. Sachse et al. [70]	•	•	Bolts	I M7/8552
O. Kolednik et al. [19]	•		Soft interlayers	Al/Al-multilayers
P. L. Cruz [71]	•		Fasteners	5320 T650 33/145
M. Yasaee [18]	•		Fasteners	E-glass fiber/913 epoxy
I. Floros, K. Tserpes [63]	•	•	Fasteners	8552/IM7
K. Tserpes [25]		•	Bolts	8552/IM7

Table 1. *Cont.*

Authors	Experimental	Simulation	Type of CAF	Substrates'/Parent Material
R. Tao [20]	•	•	Corrugation and Bolts	T700/M21
P. Chang et al. [27]	•		z-pins	carbon/epoxy
D. Holzhüter et al. [14]	•		Hybrid bondline	8552/IM7
L. W. Byrd et al. [29]	•	•	Cocured z-pins	Carbon/epoxy and Glass/epoxy
K. Maloney, N. Fleck [26]	•		Stop holes, woven copper wire mesh	Al. 6082-T651
T. Löbel et al. [64]	•		Staple-like pins	IMS 5131 24k
T. M. Koh et al. [28]	•		z-pins	700 carbon fiber/ Epoxy
E. D. Brunn et al. [69]	•		Bolted fastener	Thermoset composite
G. Kelly [72]	•	•	Bolted fastener	T700/LV 828
S. Minakuchi, N. Takeda [22]	•	•	Fiber reinforcement	T700S/2592
S. Minakuchi [23]	•		Fiber reinforcement	T700S/2592
I. Sioutis et al. [73]	•	•	RFSSW	LM-PAEK/T700
N. M. Andrè et al. [74]	•		-	2024-T3 and CF-PPS
N. Z. Borba et al. [76]	•	•	Rivet	Ti-6Al-4V and GFR-polyester
S. M. Goushegir et al. [75]	•		-	AA2024-T3 and CF-PPS
S. M. Goushegir [77]	•		-	AA2024-T3 and CF-PPS
B. C. de Proença et al. [74]	•		Rivet	AA 6056 T6 and PA6
Y. Hirose et al. [78]	•		Splice-type arrester	UT500/#135
L. Richard et al. [84]	•	•	Bolts	T800/3900-2
J. M. McKinley [80]	•		Interleaved crack stopper straps	Boron/epoxy
N. Jeevan Kumar et al. [83]		•	z-fiber pins	Carbon/epoxy and Glass/epoxy
Y. Hirose et al. [79]	•		Semicylindrical insert	UT500/#135
C. S. Chu [16]	•		Softening strips	AS/3501-6 graphite-epoxy
T. L. Norman [81]	•		Adhesive strips	AS4/3501-6
H. O. Psihoyos et al. [85]		•	Butt-joined transverse elements	AS4D/PEKK
F. Smith [31]	•		Comeld™ surface treatment	Stainless steel/E-glass woven composite
S. Ucsnik et al. [32,33]	•		Metallic surface treatment (CMT)	Stainless steel/CFRP
M. C. Corbett et al. [41]		•	Interlocking surfaces	Alum. alloy AA5754
A. Fawcett et al. [37]	•		Protrusive "hooks"	GFRP/aluminum
D. P. Graham et al. [44]	•		Interlocking pins	Stainless steel/E-glass epoxy
M. O'Brien et al. [40]	•		Interlocking surfaces	Alum. alloy AA5754
P. N. Parkes et al. [43]	•		Laser sintered HYPER pins	Titanium/CFRP
K. Ramaswamy et al. [35,38,39,42]	•		Interlocking features	AA5754-H111/PA12 woven composite
H. Tang & L. Liu [34]	•	•	Metallic pins	LY12 aluminum/CFRP
M. R. Gude et al. [58]	•		CNT- and CNF-toughened adhesive	Hexply 8552/33%/268/IM7-12K
A. Wagih et al. [59]	•		Bio-inspired adhesive voiding	Hexply T700/M21

5. Conclusions and Discussion

The research works that were briefly presented above studied the impact of various crack arrester concepts on composite materials and joints as well as their capability to decelerate or stop crack propagation in composite and composite joints. Extensive experimental and numerical studies have been conducted by numerous researchers on both production- and postproduction-based crack arrest features. The most common experimental approach for the determination of the crack-arresting abilities of the CAFs is fracture toughness mechanical testing. A comparison between the reference and a CAF including specimens provides valuable data regarding the feature's efficiency. Testing configurations of double cantilever beam, edge notch flexure and single-lap shear coupons are amongst the most commonly used in the experimental studies in the literature. Furthermore, a wide variety of works focused on the numerical evaluation of the CAFs' efficiency through a series of finite element models, either by virtually optimizing the performance or by validating previously conducted mechanical tests.

From the various studies found in the literature, it can be concluded that most of the suggested and investigated features could potentially be effective for arresting interfacial and interlaminar damage. However, before their application, special attention should be paid to the crucial parameters' optimization and the mechanism's design. Postproduction pinning, for example, requires the specification of the pin diameter, material and the amount and density of pins to be inserted. Some other parameters that should be taken into consideration are the type of the primary bond type (adhesive, welding or cocuring), the joint and the loading to which the structure under design is subjected. Furthermore, the designer of a CAF-containing engineering component should also take into consideration the technoeconomical aspects of the structure. Postproduction-installed features potentially offer higher practicality during the manufacturing process of the individual substrates; however, the assembly procedure could benefit from the production-based CAFs.

Concluding the present study, it was found that a substantial gap is still present in the literature regarding the investigation of the various CAFs' effectiveness on realistic loading conditions. Since fatigue should be the main consideration for aerospace and aeronautical components' design, research should lean more towards the experimental evaluation of the features' performance under cyclic loading. A plethora of the works were focused solely on the quasistatic response of the suggested CAFs. Although the performance in such conditions is well worth examining, the crack confinement effectiveness is not necessarily ensured in fatigue.

Moreover, it should be stated that the literature findings based on thermoplastic composites and thermoplastic welded joints are very limited. Considering the advantages of these materials and their rising application in aerospace structures, emphasis should be given to the further testing and modeling of crack stoppers for thermoplastic welded bonds. The nature of thermoplastics to be reformed when subjected to suitable heat and pressure conditions could open up new possibilities for postproduction-induced CAFs. As an example, heat-inserted rivets and refill friction stir spot welds could stand as suitable candidates for broadening the available crack-arresting techniques while at the same time minimizing the manufacturing cost of aerospace structures [87–90].

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