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Bond-Related Aircraft Accidents/Incidents: A Review

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Final report

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16. Abstract

This work surveyed aircraft accidents/incidents in which a bond failure was a contributing factor. This survey was used to identify potential shortfalls in the certification of bonded structures. We reviewed, summarized, and compiled investigation reports, safety recommendations, and airworthiness directives associated with bond failure-related events. These documents originated mainly from countries with large civil aviation fleets that maintain online, publicly available databases. This survey was limited to type-certified, civil aeronautical products, irrespective of the manufacturer, model, size, or age. A total of 73 bond-related events involving aircraft registered in 13 countries on five continents were found. We grouped these events according to the aeronautical product—transport airplanes, general aviation airplanes, rotorcraft, propellers, and engines—containing the failed bonded joint. Each of these groups is type-certified under specific airworthiness requirements. For each event, we classified the bond failure's root causes into the following categories: design, production, operation, and maintenance. Analysis of the compiled data revealed that maintenance or production issues often contributed to the reviewed bond-related events. This analysis also emphasized the need for process control/validation and durability substantiation to ensure the long-term safe operation of bonded structures. The data supports a conclusion that no additional layer of protection—e.g., load path redundancy, damage growth arrest features, environmental protection measures, damage tolerance-based maintenance actions, or advanced nondestructive inspections—can *alone* guarantee the expected joint structural performance in case of substandard bonding without adequate material and process control. These observations are consistent with current certification guidance materials.

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Acronyms

Acronym	Definition
AD	Airworthiness Directive
ASTB	Australian Safety Transport Bureau
CAA	Civil Aviation Authority
CENIPA	Aeronautical Accidents Investigation and Prevention Center (Brazil)
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration (USA)
FMEA	Failure Mode Effect Analysis
GA	General Aviation
ICAO	International Civil Aviation Organization
MRB	Main rotor blade
NDI	Nondestructive inspection
NTSB	National Transportation Safety Board
OEM	Original Equipment Manufacturer
SB	Service Bulletin
STC	Supplemental Type Certificate
TRB	Tail rotor blade

Executive summary

Bonding has many advantages—in structural performance, design flexibility, and weight and cost savings—over riveting or other mechanical fasteners [1–3]. These advantages have motivated many applications of bonded joints dating to the beginning of aviation [3]. In the 1950s, aircraft were designed to fly higher, more frequently, and with longer service life. As a result, the challenges for ensuring the durability of bonded joints throughout the aircraft's operational life became more evident [4]. These challenges include virtually undetectable bondline failure modes and environmental degradations [5,6]. Bondline defects and degradation modes are difficult to simulate numerically or reproduce experimentally, magnifying the value of in-service data [7–9]. Despite these challenges, the aeronautic use of structural bonding has been expanding since the 1950s. Today, structural bonding encompasses a wide range of applications that spans from small [10] to transport [11,12] airplanes and rotorcraft [13,14]. It also includes propellers [15] and engines [16], pristine structures, and repairs [17,18], in both civil [19] and military [20] aircraft.

Since 1944, the International Civil Aviation Organization (ICAO) has recommended member states to report, investigate, and document aircraft accidents and incidents [21,22]. This recommendation aims to prevent these events from happening again. Since its foundation, ICAO encompasses several countries. As a result, there are presently many publicly available databases worldwide. These databases contain thousands of accident/incident investigation reports and safety recommendations. Qualified investigators typically create these documents based on inspections, data review, and interviews. Additional engineering data—e.g., material analysis, mechanical tests, numerical simulations—from accredited institutions—e.g., research institutes, original equipment manufacturers (OEM), or universities—often complement these investigations.

Despite the decade-long accumulation of valuable operational experience data, no comprehensive review of bond-related failures contributing to aircraft accidents/incidents was found. The present work surveyed aircraft events in which a bond failure was a contributing factor. This survey was used to identify potential shortfalls in the certification of bonded structures. This survey was limited to type-certified, civil aeronautical products (aircraft, engines, and propellers)—irrespective of the manufacturer, model, size, or age. A total of 73 bond-related accidents/incidents involving aircraft registered in 13 countries on five continents were found. We reviewed, summarized, and compiled investigation reports, safety recommendations, and airworthiness directives (ADs) associated with these events. These

documents originated mainly from countries with sizeable civil aviation fleets that maintain publicly available online databases.

We grouped the identified bond-related events according to the aeronautical product where the bond failed. There were five groups: transport airplanes, general aviation (GA) airplanes, rotorcraft, propellers, and engines. The type-certification of each of these groups follows separate airworthiness requirements—e.g., Title 14, Code of Federal Regulations (14 CFR) parts 23-35. We classified the root causes of the bond failure into four categories: design, production, operation, and maintenance. Each of these categories is certified against specific rules—e.g., 14 CFR parts 21, 43, 121, and 145.

The reviewed bond-related events support the following observations:

- Maintenance or production issues often contributed to the reviewed bond-related events;
- Bonded joints, whose failure contributed to aircraft accidents/incidents, could be found in all products (transport airplanes, general aviation airplanes, rotorcraft, propellers, and engines);
- In most of the reviewed bond-related events, the accident investigators reported evidence of bond environmental degradation or adhesion failure;
- Among the reviewed events, those involving GA airplanes and rotorcraft led to more severe damage to the aircraft and injury to the occupants than those involving transport airplanes;
- Events involving helicopters were observed considerably more often than those involving GA or transport airplanes. In most of them, failures were in the rotor blades;
- Substandard bonding in structures that are not typically classified as safety-critical can lead to potentially unsafe conditions; and
- The investigations' level of rigor varied among the reviewed events, which might have impacted bond failure modes' identification. This identification is important for safety recommendations.

These observations emphasize the need for process control/validation and a thorough durability assessment to ensure the long-term safe operation of bonded structures—in line with current certification policies [5,23]. No additional layer of protection (e.g., load path redundancy, damage growth arrest features, airframe environmental protection measures, damage tolerance-based maintenance actions, or advanced NDI) can *alone* ensure the required minimum level of safety throughout the aircraft operational life in case of substandard bonding.

1 Introduction

Compared to other joining methods, adhesive bonding offers many advantages in structural performance, design flexibility, and weight and cost savings [1–3]. Aircraft design pioneers acknowledged this potential long ago [3]. The invention of metal bonding occurred almost simultaneously with the first metallic airframe parts [4]. Nonetheless, as aircraft were designed to fly higher, more often, and with service life increasing to decades, the challenges for the lifelong safe operation of adhesive bonding became more evident [4]. Challenges in ensuring the service life of bonded joints include the possibility of virtually undetectable modes of failures ('weak bond') and environmental degradation of the bondline [5,6]. Because of bonding's strong process dependence and the complexity of adhesion phenomena, these types of defects are difficult to simulate numerically or to reproduce experimentally [7–9]. Despite these technical challenges, the aeronautic use of structural bonding has been expanding since the 1950s. Today, structural bonding encompasses a wide range of applications that spans from small [10] to transport [11,12] airplanes and rotorcraft [13,14]. It also includes propellers [15] and engines, pristine airframe, and repairs [17,18], in both civil [19] and military [20] aircraft.

Since 1944, the International Civil Aviation Organization (ICAO) has recommended that member states investigate and document aircraft accidents and incidents and report their findings to prevent them from happening again [21,22]. Since its early years, ICAO has grown from 52 to 193 member states worldwide [21,24]. Today there are many publicly available databases—e.g., Australian Safety Transport Bureau (ASTB), Aeronautical Accidents Investigation and Prevention Center (CENIPA), National Transportation Safety Board (NTSB)—containing data on aircraft accidents and incidents. These databases have numerous accident/incident investigation reports and safety recommendations. For instance, since 1962, the NTSB aviation accident database has accumulated over 76,800 investigation reports of civil aviation accidents and selected incidents involving type-certified aircraft [25]. To support these reports, qualified investigators typically perform wreckage visual inspections, flight data analysis, operation/maintenance records review, and witness/crew interviews. In many cases, detailed engineering data—nondestructive inspections (NDIs), microscopic examinations, material analysis, mechanical tests, numerical simulations—from accredited institutions (e.g., research laboratories, original equipment manufacturer [OEM], and universities) complement these investigations.

Despite this decades-long accumulation of valuable operational experience data, no comprehensive survey of bond-related failures contributing to aircraft accidents/incidents were found. The challenge of reproducing service conditions during certification highlights the importance of field data [7]. In this work, we reviewed, summarized, and compiled 73 bond-related events involving aircraft registered in 13 countries on five continents. For each identified bond-related event, we classified the bond failure's root causes into the following categories: design, production, operation, and maintenance. This survey was limited to type-certified civil aircraft, regardless of the manufacturer, model, size, or age.

This report is structured as follows:

- Section 2 describes the reviewed bond-related events,
- Section 3 analyzes the compiled data,
- Section 4 presents observations based on these data,
- Section 5 recommends future related research, and
- Appendix A summarizes the reviewed bond-related events in a table format.

2 Compilation of the reviewed bond-related events

This survey was primarily based on aircraft event investigation reports from countries with large civil aircraft fleets that maintain readily, publicly available online databases, such as the USA, the UK, Germany, Canada, Brazil, and Australia. We occasionally included other documents—e.g., airworthiness directives (ADs)—and investigation reports from other countries. We reviewed, summarized, and compiled 73 bond-related events. These events are organized into five subsections: transport airplanes (2.1), general aviation (GA) airplanes (2.2), rotorcraft (2.3), propellers (2.4), and engines (2.5). Each subsection groups events involving aeronautical products type-certified against similar airworthiness regulations (e.g., Title 14, Code of Federal Regulations (14 CFR) part 25 for transport aircraft, part 33 for engines, etc.). These events are typically presented chronologically within each subsection, subdivided into the major airframe groups (e.g., wing, fuselage) containing the failed bonded joint, considering the available data. An identification number identifies each event. The summary table in Appendix A summarizes the reviewed events' main details, characteristics, and references.

2.1 Transport airplanes

With the advent of the metallic airframe in the 1950s, several early transport airplane models (e.g., DH 106 Comet, Fokker F27 Friendship, Boeing 727) extensively employed structural bonding [4,26–28]. Since then, there have been more widespread bonding applications in large civil airplanes [11,12,29,30]. Table 1 lists 15 reviewed bond-related events involving transport airplanes. These events are subsequently described, sub-divided into fuselage (2.1.1), wing (2.1.2), and movable surfaces (2.1.3).

Table 1. Bond-related events involving transport airplanes

ID	Aircraft make	Model	Marks	State of registry	Date
TA01	Boeing	737-200	N73711	USA	04/28/88
TA02	Boeing	747-200B	VH-EBQ	Australia	12/27/90
TA03	Airbus	A300	N16982	USA	12/06/93
TA04	Boeing	747-200C	N470EV	USA	05/19/96
TA05	Boeing	777-200	G-YMMP	UK	06/14/10
TA06	Boeing	DC-10-30	YV-134	Venezuela	09/01/83
TA07	BAE/SNIAS[a]	Concorde Type 1	G-BOAF	UK	04/12/89
TA08	BAE/SNIAS[a]	Concorde Type 1	G-BOAC	UK	05/25/98
TA09	BAE/SNIAS[a]	Concorde Type 1	G-BOAC	UK	10/08/98
TA10	Boeing	MD-11	B-150	China	12/07/92
TA11	Boeing	737-200	N457TM	USA	06/29/95
TA12	Boeing	727-61	N530KF	USA	10/17/00
TA13	Airbus	A310-300	C-GPAT	Canada	03/06/05
TA14	Airbus	A300-600	N717FE	USA	11/27/05
TA15	Boeing	737-200	VH-OZX	Australia	12/31/07

Note: [a]British Aerospace and Société Nationale Industrielle Aérospatiale

2.1.1 Fuselage

One of the most well-known aircraft accidents is the Aloha Airlines flight 243 in 1988 (**TA01**). In this event, the single-aisle airliner experienced abrupt failure of about 5.5 meters of the main cabin fuselage upper lobe during cruise flight. Despite the substantial airframe damage, the crew managed to conduct a safe emergency landing. There was one fatality and several injuries among the 95 occupants. According to the investigators, the probable cause was that the maintenance program did not detect significant disbond and fatigue cracks in the fuselage skin lap joints. As illustrated in Figure 1, these joints were cold bonded and riveted (load path redundancy). Examination revealed a critical safety issue associated with improper surface preparation. This substandard bonding led to inadequate joint environmental durability [31,32].

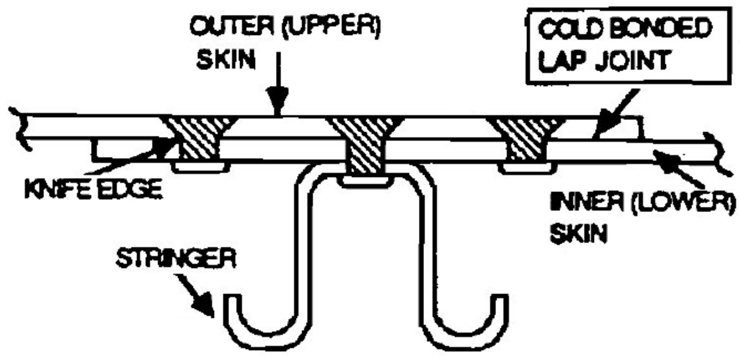


Figure 1. Typical fuselage skin lap joint [31] (modified)

2.1.2 Wing

We found four events involving fixed parts of the transport airplane wings.

In 1990, the four-engine, wide-body airliner of event **TA02** lost a 2.7- x 0.18-meter portion of a wing trailing edge composite panel during climb. Visual inspection from the cabin confirmed the separation. The crew declared an emergency, dumped the fuel, and landed uneventfully at the airport of origin. Investigation concluded that pre-load resulting from contact with the flaps caused the disbond of a trailing edge composite panel. This panel was tap and push tested during an 'A' check 19 days before this incident. The operator and manufacturer reported several similar events [33].

In 1993, during the landing roll, one of the 3.6- x 1.8-meter engine cowls departed the twin-aisle airliner of event **TA03**. This departure inflicted minor damage to this airliner and another aircraft using the same runway immediately afterward. No one was injured. Inadequate adhesive thickness control and surface preparation during a repair led to the adhesion failure of an aluminum bonded joint. The engine OEM contributed to the investigation with a report. This report classified this incident as an isolated case, noting that similar bonding issues with this joint in other aircraft of the same model were detected before complete cowl separation. Once the engine OEM shop manual had not included a procedure for this bonded joint repair, variation among the procedures developed by third-party overhaul shops might have existed [34].

In 1996, parts of a composite sandwich panel of the wing fixed trailing edge separated from a four-engine, wide-body freighter during climb. This separation caused secondary damage to the airplane but no harm to the crew (**TA04**). The crew decided to return and landed safely. The detected disbond was associated with expanding/contracting cycles of absorbed environmental moisture. When notified, the OEM acknowledged reports of 245 other similar disbonds, 95 of them in flight. As a result of these previous reports, this panel had been redesigned twice, and a service bulletin (SB) had been issued and subsequently revised several times. The latest revised

SB ultimately had replaced the established NDI technique (from tap coin to ultrasound). Before **TA04**, this particular aircraft operator had opted not to substitute the inspection method, as per this SB [35].

In 2010, the crew of the wide-body airliner of event **TA05** flying from Singapore to London observed abnormalities in the right-engine performance. The crew elected to divert to Amsterdam. After an uneventful landing, all 214 occupants disembarked safely. The post-flight inspection detected severe damage at, and missing parts of, the aft inner nacelle on the right-engine. Investigation detected areas with evidence of significant overheating and interfacial disbonds between the core and the composite skin. Motivated by similar incidents, about five years before this event, the OEM had issued—and later revised—some SBs requiring one-time inspections and others requiring repetitive inspections to this region. As these inspections had been unable to prevent further similar events, about one year before this event, the OEM had published an extensive SB acknowledging that the existing thermal protection was insufficient and hence specifying a new one. The latest SB was not incorporated into this aircraft at the time of this event [36].

2.1.3 Moving surfaces

Among the reviewed events, we found ten events associated with bond failures in moving surfaces of transport airplanes.

In 1983, the twin-aisle airliner of event **TA06** was approaching land when approximately 1.3 meters of the right-flap vane separated from the airplane. The airplane landed safely with minor damages. The 201 occupants were uninjured. Investigation revealed that moisture ingress caused skin disbond. A major contributing factor was a skin repair performed using inadequate surface preparation and insufficient cure pressure [37].

In 1989, a supersonic airliner of event **TA07** in a charter flight experienced moderate vibration during descent. Considering no abnormal indications, the crew proceeded as planned, and the airplane landed uneventfully. Post-flight inspection detected damage in the rudder. For redundancy purposes, the rudder design comprised two portions (upper and lower). Each portion was made of two independent bonded aluminum sandwich 'wedges' connected by a control mechanism. A large portion of the upper 'wedge' of the upper rudder was missing. An OEM modification extended the rudder's trailing edge for performance improvement. This extension comprised an epoxy-filled aluminum part bonded and fastened to the original structure. Examination revealed extensive, progressive corrosion and disbonds caused by moisture (e.g., freeze-thaw cycles). Moisture ingressed past the trailing edge extension blind fastener holes.

Investigation concluded that production staff had not complied in full with modification drawing requirements (e.g., fasteners' wet installation). These requirements were deemed difficult to attain. Paint strippers might also have contributed to removing fasteners' environmental protections. This event prompted special inspections to the fleet, which identified an aircraft with similar rudder disbond patterns [38]. Other similar events followed:

- About nine years after **TA07**, another supersonic airliner experienced a slight shudder while en route (**TA08**). After inspecting the elevons through the cabin windows, the crew detected the detachment of a portion of one of the six elevons on the left-wing trailing edge and rapid oscillations of the adjacent remnant structure. The crew declared an emergency and returned to the airport of origin. The landing was uneventful, and all 64 occupants disembarked unharmed. A post-flight inspection revealed that the rearmost one-third of the failed elevon was missing. This elevon was a bonded metallic sandwich structure similar to the rudder. The OEM had repaired the elevon's trailing edge more than once due to disbond. In the last of these repairs, the elevon trailing edge had been completely refabricated, and additional doublers and anti-peel blind fasteners were incorporated. The repaired region's maintenance program established NDI with capabilities beyond what was required to comply with the mandatory requirements. Some of these NDIs were performed two days before this incident. Examination disclosed evidence of adhesion failure and disbond growth. About half of the repaired area was found not inspectable due to overlaps. Investigation concluded that the most probable failure scenario consisted of the undetected growth of a relatively small disbonded area leading to an abrupt failure [39].

- About four months after **TA08**, the *same airplane* was involved in a similar incident (**TA09**). While cruising at supersonic speed, the crew felt vibration and a thump. Visual inspections from the cabin and performance checks revealed no abnormal condition. Thus, the crew elected to proceed with the flight as planned. The landing was normal, and all 71 occupants disembarked unscathed. Post-flight inspection detected that 60-70% of one of the lower rudder's 'wedge' was missing. The 'wedge' trailing edge comprised a bonded metallic tip, which was reinforced by fail-safe blind fasteners installed after the bonding. During manufacturing, the failed rudder's trailing edge had been damaged (disbond) and repaired. The maintenance program established frequent detailed visual inspections and NDIs, particularly for repaired regions. The last of these inspections had been performed five days before this incident and had revealed no defects. None of the in-service NDI techniques could detect disbonds in solid metal/metal bonds, such as the trailing edges, repairs, and closing ribs. Post-incident inspections (NDI and tear-down) of the remaining lower rudder's 'wedge' (the failed one was not retrieved) disclosed large (mainly cohesive) disbonds in the trailing edge and closing ribs. Investigation concluded that the process of forming the blind rivets at the bonded trailing edge during manufacture introduced small disbonds that grew undetected in-service up failure [40].

In 1992, while en route, the wide-body airliner of event **TA10** encountered severe turbulence. During this turbulence, about 1.6- x 0.7-meter portions of both composite elevators disbonded and separated from the airplane. The airplane landed uneventfully with minor damage, and none of the 265 occupants were injured. Investigation concluded that the probable leading cause of these disbonds was overstress associated with a stall buffet. Detailed examination—comprising visual and microscopic inspections and mechanical testing—disclosed adhesion failure, porosity, and lack of sanding during surface preparation. These substandard bondlines were identified as contributing factors to this accident [41].

In 1995, the narrow-body airliner of event **TA11** experienced a separation of a half-meter long part of the aileron from the wing while descending. The airplane was slightly damaged, and all 84 occupants were unscathed. During the investigation, the OEM mentioned being unaware of any similar events. The likely cause of the disbond was improper repair (expired adhesive shelf-life) [42].

In 2000, a 1.8- by 0.4-meter portion of the flap metallic sandwich panel separated from the single-aisle airliner of event **TA12** during approach. This separation had minor consequences to the airplane and none to the 108 occupants. Investigation disclosed bond degradation associated with improper surface preparation (phosphoric acid anodization) performed during an overhaul. Insufficient information (e.g., maximum repair size) in the OEM structural repair manual also contributed to this incident [43].

In 2005, the wide-body airliner of event **TA13** lost its rudder during cruise causing Dutch roll. The crew managed to control the aircraft and land it safely at the airport of origin. There was no injury to the 271 occupants, despite substantial damage to the airplane. Investigation concluded that the likely sequence of events started with existing damage (weak bond) in the bondline of the composite sandwich rudder's inner skin. This damage grew due to the pressure difference between the core interior and the ambient air at altitude, remaining undetected for some time. Eventually, the damage suffered sudden explosive growth, causing collateral structural damages to the rudder. These collateral damages reduced the rudder torsion stiffness, resulting in flutter, which led to the separation of most of the rudder from the airplane [44]. As a result of this investigation, different civil aviation authorities (CAAs) issued airworthiness directives (ADs) requiring one-time and repetitive NDI of similar aircraft models' rudders. Similar findings were reported. For instance, about eight months after this event, a similar rudder of a wide-body airliner had been damaged during routine maintenance (**TA14**). As the lower rudder rib was removed for inspection, besides the damage that occurred during maintenance, an 838- x 355-millimeter disbond between the core and fiberglass composite skin was found. The region was contaminated with hydraulic fluid and water. These fluids chemically interacted with each other producing phosphoric acid. This acid led to the progressive growth of this disbond. This rudder was sent to the OEM for further examination. The OEM examination revealed disbond areas not covered by existing mandatory inspections. Other ADs mandating OEM documents followed this event [45].

In 2007, the narrow-body airliner of event **TA15** experienced severe vibration throughout the airframe during climb. The crew declared an emergency and landed uneventfully in the airport of origin. A post-flight inspection detected that a part of the right-elevator tab had separated and was missing. Investigation concluded that loose screws led to cracks and eventually to fiberglass skin-to-honeycomb core adhesion failure. This bond failure mode is typically linked to bonding process issues [17]. The report of prior similar events had led the OEM to issue SBs, and the Federal Aviation Administration (FAA) and Australian CAA to publish ADs. Maintenance records showed compliance with these ADs. In the airplane maintenance manual, the procedure for inspections to be followed after reported airframe vibrations was divided into two subparts: level I and level II inspections. Level I inspections were general inspections performed from the ground. In contrast, level II inspections required panel removal, measurements, and ground tests. The maintenance manual established level II inspections in case of detailed vibration reports (e.g., including specific vibration type, location, flight conditions). Despite the report of specific vibrations towards the rear of the aircraft the day before the event, the maintenance technician performed only general inspections (level I) of the region. These inspections had detected no anomaly. The fact that the aircraft's livery incorporated a black horizontal stabilizer might also have prevented a clear view of the region from the ground [46].

2.2 General aviation airplane

Bonded structures have been employed in general aviation (GA) airplanes for decades, including primary structures and even fully bonded airframes [10,47,48]. Table 2 lists 12 reviewed bond-related events involving GA airplanes. These events are subsequently sub-divided into wing (2.2.1), movable surfaces (2.2.2), and landing devices (2.2.3).

Table 2. Bond-related events involving GA airplanes

ID	Aircraft make	Model	Marks	State of registry	Date
GA01	SZD[a]	SZD-24-4A	N21714	USA	06/15/74
GA02	DG	DG-400	N400FJ	USA	05/01/99
GA03	ADC[b]	D4	unknown	unknown	03/22/00
GA04	Schempp-Hirth	Duo-Discus	unknown	unknown	07/25/03
GA05	Schempp-Hirth	Duo-Discus CS	D-8515	Germany	07/29/03
GA06	Textron Aviation	LC41-550FG	unknown	USA	12/06/10
GA07	Alexander Schleicher	K7	N12053	USA	03/30/13
GA08	Alexander Schleicher	ASW-15	N3644	USA	06/05/71
GA09	RUAG	DO 228-200	unknown	unknown	10/16/02
GA10	Flight Design	CTSW	D-MNOH	Germany	07/27/12
GA11	Textron Aviation	U206B	N206KY	USA	09/06/97
GA12	Diamond	DA 40	N323JT	USA	05/16/09
Note: [a]Szybowcowy Zaklad Doswiadczalny; [b]Aircraft Design Certification					

2.2.1 Wing

We found seven events involving bond failure of GA airplane wings.

In 1974, the sailplane of event **GA01** suffered an in-flight structural failure shortly after release from the tow plane. The pilot was killed, and the airplane was destroyed. The left wing folded over the fuselage and then detached from the aircraft. The wing structural layout consisted of a sparless torsion-box with a plywood-sandwich skin. Examination disclosed several substandard bonded joints within wing primary structures characterized by thick bondlines, poor adhesive bonding, and lack of adhesive. The aircraft's annual inspection had been performed about two months/twenty flight hours before this event. Investigation concluded that inadequate adhesive bonding and improper maintenance inspection procedures were the probable cause of this accident [49,50].

In 1999, the glider of event **GA02** experienced a loud bang while flying straight and level. The pilot lost control, elected to egress from the glider, and parachuted with only minor injuries. The aircraft broke apart in flight and was destroyed. Examination revealed that the structural failure started in a wing-to-fuselage attachment. In this attachment, an aluminum frame is held in place by inserting fiberglass tapes through this frame and then bonding these tapes to the fiberglass skin. Voids and evidence of adhesion failure were identified in this bonded region [51].

In 2000, the very light airplane of event **GA03** lost a large portion of the left wing during cruise flight. Once the aircraft emergency parachute failed, the airplane was destroyed, and both occupants perished. Inspections disclosed discolored (degraded) adhesive, voids, and interfacial failure in bonded joints of the wing spar leading edge skin and ribs. In some of these regions, disbonds were repaired during production by adding adhesive. Examination established that bonding failures in the leading-edge cause peel stress in the wing box bonded joints, eventually resulting in the wing overall failure. The investigators concluded that problems in the wing's bonding manufacturing process were the foremost cause of this accident. The investigators referred to temperature-related adhesive degradation—associated with dark color external painting—and high loading due to wind shear gusts as possible contributing factors to this accident [52].

In 2003, part of the left-outboard wing separated from the glider of event **GA04** during a typical maneuver to gain altitude. At the time of this accident, this plane had only 18 flight hours. The pilot managed to position the plane for a safe emergency jump. Both occupants parachuted safely while the glider was destroyed. The inspection detected a 200-millimeter adhesion failure in the bonded joint between the composite wing spar web and flange. Examination revealed that the know-how for the wing manufacturing involving different OEM sites was mainly based on on-the-job training, with limited written documentation for workforce instructions, process specifications, and acceptance criteria. Thus, investigation determined that the wing bonding process's improper quality control was the probable root cause of this event [53]. Only four days later, an accident alike involving an older airplane (with about 900 flight hours) of a similar model occurred (**GA05**). The glider lost a large part of the right-wing in flight due to a 400-millimeter bonding discrepancy in the flange-to-web spar joint, causing the plane's destruction and minor injuries to the pilot [54]. As a reaction to both events, the OEM published SBs, and the German and French CAAs issued emergency ADs.

In 2010, the composite wing of the airplane of event **GA06** experienced a substantial structural failure during a production audit test flight. About a 2.1-meter part of the sandwich skin disbonded from the upper front spar, damaging a fuel tank. The FAA test pilot precautionarily landed successfully. Examination disclosed that excessive moisture during manufacturing led to bond curing issues. This event prompted emergency ADs grounding 13 airplanes [19,55].

In 2013, the sailplane of event **GA07**, which was not approved for acrobatic maneuvers, had part of the right wing separated in flight during a tight loop that produced excessive loading. The airplane was substantially damaged, and both occupants perished. Examination revealed moisture ingress, adhesion failure, and cracked adhesives. The investigators concluded that bonding degradation, which was not detected during routine inspections, was a contributing factor to this accident [56].

2.2.2 Empennage

We found three bond-related events involving GA airplane empennages.

In 1971, the glass fiber sailplane of event **GA08** incurred an in-flight breakup and crashed. The student pilot perished. Examination revealed that the right-stabilizer detached from the aircraft, followed by other structures such as the left-stabilizer and the wing. Investigation determined that a lack of adhesion in the stabilizer leading edge caused this accident [57,58].

In 2002, while en route to a scheduled flight, the twin-turboprop airplane of **GA09** suddenly experienced severe vibration. This vibration led to reduced controllability, which prompted an emergency landing. Though substantial airplane damages occurred, all occupants debarked unharmed. Examination disclosed adhesion failure in the disbonded rudder skin that had detached in flight. During a repair performed three days before this event, the metallic rudder's bonded polyester skin had been replaced. This repair had been performed using adhesive material and surface preparation process per the German Aero Club procedure manual #101, which differed from the corresponding OEM maintenance manual. This lack of adherence to the manufacturer's data was the likely root cause of this accident [59].

In 2012, after hearing a loud bang, the pilot of the very light airplane of event **GA10** lost control and activated the emergency system. The aircraft was substantially damaged, and the occupant was severely injured. The left-horizontal composite stabilizer separated in-flight. Examination detected bonding discrepancies, including poor wetting, insufficient penetration, contaminations, and adhesion failure. Investigation concluded that this accident was caused mainly by the exceedance of the airplane speed limit (V_{ne}). The inadequate bonding resulting from improper quality control was a contributing factor [60,61].

2.2.3 Landing devices

We found two events involving bond failure in landing structures of GA airplanes.

In 1997, the seaplane of event **GA11** nosed over during a water landing. The aircraft was destroyed, and two of the four occupants were fatally injured. The outside hull metallic skins of the right-float disbonded from the keel. This region was found to be improperly repaired 48 flight hours before this event. The actual repair had not followed the component repair manual, which required riveting instead of bonding if the hull skin (initially bonded) needed to be reattached to the keel. Moreover, an inadequate disassembling method used during repair introduced defects in the bondline [62].

In 2009, a student pilot in his/her first solo flight caused the single-engine piston airplane of event **GA12** to enter a severe left skidding during land. The airplane was substantially damaged while the pilot suffered minor injuries. Investigation concluded that excessive side loads likely caused the main landing gear failure. Nonetheless, examination also disclosed adhesion failure, excessive adhesive thickness, and voids up to 35% in area in some composite main landing gear rib to airframe bonded joints [63].

2.3 Rotorcraft

There exist many type-certified rotorcraft models. For instance, in the USA alone, there are currently over 350 [64]. Structural bonding is typically applied in helicopters, particularly in rotor blades [65]. This section describes 39 bond-related events involving rotorcraft. These events are subsequently described, sub-divided into main rotor blade (MRB) (2.3.1), tail rotor blade (TRB) (2.3.2), and other than rotor blade (2.3.3) primary failure.

2.3.1 Main rotor blade primary failure

Table 3 lists 20 bond-related events involving rotorcraft in which MRB failure was a major contributing factor.

Table 3. Bond-related events involving rotorcraft caused by MRB failure

ID	Aircraft make	Model	Marks	State of registry	Date
R01	MDHI	369D	D-HMEN	Germany	08/18/95
R02	MDHI	369D	C-FDTN	Canada	12/10/97
R03	MDHI	369D	N5225C	USA	07/22/14
R04	Bell	407	PT-YSL	Brazil	04/09/00
R05	MDHI	369	C-GXON	Canada	10/31/00
R06	Robinson	R22	VH-OHA	Australia	06/20/03
R07	Robinson	R22	4X-BDM	Israel	02/29/04
R08	Robinson	R22	ZK-HWP	New Zealand	11/27/04
R09	Robinson	R44	VH-AIC	Australia	02/12/03
R10	Robinson	R22	ZK-HLC	New Zealand	03/04/06
R11	Robinson	R44	HI-803CT	Dominican Republic	10/11/06
R12	Robinson	R44	DQ-IHE	Fiji	12/05/06
R13	Robinson	R22 Beta II	VH-HPI	Australia	03/15/07

ID	Aircraft make	Model	Marks	State of registry	Date
R14	Robinson	R22 Beta	VH-HZB	Australia	12/29/08
R15	Robinson	R44	VT-HPC	India	08/14/13
R16	Bell	212	C-GNHX	Canada	06/10/05
R17	Bell	206L-1	N37AE	USA	08/31/08
R18	Bell	206L	C-GDQH	Canada	11/02/11
R19	Bell	206L-3	N708M	USA	03/29/09
R20	Leonardo	AW109SP	G-HLCM	UK	08/02/17

In 1995, the single-turbine-powered helicopter of event **R01** experienced separation of one of the five metallic MRBs before takeoff in Europe. The rotorcraft sustained severe damage, but all occupants were uninjured. Though the failed MRB was just short of its mandatory retirement, the post-accident inspection detected chordwise fatigue cracks and disbonds at the MRB root attachment. As illustrated in Figure 2, this attachment comprised five bolts connecting root fittings bonded to doublers, subsequently bonded to the MRB skin. Examination disclosed fatigue cracks stemming from the outer bolt region and lower root fitting-to-doubler disbonding. About 30% of the total disbond area had existed since manufacture. Close to 35% of the total disbond area had disbonded in-service before this accident. A similar rate of disbonding was found when the upper fitting was forcefully separated for examination. The manufacturing process review indicated the blade's misalignment in its fixture. This misalignment led to an improper adhesive cure. Moreover, the expected squeezing out of excessive adhesive was missing, and sealant was used to close the gap between parts. This use of sealant was disclosed as a common practice. The investigators concluded that improper bonding manufacturing likely resulted in the fatigue crack initiation, and eventually, the MRB failure. The OEM reacted to this event with SBs, and the FAA with ADs, which required one-time and repetitive inspections. Within ten years, similar fatigue cracks findings were reported in eight MRBs [66]. Similar events followed:

- A similar event (**R02**) occurred in North America with another helicopter of the same model about two years after **R01**. One metallic MRB departed almost entirely from the rotorcraft while entering a hover. The resulting violent lateral vibration caused the tail boom to separate. The aircraft was destroyed, and the pilot was severely injured. Investigation revealed that the blade failure included disbonds and chordwise fatigue cracks triggered by production non-conformities. These discrepancies consisted of non-conforming doubler curvature relative to the blade skin (Figure 2). These discrepant components were initially rejected but subsequently accepted. Such defects likely led to varying adhesive thickness, areas of improper bonding, and significant residual stresses in the blade skin, which eventually started the disbonds and fatigue cracks. Examination of the other four MRBs detected similar cracks and disbonds in the same location. This region had been inspected less than 50 flight hours before this event. After this event, the OEM established additional repetitive inspections in SBs. The FAA mandated these SBs [67,68].

- About 17 years after **R02**, in North America, another rotorcraft of the same model lost one MRB during an external load operation and subsequently crashed (**R03**). The rotorcraft was substantially damaged, and the pilot was seriously injured. The failure occurred in the bonded-bolted attachment at the blade root (see Figure 2). Material laboratory examination identified numerous fatigue cracks in the metallic adherends, adhesion failure, and contamination in the bondline. At the time of this event, SBs/ADs required inspections of that attachment, looking for possible disbonds/cracks. Investigation concluded that improper compliance with these documents was the probable cause of this event, aggravated by ambiguous inspection procedures. The OEM updated these procedures afterward [69].

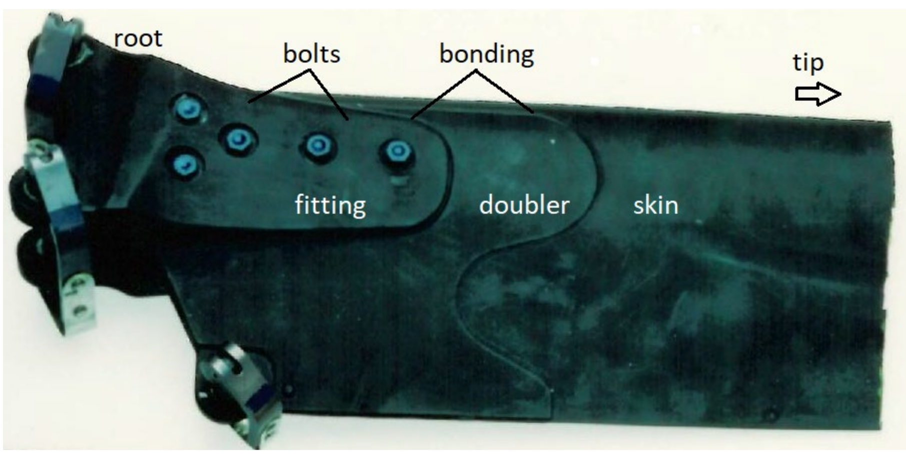


Figure 2. MRB root attachment [68] (modified)

In 2000, the seven-seat turbine-powered rotorcraft of event **R04** started vibrating while on cruise. The pilot performed an unscheduled off-airport landing for visual inspection. This inspection detected no anomaly. The pilot continued the planned flight, but vibration prompted a diversion to the closest airport. Another post-flight visual inspection again failed to detect any anomaly. Later inspections performed by maintenance personnel detected disbond in one of the MRBs. This MRB was removed from service and sent to the OEM for further investigations. These investigations identified a 1.4- by 0.13-meter disbond between one MRB's composite skin and honeycomb. Microscopic examinations revealed adhesion failure. Mechanical tests of samples showed signs of progression of the disbond, which were not detected by the NDI performed during production. The OEM claimed that it was an isolated case in the worldwide fleet. Investigation concluded that improper cure process control and inadequate post-cure inspections were probable causes of this incident [70].

Later that year, two-thirds of one of the five metallic MRBs separated from the single-turbine-powered rotorcraft of event **R05** while en route. This separation caused a loss of control and crash landing. The rotorcraft was destroyed, and the pilot perished. Visual and microscopic examination identified large voids in the bondline between the blade skin and the spar. Inside these voids, corrosion pits in the spar led to fatigue cracking, which eventually became unstable and failed before surfacing. Shortly after the accident, the OEM released an SB, which was mandated by an FAA AD. This SB called for a one-time inspection of the affected blades before the next flight and updating the acceptable void sizes for all new blades. These inspections revealed voids in several blades, which led to their removal from service [71].

In 2003, during a training flight, the two-seat piston-powered helicopter of event **R06** suffered an in-flight breakup and crashed. This crash fatally injured the flight instructor and student pilot. Wreckage inspections determined that one MRB failed in-flight at the root attachment. As illustrated in Figure 3, this attachment comprised bolted-bonded joints of metallic fitting, spar, skins, doubler, and core. Laboratory examination concluded that the MRB root attachment failed due to fatigue crack growth in the fitting and that disbond in that region was a contributing factor. The disbond increased bolt loads, prevented crack detection, and created a path for the ingress of water and other substances. These substances led to corrosion pits, fatigue crack nucleation, and ultimately the reduction in the time to fatigue failure. Two extensive surveys of retired MRBs (one including ten blades in Australia and another comprising 51 blades from different countries) with different times in-service and operational characteristics indicated that the disbonds were widespread [72–74]. Within the following 18 months, at least two similar accidents involving helicopters of the same model occurred: one (**R07**) during a powerline survey in the Middle East, leaving the two occupants dead [72,74], and another (**R08**) during an aerial agricultural operation in Oceania, resulting in severe injuries to the pilot [72]. These three events shared similarities regarding the disbond characteristics, fatigue crack patterns, and the fact that the failed MRBs had not reached the mandatory retirement life [72]. Reactions to these events included OEM SBs and ADs from different CAAs requiring either inspections in the MRB root attachment, MRBs removal from service, or reducing MRB retirement life.

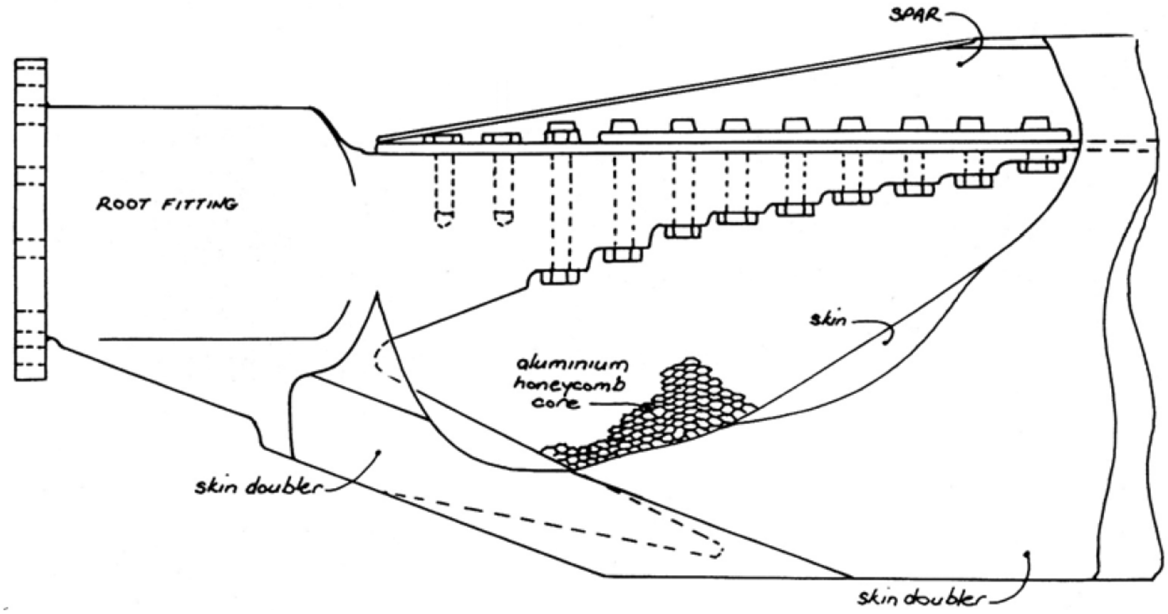


Figure 3. MRB spar root attachment [73] (modified)

Also in 2003, the four-seat piston-powered helicopter of event **R09** suddenly experienced an unusual noise associate with the MRB during cruise flight in Oceania. Intense vibration necessitated a forced landing in a paddock. The rotorcraft was substantially damaged, but the pilot and passenger suffered only minor injuries. Inspection detected a skin disbond of 1070- by 60-millimeter from the tip in one MRB and initial disbond in the other MRB. The local CAA subsequently issued ADs [75]. Similar events followed:

- About three years after **R09**, in Oceania, a two-seat rotorcraft of a similar model suffered an in-flight breakup and crashed, fatally injuring the two occupants (**R10**). The local CAA determined that this accident's root cause was the extensive damage to one of the metallic MRBs, which was impacted by a door that detached in-flight [76]. There was evidence of significant disbond, porosity, understrength (degraded) adhesive, and a high percentage of adhesion failure in the skin-to-spar joint towards the MRB tip. This evidence led to the conclusion that MRB substandard bonding was also a contributing factor to this event [77,78].
- About seven months after **R10**, in Central America, a similar accident occurred with a four-seat helicopter of a similar model (**R11**). One MRB skin's partial disbond caused the other MRB to hit the airframe and cut the empennage entirely off. The rotorcraft was destroyed, and all four people aboard were killed. Investigation disclosed high levels of adhesion failure and concluded that the MRB skin bonded joint strength had deteriorated over time [77,79];

- Less than two months after **R11**, in Asia, another similar event involving the same model led to the helicopter's destruction and the pilot's death (**R12**). While the cause of the accident has yet to be determined, widespread adhesion failure in the MRB skin towards the tip starting from the leading edge indicated bondline degradation [77];
- About five months after **R12**, in Oceania, a two-seat rotorcraft of a similar model suddenly experienced severe vibration during a demonstration of autorotation descent (**R13**). After the rotorcraft landed safely, a 450-millimeter disbond was found at the lower skin towards the tip of one of the metallic MRBs. Dusty environment caused erosion that abraded the MRB leading edge protective paint coatings. The exposed butt bondline eroded in a channel-like form, eventually leading to skin peeling separation. Investigation concluded that bonding manufacture defects such as voids and gaps contributed to environmental ingress, causing bondline degradation and skin corrosion, thus exacerbating the skin lifting. Evidence of a mixture of cohesion and adhesion failure in the bondline was also reported [80,81];
- Less than two years after **R13**, also in Oceania, another similar incident with the same model occurred (**R14**). Vibration caused by a 160-millimeter disbond in the metallic MRB prompted immediate, safe landing. Examination revealed porosity, micro-voids, and adhesion failure in the bondline. No evidence of compliance with relevant ADs was found in the maintenance logbooks [82];
- Almost five years after **R14**, a four-seat rotorcraft of a similar model suddenly shuddered exceedingly while en route in Asia (**R15**). A successful precautionary landing allowed the four occupants to disembark unharmed, though the rotorcraft was destroyed. Examination disclosed that one-third of one of the MRBs' outermost skin separated due to extensive disbonds. These disbonds started close to eroded finishings and comprised extensive adhesion failure. Post-accident examination of the other MRB revealed signs of similar disbond setting in. Both MRBs were from the same lot and had similar life at the time of this event. The rotorcraft was found to comply with applicable ADs and SBs motivated by previous similar events. A repair station had turned this helicopter to service one day before this accident. Three pre-flight inspections had been performed on the accident day [83].

At the time of these events, the failed MRBs had not exceeded the mandatory retirement life. Moreover, the percentage of adhesion failure in some areas was within the acceptable levels per OEM specifications. During the investigations, similar disbonds detected during routine maintenance were reported in at least ten other MRBs [77]. Throughout the years, the investigators of these similar events issued safety recommendations regarding bond durability issues and NDI [77]. In reactions to these events and related safety recommendations, the OEM issued several SBs and redesigned the MRB. Additionally, different CAAs published ADs, revised related airworthiness requirements, and the associated advisor circulars FAA AC 27-1B [84] and 29-2C [85].

In 2005, during cruise flight, the 15-seat twin-engine rotorcraft of event **R16** started to shake considerably after a series of loud bangs. Despite the reduced controllability, the pilot managed to perform a successful emergency landing. There was no injury to the three occupants, but the helicopter was substantially damaged. Post-flight inspections identified a 640- x 50-millimeter disbond in the lower skin close to the tip of one of the two metallic MRBs. Though a large area adjacent to this disbond had been repaired only four hours before this event, the investigation found no correlation between this repair and the observed disbond. Examination revealed core-to-skin disbonds and adhesion failures associated with manufacturing process deficiencies [86,87].

In 2008, the seven-seat turbine-powered rotorcraft of event **R17** experienced separation of a 2.4-meter section of one of the two aluminum MRBs while climbing. This separation rendered the aircraft uncontrollable, ultimately causing its destruction and the death of all three occupants. This failure was linked to production discrepancies, such as spar residual stresses and large voids (e.g., 234 x10 millimeters) in the lead weight-to-spar bonded joint. These discrepancies led to spar fatigue cracks. About one year later, the OEM issued an alert SB affecting over 2,500 blades that potentially contained similar manufacturing defects. This SB recommended recurring aided visual or definitive x-ray inspections for detecting cracks or voids. Due to the discovery of another manufacturing defect (oversize spar spacer), the OEM released another alert SB recommending reducing the service life of affected blades [88,89]. The primary CAA approved these SBs and mandated no further safety actions. About two years after the SBs' release, a similar accident occurred with a rotorcraft of the same model (**R18**). The rotorcraft was destroyed, and all three people on board perished. Besides the spar residual stress and large voids, in this case, the investigation also revealed microcracks in the inertia weight-to-spar bondline. These microcracks allowed moisture ingress in the void region, leading to metallic corrosion, which accelerated fatigue cracking. The recurring aided visual inspections recommended by the SB had been conducted 16 times before this event but did not detect the cracks [90].

In 2009, during a routine post-flight inspection in the metallic MRBs of a seven-seat turbine-powered helicopter, the crew detected some 230-millimeter long fatigue cracks at the trailing edge skin (**R19**). Investigation of this incident concluded that interconnected porosity in the bondline permitted environmental moisture ingress that subsequently led to corrosion and, ultimately, to these fatigue cracks' nucleation. The OEM noted that the manufacturing process included two independent leak tests to identify porosity in this bonded joint, but the corresponding test records indicated no discrepancy. The OEM also considered this event rare and detectable during routine maintenance or as a one-per-revolution vibration in flight [91,92].

In 2017, as the eight-seat twin-engine helicopter of event **R20** approached for landing, the pilot noticed controls and airframe vibration and safely landed in an adjacent field. A post-flight walk-around revealed that the tip cap of one of the MRBs was missing. Investigation determined that an error in the tip cap bonded joint's surface preparation likely caused its detachment in flight. The OEM published an SB, mandated by an emergency AD. This SB introduced recurring inspections to the potentially affected blades [93].

2.3.2 Tail rotor blade primary failure

Table 4 lists eight bond-related events involving rotorcraft in which TRB failure was a major contributing factor.

Table 4. Bond-related events involving rotorcraft caused by TRB failure

ID	Aircraft make	Model	Marks	State of registry	Date
R21	MDHI	369D	C-GPDH	Canada	05/10/94
R22	Air Space Design	FH-1100	N8171U	USA	08/14/98
R23	MDHI	369HS	N4278M	USA	06/07/99
R24	Southwest Florida Aviation	SW204	N37BA	USA	05/24/00
R25	Bell	212	C-FHDY	Canada	06/03/00
R26	MDHI	369E	N142MK	USA	01/21/05
R27	Robinson	R22	PT-YPB	Brazil	03/10/15
R28	Bell	407	N457PH	USA	05/02/17

In 1994, shortly after takeoff, the abrasion strip of one of the metallic TRBs separated from the single-turbine-powered rotorcraft of event **R21**. This separation caused the tail rotor assembly imbalance and, eventually, its departure from the rotorcraft. The pilot entered an autorotation and landed in a clearing. The helicopter suffered substantial damage, but the pilot and the two passengers were unscathed. At the time of the event, ADs requested additional rivets to work as a secondary load path to the abrasion strip bonding. These ADs also requested daily pre-flight inspections of the abrasion strip bonding. Investigation found that the operator complied with these ADs. Nonetheless, neither the inspection nor the redundant design feature prevented the in-flight separation of the abrasion strip. Though detailed examination revealed bonding adhesion failure, the investigators did not establish the cause of this joint failure [94].

In 1998, the four-seat turbine-powered helicopter of event **R22** experienced the separation of a large part of one of the metallic TRBs while in cruise flight. The rotorcraft was destroyed, and the pilot perished. One likely cause of this separation was an improper repair on the doubler-to-skin bonded joint to fix disbonds. At the time of this accident, the OEM maintenance manual explicitly did not permit skin, ribs, or doubler replacement. No approved data supporting this repair was found [95].

In 1999, the single-turbine-powered rotorcraft of event **R23** was in cruise flight when it suddenly started vibrating severely. The tail rotor assembly detached from the rotorcraft, which became uncontrollable, and crashed. Though the helicopter was destroyed, the occupants suffered only minor injuries. Investigation revealed that some weeks before the accident, the TRBs' adhesion strip had been removed by applying direct heat, which likely damaged bondlines in the blade. This repair had neither been approved nor recorded in the logbooks. A few days before the accident, the pilot, who was also a mechanic, had noted a gap in the TRB tip cap. The pilot tap-tested the region and repaired the gap with resin. At that time, an OEM SB required blade replacement when disbond evidence was detected [96].

In 2000, the single-turbine-powered helicopter of event **R24** lost control and was substantially damaged after a tail rotor tip weight separated in-flight. The pilot was uninjured. Both the bonded joint (primary load path) and the precautionary fasteners (secondary load path) failed. The installation of a suspected unapproved TRB was the probable cause [97].

In the same year, a TRB's tip weight on the 15-seat twin-engine helicopter of event **R25** detached in-flight during a practice power recovery autorotation. This detachment caused severe vibration. The crew was left unhurt from the emergency landing, despite substantial damages to the rotorcraft. Investigation determined that the probable cause was inadequate TRB's tip weight joint manufacturing. These manufacturing issues led to (i) disbond caused by environmental moisture degradation and (ii) precautionary fasteners failure due to holes being drilled larger than specified in the OEM's drawing [98].

In 2005, a TRB abrasion strip departed the single-turbine-powered rotorcraft of event **R26** in-flight. The resulting imbalance forced an off-airport autorotational landing. Though there was substantial damage to the aircraft, all five occupants were unscathed. These TRB abrasion strips were held to the blade primarily by bonding and secondarily by fasteners. Investigation determined that adhesion failure and fatigue fracture at the metallic strip's rivets were the probable cause for the strip separation from the TRB. Though the cause of the bond degradation was deemed unknown, there were indications that the strip was disbonded entirely for some time. The pre-flight and 100-hour maintenance actions required only visual inspections. Only if these visual inspections detected disbond at the strip's edge were additional NDIs required [99].

In 2015, the two-seat piston-powered helicopter of event **R27** lost the tip cap of one of the metallic TRBs during an instruction flight. The emergency landing rendered minor damage to the aircraft but no harm to the crew. At the time the investigation report was issued, the cause of the disbond remained undetermined. However, the investigation suspected environmental degradation of the adhesive [100].

In 2017, while en route, the seven-seat turbine-powered helicopter of event **R28** lost the tip block and weights of one of the composite TRBs. The rotorcraft was severely damaged, but none of the six occupants were injured. Examination revealed incomplete bonding due to voids in about half of the bond area. The tip block had been repaired approximately 65 hours before this event. According to the OEM, after a TRB was repaired, the tip block was pull-tested (considering the blade maximum angular velocity), tap-tested for void detection, water-tested for leakage check, and the skin patch material was peel-tested. The investigators concluded that these post-repair tests were inadequate to detect insufficient adhesive bonding. After the accident, the OEM revised the repair procedures to use only positive pressure instead of vacuum during the curing cycle. The revised repair procedures also expanded post-repair inspections [101,102].

2.3.3 Other than rotor blade primary failure

Many rotorcraft contain bonding in structures other than rotor blades. Table 5 lists the 11 bond-related events involving rotorcraft in which the main contributing factor was a structural failure of a structure other than the rotor blades.

Table 5. Bond-related events involving rotorcraft caused by not blade-related failure

ID	Aircraft make	Model	Marks	State of registry	Date
R29	Bell	206B	N33PW	USA	08/12/87
R30	Bell	206B	N90307	USA	08/23/00
R31	Bell	206B	N21424	USA	06/17/93
R32	Bell	206B	N7929J	USA	08/23/97
R33	Sikorsky	S-92A	G-CHCK	UK	04/23/07
R34	Sikorsky	S-76A	N574EH	USA	03/15/13

ID	Aircraft make	Model	Marks	State of registry	Date
R35	Airbus Helicopters	AS355	ZK-IAV	New Zealand	04/13/08
R36	Leonardo	AW139	A7-GHC	Qatar	08/25/09
R37	Bell	UH-1H	N205KS	USA	06/24/10
R38	Sikorsky	S-76A	C-GHJT	Canada	08/13/12
R39	Leonardo	A109E	G-ETPI	UK	06/27/19

In 1987, the five-seat turbine-powered rotorcraft of event **R29** suddenly experienced severe vibration while in cruise flight. This vibration prompted an autorotation to a road. This emergency landing rendered substantial aircraft damaged. All four occupants were unhurt. The vibration was caused by the joint's disbond between the upper plate and the rubber damper element (molded gasket) of a pylon isolation mount, as illustrated in Figure 4. Investigation revealed that the likely cause was bond degradation due to exposure to oil and grease. Despite the indications that the degradation occurred over a long time, periodic inspections had not detected this degradation [103]. About 13 years later, a similar event (**R30**) occurred with another helicopter of this model shortly after landing. The rotorcraft was also substantially damaged, but the pilot, the sole occupant, was unharmed. Examination concluded that inadequate surface preparation of the metallic center plate to the elastomeric blocks bond likely caused the pylon isolation mount interfacial disbond [104,105].

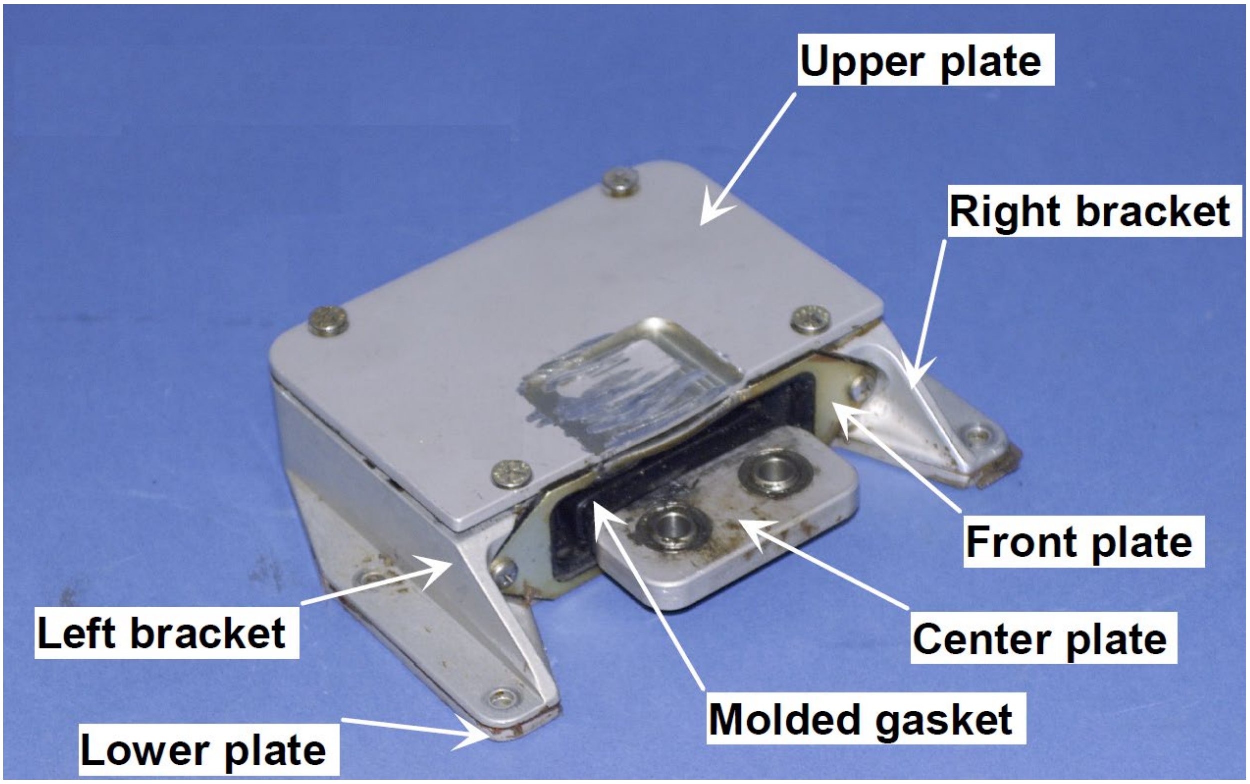


Figure 4. Pylon isolation mount [103] (modified)

In 1993, the five-seat turbine-powered rotorcraft of event **R31** was approaching landing when it lost tail rotor control due to a tail rotor drive shaft failure. All four occupants were unscathed despite substantial aircraft damages. This helicopter had been previously involved in a tail strike accident. The same metallic shaft had been installed back in the aircraft after inspections for damage. For these inspections, an unapproved process (plastic medium blasting) for paint/coating stripping was employed. This process triggered irregular edges and induced stresses in some of the shaft bondlines. These discrepancies caused disbonds between the shaft and the couplings. Together with existing voids, these voids eventually led to shaft failure. Some shaft sections disbonded only when the rotorcraft impacted the ground during this accident [106]. Four years later, a helicopter of a similar model lost a metallic tail rotor drive shaft during an external load operation, reducing aircraft controllability (**R32**). The reduced controllability damaged the aircraft substantially. The pilot suffered no injury. Examining the joint's disbond between the shaft tube and the fitting flange showed adhesion failure and adhesive degradation. The use of an unapproved surface preparation process (blast media impingement) during a repair likely caused these defects. This unapproved process compromised the moisture barrier of the joint, allowing moist chloride ingression that eventually chemically attacked the joint [107].

In 2007, the twin-engine transport rotorcraft of event **R33** suddenly started vibrating heavily while en route over water. The crew managed to continue to fly for about half an hour until performing a successful precautionary landing. None of the 17 occupants onboard were injured. Investigation concluded that a disbond of the bearing retainer from the flexible spar probably led to a TRB pivot detachment. This detachment caused the tail rotor to become out of balance and ultimately produced severe vibration. As illustrated in Figure 5, these pivots comprise elastomeric bearings connecting the composite TRB flexible spars to the graphite-epoxy torque tube. At the time the investigation report was published, the root cause of the retainer disbond was undetermined. At that time, there were reports of at least sixteen similar events. The OEM revised the maintenance manual to establish repetitive visual inspections. This rotorcraft's tail had been inspected 53 flight hours before this incident without any defect reported [108]. A TRB detached the tail rotor of the twin-engine transport rotorcraft of event **R34** during a post-maintenance flight about six years later. The rotorcraft was destroyed, and all three occupants perished. The tail rotor comprised two blade assemblies. Each assembly consisted of one composite spar and two TRBs. Each TRB was attached to the spar via bolts at the tip and elastomeric pivot bearing at the root. The failed TRB fractured its spar close to the pivot bearing. Examination revealed adhesion failure in the bonded pivot bearing retainer (primer/rubber and primer/metal interfaces). Adhesion failure is typically linked to bonding process issues [17]. The last 1500-hour inspection, which requires pivot bearing disassembly for inspection, had been performed about six flight hours before this accident. Investigation could not determine the cause of this accident, as many failed parts were not retrieved. Nonetheless, the pivot bearing's anomalous operation was deemed a possible cause [109,110].

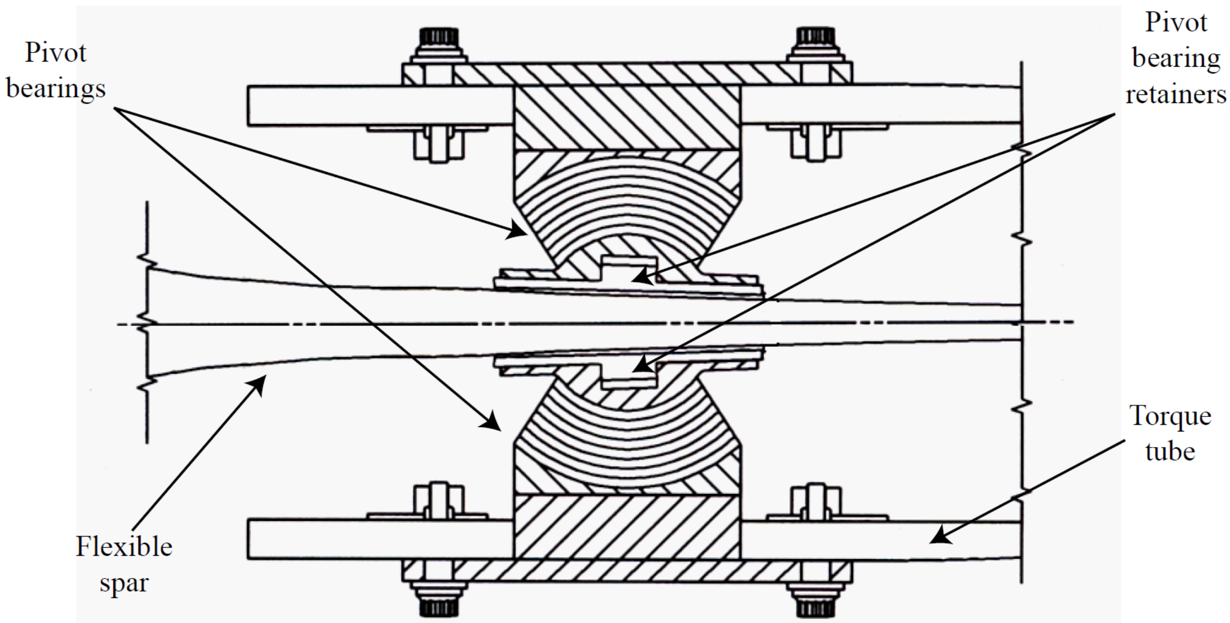
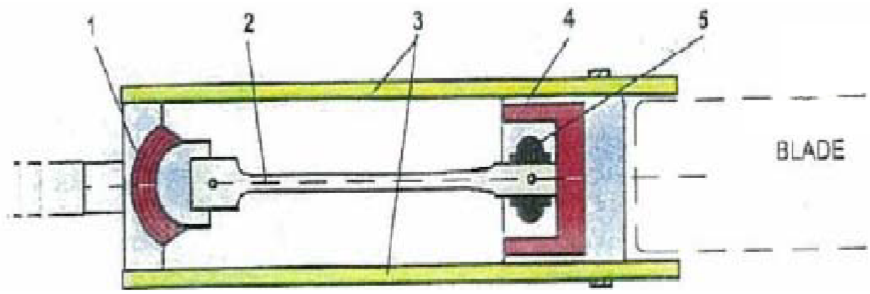


Figure 5. Longitudinal section through the tail rotor pivot bearing [106] (modified)

In 2008, the five-seat twin-engine helicopter of event **R35** made loud bangs two minutes after taking off. Reduced controllability prompted a precautionary landing on a field. The helicopter ended substantially damaged while both occupants were unhurt. One of the three MRB spherical thrust bearings failed. As illustrated in Figure 6, this bearing comprised elastomers bonded to metallic parts. A pre-existing disbond led to interface corrosion and then to bond failure. About half of the failed interface presented evidence of corrosion pits or smooth separation. No noticeable deterioration of the elastomer itself was observed. These bearings had a retirement life based on flight hours, not on calendar. The rotorcraft had been stored for 25 years before returning to service. Between the return to service and the accident day, at least four different repair stations had inspected the on-condition elastomers and associated bonded joints several times and had considered them airworthy [111].



1. Laminated spherical stop
2. Star arm (glass fiber reinforced plastic)
3. Sleeves (glass fibler reinforced plastic)
4. Elastomer blocks
5. Self-lubricating balljoint

Figure 6. Main rotor head cross-section [109] (modified)

In 2009, the twin-engine transport helicopter of event **R36** experienced a tail boom structural collapse during taxi. All 14 occupants debarked unharmed, but the rotorcraft was substantially damaged. The tail boom sandwich panels suffered widespread disbond. According to the investigation report [112], these panels were made of aluminum facings bonded to a Nomex honeycomb core. Extensive mechanical tests, simulations, and inspections supported the inspector's conclusion that pre-existing hidden Nomex damage likely caused the mainly cohesive disbond. Some months before this event, there had been a tail strike. The tail structural repair had been performed per the manufacturer's instructions, but the requested hammer tap test had not detected any Nomex damage. The investigators found reports of other in-service tail boom panel disbond. Such findings prompted several OEM SBs mandated by European emergency ADs requesting recurring NDIs in the region [112].

In 2010, the pilot heard a loud sound while hovering, as the single-turbine-powered rotorcraft of event **R37** started to yaw slightly; the pilot opted for a precautionary landing. None of the five occupants were hurt, despite the helicopter being substantially damaged. Examination revealed that a metallic tail boom attachment fitting failed. This fitting was bonded and riveted to the longeron. These fitting-to-longeron bonded surfaces showed evidence of fretting and corrosion, from which fatigue cracks had nucleated. Investigation did not establish the exact cause of fatigue failure. Nonetheless, bond failure and defects could permit relative movement and moisture ingress between these surfaces. No OEM or third-party fatigue analyses of this fitting or adjacent structures had been located. Numerous supplemental type certificates (STCs) (e.g., updated engine, strakes, TRB) modified this rotorcraft, but no engineering data addressing the impact of multiple STCs on structural integrity was found. The investigators found reports of similar failures during maintenance due to excessive assembly loads resulting from misalignment and improper shimming [113,114].

In 2012, the twin-engine transport rotorcraft of event **R38** experienced an engine failure while about 23 meters away from a floating helipad and 15 meters from the water. The pilot deployed the emergency flotation system and successfully ditched the helicopter. Both occupants disembarked safely. About four minutes after ditching, the aircraft rolled over and sank. Examination revealed that the failure of the outer combustion case caused the loss of power in one engine. Examination also disclosed that the failure of an inflatable nose float bonded seam led to the destruction of the rotorcraft. Signs of cracks, adhesion failure, and adhesive peel and shear understrength indicated bondline degradation. Existing maintenance inspections had not detected this degradation. The investigators concluded that, in this case, the emergency floats fulfilled their intent to allow the occupants time to exit the aircraft. However, the investigators acknowledged the risks of floats failures considering the potential bond degradation associated with limited inspection standards and the lack of life limits [115].

In 2019, during a post-maintenance flight, the door acrylic window separated from the eight-seat twin-engine rotorcraft of event **R39**. Fortunately, the separation caused no secondary damage, and the helicopter landed without further incidents. Investigation determined that the likely cause of the disbond was deviations from the prescribed procedures in the maintenance manual during the window reinstallation. Such deviations included: the application of an inadequate quantity of adhesive, excessive use of an overly soapy solution to fit the seal, and the lack of staged independent inspection [116].

2.4 Propellers

There are numerous bonding applications in propellers, spanning from protective shields to primary hybrid joints [15]. Table 6 lists five bond-related events involving propellers.

Table 6. Bond-related events caused by propeller failure

ID	Make[a]	Model[a]	Marks	State of reg.	Date
P01	Textron (Hartzell)	1900D (HC-E4A-31)	N251GL	USA	08/19/98
P02	Embraer (Hartzell)	EMB-120 (unknown)	VH-FNQ	Australia	11/13/99
P03	B-N (Hartzell)	BN2A (HC-C3YR-2CUF)	G-BEVT	UK	07/23/04
P04	B-N (Hartzell)	BN2A (HC-C3YR-2CUF)	G-BEVT	UK	04/24/05
P05	GROB (Hoffmann)	G115 (HO-V 343 K-V)	G-BYVE	UK	08/24/16
Note: [a]aircraft (propeller)					

In 1998, shortly after takeoff, a nickel erosion shield detached from a composite propeller of a twin-turboprop commuter airplane's left-engine. This detachment caused vibration and noise that prompted the crew to return and land safely (**P01**). Debris penetrated the passenger cabin, traveling so far as to damage the inner window pane on the fuselage's opposite side. Despite the airplane's substantial damages, only one of the 15 occupants sustained minor injuries. About one month before this event, all four propellers had been last overhauled and repaired using adhesive injection. Inspections of the failed surface identified the repaired area and revealed extensive adhesion failure. Chemical analyses of the adhesive EA9330 indicated that part A and B mixing ratio in use did not match the adhesive material datasheet. Inspections (e.g., tap test) and disassembly of the other three propellers detected similar interfacial disbond and cracks [117–119].

In 1999, in a similar incident (**P02**), a twin-turboprop regional airliner lost the nickel leading edge erosion protection strip of a left-engine composite propeller while applying takeoff power. This strip bounced off the tarmac and hit one of the right-propellers. The crew turned all engines off, and all occupants debarked safely. Examination revealed bondline contamination with silicone from an adhesive tape used in the bond process during a repair. As reactions to this event, these bond procedures were updated and incorporated in the component maintenance manual [120].

In 2004, shortly after takeoff, a loud bang was heard inside the ten-seat three-piston airplane of event **P03**. The pilot elected to return and landed safely in the airport of origin. A post-flight inspection observed that the de-icer boot disbonded and separated from one of the left-engine propellers. The separated de-icer boot broke a cabin window, seriously injured one passenger, and slightly injured another. This de-icer boot eventually came to rest on a seat. Investigation determined that the bonding probably failed in peel due to adhesive degradation. A requested sealant fillet had not been applied during maintenance. The lack of this sealant fillet allowed moisture and contaminants to ingress, generating peel stresses. These contaminants and stresses led a pre-existing small unbonded area close to the propeller's root to grow up to an abrupt failure of the remainder of the adhesive. After this event, the UK CAA identified about 100 propellers overhauled without applying the required sealant fillet [121]. Some months later, the *same aircraft* experienced a muffled bang during the takeoff ground roll. As all indications were standard, the crew proceeded to the planned destination (**P04**). Upon arrival, the de-icer boot—this time from a right-engine propeller—was missing. This propeller had already been overhauled considering the revised procedures to ensure the application of the required sealant fillet and the use of an alternative adhesive system recommended by the propeller OEM. Investigation revealed that the cause of the separation was not the same as in the previous event.

In this case, inadequate adhesion between the boot and the adhesive allowed moisture ingress. Moisture led to adhesive degradation and, ultimately, adhesion failure. Examination disclosed the use of an accepted alternative boot and differences in the curing cycle between the propeller OEM's and the boots manufacturer's manuals. For proper boots bonding, investigators recommended good practices highlighting that "apparently quite minor deviations in the process can cause a reduction in bond strength" [122].

In 2016, during takeoff, the two-seat single-piston airplane of event **P05** started to vibrate severely after a loud noise was heard. The pilot completed an emergency landing uneventfully. A walk-around detected the separation of the anti-erosion sheath from one of the composite propeller blades. Investigation determined that the disbond was likely caused by insufficient adhesive, excessive sanding during surface preparation, and improper cleaning before bonding [123].

2.5 Engines

In relatively cold areas of engines, there are some applications of structural bonding. Table 7 lists two bond-related events involving engines.

Table 7. Bond-related events caused by engine failure

ID	Make[a]	Model[a]	Marks	State of reg.	Date
E01	Boeing (Rolls Royce)	747-400 (RB211-524)	G-BNLD	UK	03/01/02
E02	Fokker (Rolls Royce)	F28 (TAY-620-15)	unknown	unknown	01/05/04
Note: [a]aircraft (engine)					

In 2002, the failure of one of the four engines caused severe vibration to the wide-body airliner of event **E01**. The airplane safely landed in the airport of origin, substantially damaged but with no harm to any of the 290 occupants. Post-flight inspections revealed that a sandwich blade—made of two titanium plates and a metallic honeycomb core—separated from the first-stage, low-pressure compressor in-flight. The blade separation led to secondary damage to the engine in which it was installed, the wing, the flaps, the fuselage, the horizontal stabilizer, and the adjacent engine. Fatigue cracks originating in a pre-existing disbond—depicted in Figure 7—led to the blade separation. The engine OEM had detected and 'concessionally' accepted this pre-existing disbond during manufacture. This approximately round disbond grew in service from 12 mm to about 22 mm in diameter. None of the three different required maintenance NDIs—established for spotting other probable defects in the blade—had detected the disbond growth or the fatigue cracks before becoming critical. After this accident, the engine OEM revised the 'concessional' acceptance system and reduced by half the related allowable damage. The engine OEM also issued SBs applicable to the other aircraft models using a similar engine. These SBs recommended the removal from service of all blades with similar manufacturing defects [124].

Figure 7. Failed blade: a) Cross-section showing the disbond (D); b) Initial (Di) and final disbond (Df) shape [124] (modified).

In 2004, the twin-jet regional airliner of event **E02** experienced heavy vibrations in, and partial power loss of, engines during approach. The crew performed an emergency off-airport landing. This landing severely damaged the airplane and lightly injured three of the 32 occupants. Post-flight inspections revealed that a low-pressure compressor's obstruction led to both engines' loss of power. Disbonded ice impact panels obstructed the compressors. An engine OEM's SB—issued in response to previous bonding issues—recommended replacing these panels. Two different organizations—located in different countries (the UK and the USA)—had incorporated this SB in both engine fan cases long before this event (over 5,000 flight hours). Adhesion failure and adhesive degradation found in most of these composite-to-steel bonded joints indicated substandard surface preparation. Examination revealed that inadequate bonding procedures contributed to the substandard surface preparation. These inadequate bonding procedures included excessive cross-references among manuals, editorial errors, misleading instructions, undefined special tools, unspecified consumable materials, mismatch with the adhesive specification, and inconsistent curing data. Investigation concluded that these inadequate bonding procedures and unsuitable adhesive selection caused progressive (undetected) bond failures due to (diffused) moisture cyclic freezing. These progressive bond failures led to eventual ice impact panels peel away, the accumulation of panels' debris inside the engines' compressors, and ultimately to vibration and loss of engines' power. These bond failures negated a failure mode effect analysis (FMEA) assumption that ice impact panel failures would unlikely cause loss of both engines simultaneously. This event motivated an AD requesting visual inspections of the ice impact panels. Compliance with this AD prompted the replacement of about 30% of the affected panels. Another AD mandated an SB changing the adhesive. At least one other similar event was reported [125].

3 Analysis of the reviewed data

The previous section summarizes the 73 reviewed bond-related events. Each event's root causes were classified as design, production, operation, or maintenance. As illustrated in Table 8, maintenance and production issues were likely contributing factors in most of the reviewed bond-related events (60 of 73), which could frequently be linked to bonding process issues. As bonding is strongly process-dependent, these issues potentially represent shortfalls in type, production, or maintenance certifications.

Table 8. Root causes of the reviewed bond-related events

Root cause class	Reviewed bond-related events[i] [%]
Production	52
Maintenance	36
Design	21
Operation	3
Undetermined	8
Note: [i]As each event might have more than one root cause, the total exceeds 100%	

We grouped the reviewed bond-related events into five groups according to the joint substrate materials: metals, composite, hybrid, others, and unknown. As illustrated in Table 9, almost half of these bonded joints (33 of 73) comprised metallic adherends, and approximately one-fourth of them (17 of 73) joined composite substrates. Evidence of bond environmental degradation or adhesion failure was observed in over half of the reviewed bond-related events (at least 42 of 73). About two-thirds (21 of 33) of the metallic joints and over one-third (7 of 17) of the composite joints presented evidence of bond environmental degradation or adhesion failure.

Table 9. Reviewed bond-related events per joint substrate material

Joint substrate material	Bond-related events [%]
Metal	45
Composite	23
Hybrid[ii]	7
Other[iii]	15
Unknown	10
Notes: [ii]Hybrid=composite-metal; [iii]Other=e.g., wood, elastomer, cloth	

The reviewed data illustrated that bonded joints, the failure of which can contribute to aircraft accidents, exist in a wide range of aeronautical products. Table 10 grouped these events considering the aeronautic product category containing the primarily failed bonded joint(s).

Table 10. Reviewed bond-related events per aeronautic product category

Aeronautic product	**Bond-related events [%]**
Rotorcraft	53
Transport airplane	21
GA airplane	16
Propeller	7
Engine	3

The reviewed data permitted observations related to the current certification policies. The current certification policies [5,23] require well-defined and controlled bonding processes. As *localized* understrength might yet occur, these policies propose three choices of expected additional layers of protection: 1) demonstrate limit load capability if the bond fails between arresting features; 2) test limit load capacity of each manufactured bonded joint; or 3) use NDI to ensure the bond's full strength. The compiled data suggested that no additional protection layer *alone* can ensure the required minimum level of safety if the bond process is inadequately validated and controlled. For instance:

- Load path redundancy or damage growth arrest features might not ensure the structural integrity with the expected reliability in case of bond failure linked to inferior processing (e.g., events **TA01**, **R21**, **R24**, **R25**, R26).
- Damage tolerance-based maintenance actions or more sophisticated NDI techniques might not detect substandard bonding defects before they reach critical sizes (e.g., events **TA01**, **TA08**, **GA01**, **R28**, and **R29**).
- Environmental protections such as sealant might not prevent a substandard bonded joint from degrading over time (event **P04**).

The reviewed data also illustrated the bonding dependence on processing. Even minor deviations to the bonding process (e.g., event **P04**) might significantly impair the joint structural performance. Similarly, inadequate bonding process instructions (e.g., event **E02**) might jeopardize the expected level of safety.

The reviewed data allowed observations on the severity of the event involving different aircraft categories. The NTSB classifies the severity of damage to the aircraft resulting from an accident as minor, substantial, or destroyed [126,127]. The NTSB also classifies the level of injuries sustained because of the event as none, minor, serious, or fatal. Figure 8 illustrates the severity of the damage inflicted on aircraft for the reviewed bond-related in-service events per aircraft category. The highest level of injures among all injuries sustained because of the event is similarly depicted in Figure 9. These data suggest that more severe damage to the aircraft and injury to the occupants occurs in bond-related accidents/incidents involving GA airplanes and rotorcraft than those involving transport airplanes.

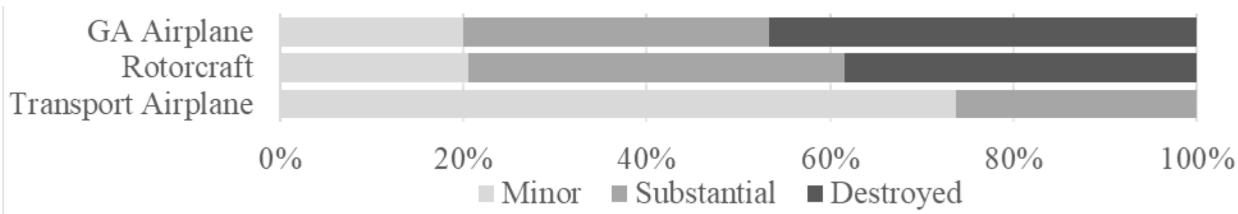


Figure 8. The severity of aircraft damage per aircraft category (engine and propeller included)

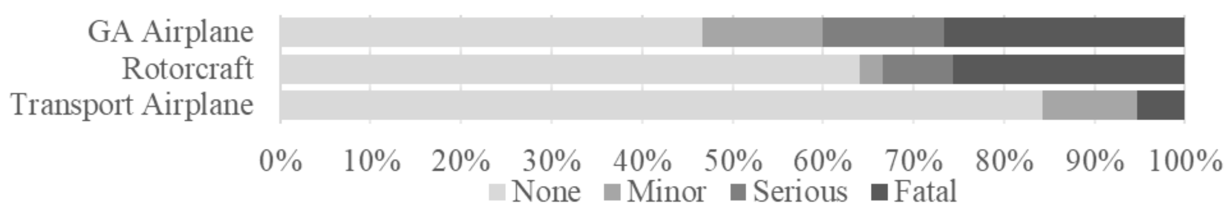


Figure 9. The highest level of injures per aircraft category (engine and propeller included)

We also investigated the potential relationship between the number of bond-related events and the different aircraft categories. The number of accidents/incidents is likely directly correlated with the size of the aircraft fleet. Thus, the number of events involving each aircraft category was weighted, considering its proportion in the fleet (Equation 1). The USA has the largest registered civil aircraft fleet in the world. For instance, in 2019, there were over 232,000 type-certified aircraft with valid US registration [128]. Though the absolute number of this fleet has more than doubled in the previous decade, the proportion of rotorcraft, transport airplanes, and GA airplanes remained relatively stable with a mean and standard deviation of 6% ±0.8%, 8% ±0.4%, and 84% ±0.4%, respectively [128]. Assuming no significant change to these proportions has occurred over time, the weighted number of bond-related events involving rotorcraft, transport airplanes, and GA airplanes is on the order of 630, 250, and 18, respectively. This result suggests that accidents/incidents in which bond failure was a contributing factor occurred more often with rotorcraft than with GA or transport airplanes. It is noteworthy that in about three-quarters of the helicopters' events, failure occurred in rotor blades or parts thereof.

$$N_w^i = \frac{N_o^i}{\left(N_a^i / N_a^t \right)} \quad (1)$$

where:
N_w^i= weighted number of events of the *i*-th aircraft category;
N_o^i= absolute number of events of the *i*-th aircraft category;
N_a^i = size of the fleet of the *i*-th aircraft category;
N_a^t = total fleet of type-certified aircraft with valid registration.

The reviewed data illustrated the adverse effects of substandard bonded joints on overall structural integrity. Even in some structures not typically classified as 'critical structure' [5], 'principal structural element' [129], or 'safety of flight structure' [130], poorly prepared bonding might lead to potentially unsafe conditions. For instance:

- the separation of doors (e.g., event **R39**) and fairings (e.g., events **TA03** and **TA05**) might lead to secondary impact damages,
- shield detachments might lead to severe vibration (e.g., events **R21**, **R23**, **R26**, **P01**, **P02**, and **P05**) or loss of engine power (e.g., event **E02**), which significantly increase the risk depending on the phase of flight and severity, and
- failure of emergency floating devices (e.g., event **R38**) might reduce survivability.

Moreover, the reviewed data illustrated that bonding defects might also indirectly contribute to structural failures. For example, microcracks, interconnected voids, or excessive porosity might permit environmental fluid ingress, triggering corrosion and the nucleation of fatigue cracks in the adherends that might grow undetected until the structural failure (e.g., events **R05**, **R18**, **R19**, R32).

It is worthy to note that the investigations' rigor level varied among the reviewed events. Some investigations included additional engineering data (e.g., NDIs, microscopic examinations, material analysis, mechanical tests, or numerical simulations), while others did not. Events with a higher degree of perceived potential unsafe conditions were investigated in more detail: for instance, severe events involving a high number of occupants (such as in transport airplanes and large helicopters (e.g., events **TA06** and **R33**)) or potentially affecting a significant part of the fleet (e.g., events **R06** to **R08**). Other factors—such as the complexity of the root cause, public opinion, and resources available by the investigating institution—might also play a role in the investigation's rigor. Regardless of the reason, a less thorough investigation might affect the proper identification of bond failure modes. The identification of bond failure modes is relevant for safety recommendations. Additionally, other aspects could also impact this identification [17]. One of them is that causes other than bond failure (e.g., weather issues or crew mishandling) are more frequently the major contributing factor of aircraft accidents/incidents. As a result, many investigators ended up having minimal exposure to bond-related investigations

[17]. Finally, the investigators' inadequate formal training on adhesive bond failure forensics might impact the proper bond failure mode identification [17].

4 Conclusions

Over the last seven decades, civil aircraft in-service experience has been documented worldwide in numerous aircraft accident/incident investigation reports, safety recommendations, and ADs. From these documents, we reviewed, summarized, and compiled 73 events where bond failures were contributing factors. These bond-related events support the following observations:

- In most of the reviewed events (59 of 73), the accident investigators identified bonding process issues that originated during maintenance/production as contributing factors. These issues potentially represent shortfalls in type, production, or maintenance certifications.
- Aircraft accidents/incidents having bonded joints failure as a major contributing factor can be found in different categories of aeronautical products such as transport and GA airplanes, rotorcraft, propellers, and engines (see Appendix A).
- In most of the reviewed events (at least 42 of 73), the accident investigators observed environmental degradation or adhesion failure in the failed bonded joints. About two-thirds (21 of 33) of the metallic joints and over one-third (7 of 17) of the composite joints presented evidence of bond environmental degradation or adhesion failure.
- Among the reviewed events, those involving GA airplanes and rotorcraft led to more severe damage to the aircraft and injury to the occupants than those involving transport airplanes (see Appendix A).
- Among the reviewed events, those involving helicopters were observed more often than those involving GA or transport airplanes. In the majority of cases in helicopters (28 of 39), failures were in rotor blades.
- The reviewed data illustrate that substandard bonding in structures that are typically not classified as safety-critical can lead to potentially unsafe conditions (e.g., events **TA03**, **TA05**, **R10**, **R20**, **R21**, **R23**, **R26**, **R38**, **R39**, **P01** to **P05**, and **E02**).
- Bonding defects might threaten the substrates' environmental protection and indirectly contribute to structural failures (e.g., events **R05**, **R18**, **R32**).
- The investigations' level of rigor varied among the reviewed events. This variation might have impacted the bond failure modes' identification. Investigators' limited training on bond failure forensic and minimal exposure to bond-related investigations might also impact this identification [17]. This identification is vital for safety recommendations.

These observations are consistent with current certification guidance materials and policies [5,23]. They emphasize the need for a "process control mentality" and durability substantiation to ensure the long-term safe operation of bonded structures. These needs are more evident in, but not restricted to, critical structures with limited load path redundancy (e.g., rotorcraft blades). No additional layer of protection—such as added load path redundancy, damage growth arrest features, airframe environmental protection, damage tolerance-based maintenance actions, or more sophisticated NDI techniques—can *alone* warrant the expected joint structural performance in case of inadequate bond process control/validation and lack of durability substantiation.

5 Recommendation for future work

This study was based on a limited number of events. Additional aircraft accident/incident investigation reports, ADs, service difficulty reports, or proprietary data from OEMs, operators, and the military fleet could complement the observations presented herein.

As the reviewed data illustrate, commonly used NDI techniques can detect some lack of adhesion (e.g., voids) but are unlikely to find substandard bonds (e.g., weak bonds) or indications that the adhesive entered a non-linear, history-dependent behavior [8,131]. Moreover, in many cases (e.g., rotor blades), critical flaw sizes depend strongly upon structural details and sections. Thus, the long-term structural reliability of such bonded joints could be enhanced by judiciously applying special NDI techniques (e.g., to detect signs of bond environmental degradation) or design features (e.g., for damage growth arrest). Research on these applications would represent a contribution to the field.

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A Summary table of reviewed bond-related events

ID[a]	Make	Model	Marks	Date	Damage Severity[b]	Highest Level of Injury[c]	Joint Type[d]	Root Cause[e]	Bond process related?[f]	Adhesion failure or env'l degr.?[f]	Ref.
TA01	Boeing	737-200	N73711	04/28/88	S	F	M	P,M	Y	Y	[31,32]
TA02	Boeing	747-200B	VH-EBQ	12/27/90	M	U	C	U	N	N	[33]
TA03	Airbus	A300	N16982	12/06/93	M	U	M	M	Y	Y	[34]
TA04	Boeing	747-200C	N470EV	05/19/96	M	U	C	D,M	N	N	[35]
TA05	Boeing	777-200	G-YMMP	06/14/10	M	U	C	D	N	Y	[36]
TA06	Boeing	DC-10-30	YV-134	09/01/83	M	U	U	M	Y	Y	[37]
TA07	BAe / SNIAS[g]	Concorde Type 1	G-BOAF	04/12/89	M	U	M	P,D	U	U	[38]
TA08	BAe / SNIAS[g]	Concorde Type 1	G-BOAC	05/25/98	M	U	M	M	U	Y	[39]
TA09	BAe / SNIAS[g]	Concorde Type 1	G-BOAC	10/08/98	M	U	M	P	N	N	[40]
TA10	Boeing	MD-11	B-150	12/07/92	M	U	C	P,O	Y	U	[41]
TA11	Boeing	737-200	N457TM	06/29/95	M	U	U	M	Y	N	[42]
TA12	Boeing	727-61	N530KF	10/17/00	M	U	M	D,M	Y	Y	[43]
TA13	Airbus	A310-300	C-GPAT	03/06/05	S	U	C	P,D	N	Y	[44]
TA14	Airbus	A300-600	N717FE	11/27/05	M	U	C	U	U	U	[45]
TA15	Boeing	737-200	VH-OZX	12/31/07	M	U	C	P,M	Y	N	[46]
GA01	SZD[h]	SZD-24-4A	N21714	06/15/74	D	U	O	P	Y	U	[49,50]
GA02	DG	DG-400	N400FJ	05/01/99	D	M	C	P	Y	Y	[51]
GA03	ADC[i]	D4	unknown	03/22/00	D	F	C	P	Y	Y	[52]

[a]TA=transport airplane; GA=general aviation airplane; R=rotorcraft; P=propeller; and E=engine
[b]D=destroyed; S=substantial; and M=minor
[c]F=fatal; S=severe; M=minor; and U=uninjured
[d]M=metallic joint; C=composite joint; H=composite-metal hybrid ; O= other (e.g, wood, rubber); and U=unkown
[e]D=design; P=production; O=operational; M=maintenance; and U=undetermined
[f]Y=yes; N=no; and U=unknown
[g]BAe/SNIAS=British Aerospace and Société Nationale Industrielle Aérospatiale
[h]Szybowcowy Zaklad Doswiadczalny
[i]Aircraft Design Certification

ID[a]	Make	Model	Marks	Date	Damage Severity[b]	Highest Level of Injury[c]	Joint Type[d]	Root Cause[e]	Bond process related?[f]	Adhesion failure or env'l degr.?[f]	Ref.
GA04	Schempp-Hirth	Duo-Discus	unknown	07/25/03	D	U	C	P	Y	N	[53]
GA05	Schempp-Hirth	Duo-Discus CS	D-8515	07/29/03	D	U	C	P	Y	N	[54]
GA06	Textron Aviation	LC41-550FG	unknown	12/06/10	S	U	C	P	Y	Y	[19,55]
GA07	Alexander Schleicher	K7	N12053	03/30/13	S	F	O	O	Y	Y	[56]
GA08	Alexander Schleicher	ASW-15	N3644	06/05/71	D	F	C	U	U	U	[57,58]
GA09	RUAG	DO 228-200	unknown	10/16/02	S	U	O	M	Y	N	[59]
GA10	Flight Design	CTSW	D-MNOH	07/27/12	S	S	C	P	Y	N	[60,61]
GA11	Textron Aviation	U206B	N206KY	09/06/97	D	F	M	M	U	U	[62]
GA12	Diamond	DA 40	N323JT	05/16/09	S	M	C	O	Y	Y	[63]
R01	MDHI	369D	D-HMEN	08/18/95	S	U	M	P	Y	Y	[66]
R02	MDHI	369D	C-FDTN	12/10/97	D	S	M	P	Y	Y	[67,68]
R03	MDHI	369D	N5225C	07/22/14	S	S	M	P,M	Y	Y	[69]
R04	Bell	407	PT-YSL	04/09/00	M	U	C	P	Y	Y	[70]
R05	MDHI	369	C-GXON	10/31/00	D	F	M	P	Y	Y	[71]
R06	Robinson	R22	VH-OHA	06/20/03	D	F	M	P	Y	Y	[72–74]
R07	Robinson	R22	4X-BDM	02/29/04	D	F	M	P	Y	Y	[72,74]
R08	Robinson	R22	ZK-HWP	11/27/04	D	S	M	P	Y	Y	[72]
R09	Robinson	R44	VH-AIC	02/12/03	S	U	M	P	Y	Y	[75]
R10	Robinson	R22	ZK-HLC	03/04/06	D	F	M	D,P	Y	Y	[76–78]
R11	Robinson	R44	HI-803CT	10/11/06	D	F	M	P,D	Y	Y	[77,79]

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[d]M=metallic joint; C=composite joint; H=composite-metal hybrid ; O= other (e.g, wood, rubber); and U=unkown
[e]D=design; P=production; O=operational; M=maintenance; and U=undetermined
[f]Y=yes; N=no; and U=unknown
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ID[a]	Make	Model	Marks	Date	Damage Severity[b]	Highest Level of Injury[c]	Joint Type[d]	Root Cause[e]	Bond process related?[f]	Adhesion failure or env'l degr.?[f]	Ref.
R12	Robinson	R44	DQ-IHE	12/05/06	D	F	M	P,D	Y	Y	[77]
R13	Robinson	R22 Beta II	VH-HPI	03/15/07	M	U	M	P,D	Y	Y	[80,81]
R14	Robinson	R22 Beta	VH-HZB	12/29/08	M	U	M	P,D,M	Y	Y	[82]
R15	Robinson	R44	VT-HPC	08/14/13	D	U	M	P	Y	Y	[83]
R16	Bell	212	C-GNHX	06/10/05	S	U	M	P	Y	Y	[86,87]
R17	Bell	206L-1	N37AE	08/31/08	D	F	M	P	Y	U	[88,89]
R18	Bell	206L	C-GDQH	11/02/11	D	F	M	P	Y	U	[90]
R19	Bell	206L-3	N708M	03/29/09	M	U	M	P	Y	N	[91,92]
R20	Leonardo	AW109SP	G-HLCM	08/02/17	M	U	U	P	Y	Y	[93]
R21	MDHI	369D	C-GPDH	05/10/94	S	U	M	U	U	Y	[94]
R22	Air Space Design	FH-1100	N8171U	08/14/98	D	F	M	M	N	N	[95]
R23	MDHI	369HS	N4278M	06/07/99	D	M	U	M	Y	U	[96]
R24	Southwest Florida Aviation	SW204	N37BA	5/24/00	S	U	U	M	Y	U	[97]
R25	Bell	212	C-FHDY	06/03/00	S	U	U	P	Y	Y	[98]
R26	MDHI	369E	N142MK	01/21/05	S	U	U	D	Y	Y	[99]
R27	Robinson	R22	PT-YPB	03/10/15	M	U	M	P	U	U	[100]
R28	Bell	407	N457PH	05/02/17	S	U	C	D,M	Y	N	[101,102]
R29	Bell	206B	N33PW	08/12/87	S	U	O	M	U	U	[103]
R30	Bell	206B	N90307	08/23/00	S	U	O	P	Y	Y	[104,105]
R31	Bell	206B	N21424	06/17/93	S	U	M	M	Y	N	[106]
R32	Bell	206B	N7929J	08/23/97	S	U	M	M	Y	Y	[107]

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[d]M=metallic joint; C=composite joint; H=composite-metal hybrid ; O= other (e.g, wood, rubber); and U=unkown
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ID[a]	Make	Model	Marks	Date	Damage Severity[b]	Highest Level of Injury[c]	Joint Type[d]	Root Cause[e]	Bond process related?[f]	Adhesion failure or env'l degr.?[f]	Ref.
R33	Sikorsky	S-92A	G-CHCK	04/23/07	M	U	H	U	U	U	[108]
R34	Sikorsky	S-76A	N574EH	03/15/13	D	F	O	U	U	Y	[109,110]
R35	Airbus Helicopters	AS355	ZK-IAV	04/13/08	S	U	O	P	U	U	[111]
R36	Leonardo	AW139	A7-GHC	08/25/09	S	U	M	U	N	N	[112]
R37	Bell	UH-1H	N205KS	06/24/10	S	U	M	U	U	U	[113,114]
R38	Sikorsky	S-76A	C-GHJT	08/13/12	D	U	O	D	N	Y	[115]
R39	Leonardo	A109E	G-ETPI	06/27/19	M	U	O	M	Y	N	[116]
P01	Textron Aviation (Hartzell)	1900D (HC-E4A-31)	N251GL	08/19/98	S	M	H	M	Y	Y	[117–119]
P02	Embraer (Hartzell)	EMB-120	VH-FNQ	11/13/99	M	U	H	M	Y	Y	[120]
P03	B-N (Hartzell)	BN2A (HC-C3YR-2CUF)	G-BEVT	07/23/04	M	S	O	M	Y	Y	[121]
P04	B-N (Hartzell)	BN2A (HC-C3YR-2CUF)	G-BEVT	04/24/05	M	U	O	D,M	Y	Y	[122]
P05	GROB (Hoffmann)	G115 (HO-V 343 K-V)	G-BYVE	08/24/16	M	U	H	M	Y	Y	[123]
E01	Boeing (Rolls Royce)	747-400 (RB211-524)	G-BNLD	03/01/02	S	U	M	P	Y	N	[124]
E02	Fokker (Rolls Royce)	F28 (TAY-620-15)	unknown	01/05/04	S	M	H	D,M	Y	Y	[125]

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