# BOND-RELATED AIRCRAFT ACCIDENTS/INCIDENTS: A REVIEW

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## ABSTRACT

Because structural bonding is strongly process-dependent and adhesion phenomena are complex, the simulation or experimental reproduction of bonded joints' long-term structural behavior under real-life conditions is challenging. This challenge magnifies the value associated with in-service data. Since 1944 the International Civil Aviation Organization has recommended member states to investigate aircraft incidents/accidents. Although there are today thousands of publicly available investigation reports, prepared by qualified investigators and often complemented by third-party engineering data, no survey of those events associated with bonding issues was found. Hence, this work identified and reviewed 72 bond-related events involving type-certified, civil aircraft from 13 countries in five continents. These events' root causes were categorized to identify potential bonding certification shortfalls. The results emphasize the need for process control and durability substantiation to ensure long-term safe operation of bonded structures and show 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) alone can guarantee the expected joint structural performance in case of substandard bonding. These findings are consistent with current certification guidance materials.

Keywords: structural bonding, certification, in-service data
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## 1. INTRODUCTION

Compared to other joining methods, adhesive bonding offers many advantages, which have been long acknowledged by aircraft design pioneers [1,2]. But as aircraft were designed to fly higher, more often, and to last longer, the challenges for life long safe operation of adhesive bonding became more evident [2]. In particular, the environmental degradation of the substrate/adhesive interface (adhesion failure) often weakens real-life bonded joints overtime while remaining virtually undetectable ('weak bond') [3,4]. Such behavior is difficult to simulate numerically or reproduce experimentally, magnifying the value of in-service data [5]. Despite these challenges, since the 1950s, the aeronautic use of structural bonding has spanned the range from small [6] to large [7] airplanes and rotorcraft [8], from propellers [9] to engines, from pristine airframe to repairs [4,10]. Since that time, the International Civil Aviation Organization (ICAO) has recommended that member states investigate and document aircraft accidents to prevent them from

happening again [11,12]. From then on, ICAO has grown from 52 to 193 member states [11,13]. Today many publicly available databases contain numerous accident investigation reports (e.g., over 76,800 reports in the USA since 1962 [14]). These reports are based on inspections (e.g., wreckage), data analyses (e.g., maintenance records), and interviews (e.g., witnesses, crew), often supported by additional engineering data (e.g., advanced inspections, chemical/mechanical tests, simulations). Despite all this accumulated in-service data, no survey of bond-related events was found. Thus, this work reviewed, summarized, and categorized to identify potential certification shortfalls 72 bond-related events from 13 countries in five continents. This survey encompassed type-certified civil aircraft containing structural bonding or sandwich structures [15], irrespective of the substrate or core materials (e.g., metal, composites, wood, elastomers).

# 2. SURVEY

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. Other documents (e.g., airworthiness directives (ADs)) and investigation reports from other countries were occasionally included. A total of 72 bond-related events identified, reviewed, and organized into five subsections: (i) transport airplanes, (ii) general aviation (GA) airplanes, (iii) rotorcraft, (iv) engines, and (v) propellers. Each subsection groups events involving aeronautical products type-certified against similar airworthiness regulations (e.g., 14 CFR Part 25 for transport aircraft, Part 33 for engines). 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.

## 2.1 Transport Airplanes

For decades, bonding has been used in transport airplanes [2,7]. Table 1 lists 14 bond-related events involving transport airplanes, which are described in the subsequent sub-sections.

Table 1. Bond-related occurrences 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 | Boeing | MD-11 | B-150 | China | 12/07/92 |
| TA08 | Boeing | 737-200 | N457TM | USA | 06/29/95 |
| TA09 | BAe/SNIAS[a] | Concorde Type 1 | G-BOAC | UK | 05/25/98 |
| TA10 | BAe/SNIAS[a] | Concorde Type 1 | G-BOAC | UK | 10/08/98 |
| TA11 | Boeing | 727-61 | N530KF | USA | 10/17/00 |
| TA12 | Airbus | A310-300 | C-GPAT | Canada | 03/06/05 |
| TA13 | Airbus | A300-600 | N717FE | USA | 11/27/05 |
| TA14 | 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, which had bond-related major contributing factors, is the Aloha Airlines flight 243 in 1998 (**TA01**). About 5.5 m of the main cabin fuselage upper lobe separated from the single-aisle airliner while en route. The airplane was substantially damaged. There were several injuries and one fatality among the 95 occupants. Investigation concluded that the maintenance program failed to detect significant disbond and fatigue cracks in the metallic fuselage cold bond lap joints. A critical safety issue identified was substandard bonding (improper surface preparation), which led to poor joint environmental durability [16].

### *2.1.2 Wing*

Four events involving fixed parts of the transport airplane wing were found. In 1990, the four-engine, wide-body airliner of event **TA02** lost a 2.7 by 0.18 m portion of a wing trailing edge composite panel during climb. Visual inspection from the cabin confirmed the separation. The crew dumped the fuel and landed uneventfully. Pre-load resulting from contact with the flaps caused the disbond. This panel had been tap and push tested during an 'A' check 19 days before this incident. The operator and manufacturer reported several similar events [17].

In 1993, during the landing roll, one of the 3.6 by 1.8 m engine cowls departed the twin-aisle airliner of event **TA03**, inflicting minor damage to the airplane. No one was injured. Inadequate adhesive thickness control and surface preparation during a repair led to adhesion failure of an aluminum bonded joint. The engine original equipment manufacturer (OEM) classified this as an isolated incident and reported similar findings (detected before separation). The lack of procedures in the OEM manual for this repair might have led to variations among repair stations [18].

In 1996, parts of a composite sandwich panel of the wing fixed trailing edge separated from the four-engine, wide-body freighter during climb, causing secondary damage to the airplane but no harm to the crew (**TA04**). The detected disbond was associated with expanding/contracting cycles of absorbed environmental moisture. The OEM acknowledged reports of 245 other similar disbonds (95 of them in flight), which had led to panel redesign twice and a service bulletin (SB) replacing the nondestructive inspections (NDI) technique (from coin-tap to ultrasound). Before **TA04**, this particular aircraft operator had opted not to replace the NDI technique [19].

In 2010, the crew of the wide-body airliner of event **TA05** lost portions of the nacelle while en route. After an uneventful landing, all 214 occupants debarked safely. Investigation revealed signs of overheat and interfacial disbond between the core and the composite skin. Previous similar events had motivated (SBs) additional inspections and thermal protection' change, which had not been incorporated into this aircraft before this event [20].

### *2.1.3 Moving Surfaces*

Nine of the reviewed events involved bond failures in moving surfaces. In 1983, the twin-aisle airliner of event **TA06** lost about 1.27 m of a flap vane during approach. The aircraft suffered minor damages, and all 201 occupants were uninjured. Investigation revealed that moisture ingress caused skin disbond. A contributing factor was a skin repair that used inadequate surface preparation and insufficient cure pressure [21].

In 1992, while en route, the wide-body airliner of event **TA07** lost 1.6 by 0.7 m portions of both composite elevators. The airplane suffered minor damage, and none of the 265 occupants were

injured. Examination (microscopy, mechanical testing) disclosed adhesion failure, porosity, and lack of sanding during surface preparation. Investigation concluded that overstress from stall buffet, aggravated by substandard bonding, caused this accident [22].

In 1995, the narrow-body airliner of event **TA08** experienced a separation of a 0.5 m long part of the aileron from the wing while descending, leaving the aircraft damaged slightly and all 84 occupants 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) [23].

In 1998, the supersonic airliner of event **TA09** lost one-third of an elevon (bonded metallic sandwich structure) while en route. The plane emergency landed uneventfully, and all 64 occupants disembarked unharmed. Previous repairs (due to disbonds) incorporated additional doublers, blind fasteners, and mandated inspections. About half of the repaired area was found not inspectable (due to overlaps) and presented evidence of adhesion failure and disbond growth. Investigation concluded that an undetected small disbond grew up to failure [24]. About four months later, the same airplane was involved in a similar incident (**TA10**). About 70 % of one side of the lower rudder (bonded metallic sandwich structure) was missing. Examinations (NDI and tear-down) disclosed large (mainly cohesive) disbond in solid metal/metal bond lines (undetectable by in-service NDI techniques). Investigation concluded that the process of forming the blind rivets (installed after bonding) introduced small disbonds that grew undetected in-service up failure [25].

In 2000, the single-aisle airliner of event **TA11** lost a 1.8 by 0.4 m portion of the flap metallic sandwich panel during approach, with 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 repair manual also contributed to this incident [26].

In 2005, the narrow-body airliner of event **TA12** lost its composite sandwich rudder during cruise causing Dutch roll. Despite substantial damage to the airplane, none of the 271 occupants were injured. Investigation concluded that existing damage (weak bond) had grown (undetected) due to the pressure difference (ground-air-ground cycle) up to failure that reduced stiffness and eventually led to flutter. This event motivated additional inspections mandated by ADs [27]. About eight months after this event, a similar anomaly in a similar rudder was reported (**TA13**). While assessing the damage that occurred during routine maintenance, inspections also detected an 838 by 355 mm disbond between the core and the composite skin. Hydraulic fluid contamination had led to the gradual growth of this disbond. OEM examinations revealed that existing inspections did not cover such disbonds. Other ADs followed this event [28].

In 2007, the narrow-body airliner of event **TA14** experienced vibration during climb. The crew declared an emergency and landed uneventfully. A portion of an elevator tab was missing. Loose screws led to cracks and eventually to fiberglass skin-to-honeycomb core adhesion failure, typically linked to bonding process issues [4]. Previous similar findings had motivated SBs/ADs. Compliance with these SBs/ADs was found. Depending on the level of vibration reported, the OEM manual required level I (from the ground) or II (disassembly, tests) inspections. In **TA14**, despite a detailed report of vibration, only level I inspections had been performed (no anomaly detected). The black aircraft's livery might have prevented a clear view [29].

## 2.2 General Aviation Airplanes

Bonding has been used in GA airplanes for decades [6,15]. Table 2 lists 12 bond-related events involving GA airplanes, which are described in the subsequent sub-sections.

Table 2. Bond-related occurrences 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 | 27/07/12 |
| 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*

Seven events involved bond failure of wing joints. 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 thick bond lines and a lack of adhesive. Annual inspection had been performed within the last 20 flight hrs. Poor bonding and inspection were likely causes [30,31].

In 1999, the glider of event **GA02** experienced a bang while flying straight and level. The pilot lost control and parachuted with only minor injuries while the plane was destroyed. Investigation revealed that the structural failure started in a wing-to-fuselage attachment (aluminum frame fixed by composite tapes bonded to the fiberglass skin). Voids and signs of adhesion failure were identified in this bonded region [32].

In 2000, the very light airplane of event **GA03** lost part of the left-wing during cruise. The aircraft parachute failed, destroying it and killing both aboard. Examination disclosed voids and adhesion failure in the spar-to-leading edge skin/rib joints. Disbonds were repaired during production by adding adhesive. Poor manufacturing was this accident's cause, aggravated by thermal adhesive degradation (enhanced due to dark paint) and high loading due to wind shear gusts [33].

In 2007, part of the composite wing separated from the glider of event **GA04** during climb. This plane had only 18 flight hrs. Both occupants parachuted safely while the glider was destroyed. Examination detected a 200 mm adhesion failure in the wing spar web to flange bonded joint. Poor processing was the cause of this accident. OEM sites had been manufacturing wings based on on-the-job training, with limited written workforce instructions, process specifications, and acceptance criteria [34]. A similar glider (**GA05**) lost part of the wing in flight only four days later

due to a 400 mm discrepancy in the flange-to-web spar bonded joint, causing the plane's destruction and minor injuries to the pilot [35]. These events motivated SBs and emergency ADs.

In 2010, about 2.1 m part of the composite wing of the airplane of event **GA06** disbonded during a production audit test flight. The FAA pilot managed to land successfully. Excessive moisture during manufacturing led to bond curing issues. Subsequent ADs grounded 13 airplanes [15,36].

In 2013, the sailplane of event **GA07** lost part of the wing in flight during a loop that produced excessive loading (the plane was not approved for aerobatics). This glider was substantially damaged, and both occupants perished. Examination revealed moisture ingress, adhesion failure, and cracked adhesives. Undetected bonding degradation contributed to this accident [37].

### *2.2.2 Empennage*

Three bond-related events involving GA airplane empennage were found. In 1971, the glass fiber glider of event **GA08** incurred an in-flight breakup and crashed. The student pilot perished. The right stabilizer detached from the aircraft, followed by the left stabilizer and the wing. A lack of adhesion in the stabilizer leading edge caused this accident [38,39].

In 2002, the twin-turboprop airplane of **GA09** experienced vibration while en route during a scheduled flight. The plane was substantially damaged, but all occupants debarked unharmed. Examination disclosed adhesion failure in the metallic rudder-to-polyester skin bonded joint, which had been repaired three days before this event using other than the OEM manual (different adhesive and surface preparation). This lack of adherence to approved data caused this event [40].

In 2012, the pilot of the very light airplane of event **GA10** heard a bang, 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 (poor wetting, insufficient penetration, contaminations, and adhesion failure). Speed limit (Vne) exceedance, aggravated by poor bonding quality control, caused this accident [41].

### *2.2.3 Landing devices*

Two events with bond failure in landing devices were found. In 1997, the seaplane of event **GA11** nosed over and crashed during water landing, killing two of the four occupants. A float's metallic skin disbonded from the keel, which had been repaired not long before. The OEM repair manual required riveting, but it had been bonded. Poor disassembling had also introduced defects [42].

In 2009, the single-engine piston airplane of event **GA12** skidded during landing. The airplane was substantially damaged while the pilot suffered minor injuries. Excessive side loads caused main landing gear failure. Examination also disclosed adhesion failure, thick adhesive, and voids up to 35% in area in a composite main landing gear rib-to-airframe bonded joint [43].

## 2.3 Rotorcraft

For decades, rotorcraft have been using structural bonding, particularly in rotor blades. This section describes 39 bond-related events involving rotorcraft, divided into primary failure of the main rotor blade (MRB), tail rotor blade (TRB), or non-rotor blade location.

### *2.3.1 Main Rotor Blade Primary Failure*

Table 3 lists 20 bond-related occurrences involving rotorcraft caused by MRB failure.

Table 3. Bond-related occurrences involving rotorcraft (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 |
| 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 | 11/01/05 |
| 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** lost one of the five metallic MRBs before takeoff. The rotorcraft sustained severe damage, but all occupants were uninjured. Inspections detected fatigue cracks and disbonds at the MRB root attachment, a shear bolted-bonded attachment connecting the root fittings to doublers and skins. Of the total disbond area, 30% had existed since manufacture, 35% had grown in-service, and 35% failed abruptly. Examination revealed improper cure (tool misalignment) and lack of adhesive squeeze out filled with sealant. This event motivated additional inspections (SBs/ADs). Within ten years, similar crack findings were reported in eight MRBs [44]. Similar events with the same model followed. About two years later, production non-conformities led to varying adhesive thickness, improper bonding, and residual stresses in the blade skin that caused the event **R02** [45,46]. This event also prompted further inspections (SBs/ADs). After 17 years, improper compliance with SBs/ADs, aggravated by ambiguous inspection procedures, led to undetected fatigue cracks, adhesion failure, and contaminations that eventually cause the event **R03** [47].

In 2000, the seven-seat, turbine-powered rotorcraft of event **R04** started vibrating during cruise. The pilot landed off-airport twice for visual inspection but detected no anomaly. Later, a technician detected disbond in one of the MRBs, which was sent to the OEM. Examinations (microscopy, mechanical tests) disclosed adhesion failure in a 1.4 by 0.13 m disbond (between composite skin and core), which had been undetected during production and had grown in service. The OEM classified it as an isolated case. Poor cure control and post-cure inspections caused this event [48].

Later that year, the single-turbine powered rotorcraft of event **R05** lost two-thirds of one of its five metallic MRBs while en route. The rotorcraft crashed, and the pilot perished. Examination of the skin-to-spar bonded joint revealed voids, inside which corrosion pits led to fatigue cracks that became unstable before surfacing. This event prompted immediate inspections (SBs/ADs). These inspections revealed voids in several blades, which led to their removal from service [49].

In 2003, during a training flight, the two-seat, piston-powered helicopter of event **R06** suffered an in-flight breakup and crashed, killing all aboard. Inspections detected fatigue cracks in the MRB root attachment, a bolted-bonded attachment connecting the metallic root fitting to the MRB skins, spars, and doublers. Investigation concluded that the disbonds contributed to the cracks' growth (increase bolt load and corrosion pit due to fluid ingress). Two surveys of retired MRBs with different in-service times and operational characteristics indicated that such disbonds were widespread [50]. Within the following 18 months, at least two similar accidents involving helicopters of the same model occurred: (i) one (**R07**) during a powerline survey in the Middle East, killing two people [50,51], and another (**R08**) during agricultural operations in Oceania, severely injuring the pilot [50]. These three events presented disbonds and fatigue cracks with similar patterns and occurred within the MRB approved service life [50]. Reactions to these events (SBs/ADs) included inspections, MRBs removal from service, and reducing MRB retirement life.

In 2003, the four-seat, piston-powered helicopter of event **R09** experienced an unusual noise during cruise. Intense vibration necessitated a forced landing. The rotorcraft was substantially damaged, but the pilot and passenger suffered only minor injuries. Inspection detected a skin disbond of 1070 by 60 mm from the tip in one MRB and initial disbonds in the other. ADs were issued [52]. Analogous occurrences with similar models followed in different parts of the world (**R10** [53–55], **R11** [53,56], **R12** [53,57], **R13** [58,59], **R14** [60] and **R15** [61]). In these events, the failed MRBs had not exceeded the mandatory retirement life, and the percentage of adhesion failure was below the (OEM) acceptable levels. During the investigations, similar disbonds detected during routine maintenance were reported in at least ten other MRBs [53]. Investigators issued safety recommendations regarding bond durability issues and NDI [53]. In reaction to these events and related safety recommendations, the OEM issued several SBs and redesigned the MRB. Different civil aviation authorities (CAAs) published ADs, revised related airworthiness requirements, and associated guidance material, such as FAA ACs 27-1B and 29-2C [53].

In 2005, the 15-seat, twin-engine rotorcraft of event **R16** started to shake after loud bangs during cruise. The emergency landing rendered substantial damage to the helicopter but no injuries to the three occupants. Examination disclosed disbonds (e.g., 640 by 50 mm) and adhesion failure in the lower skin close to the tip of one of the two metallic MRBs. Although an adjacent area had been recently repaired, the investigation concluded that poor manufacturing caused this event [62,63].

In 2008, the seven-seat, turbine-powered rotorcraft of event **R17** lost a 2.4 m portion of one of the two aluminum MRBs while climbing. The helicopter crashed, and all three occupants died. Production discrepancies such as spar residual stresses and voids (e.g., 234 by 10 mm) in the lead weight-to-spar bonded joint led to fatigue cracks. After this event, an SB required inspections of over 2,500 blades. Another manufacturing defect (oversize spar spacer) prompted a new SB reducing the service life of the affected blades [64,65]. About two years after the SBs' release, a similar accident occurred, destroying the rotorcraft (same model) and killing all three occupants (**R18**). Examination revealed residual stress, voids, and microcracks. Fluid ingress led to corrosion and crack nucleation. Inspections conducted 16 times before this event had detected no crack [66].

In 2009, post-flight inspection in the metallic MRBs of a seven-seat, turbine-powered helicopter detected 230 mm long fatigue cracks at the trailing edge skin (**R19**). Interconnected porosity in the bond line allowed fluid ingress that led to corrosion and cracks nucleation. During manufacturing, two independent leak tests had not detected porosity. The OEM considered this event rare and detectable during routine maintenance or as a one-per-revolution vibration in flight [67,68].

In 2017, the eight-seat, twin-engine helicopter of event **R20** vibrated during approach but safely landed in an adjacent field. The tip cap of one of the MRBs detached in flight due to improper bonded joint surface preparation. SBs and ADs requiring additional inspections followed [69].

### *2.3.2 Tail Rotor Blade Primary Failure*

Table 4 lists eight bond-related occurrences involving rotorcraft caused by TRB failure.

Table 4. Bond-related occurrences involving rotorcraft (TRB failure).

| ID | Aircraft make | Model | Marks | State of registry | Date |
|---|---|---|---|---|---|
| R21 | MDHI | 369D | C-GPDH | Canada | 05/10/95 |
| R22 | Southwest Florida Aviation | SW204 | N37BA | USA | 05/24/00 |
| R23 | Bell | 212 | C-FHDY | Canada | 06/03/00 |
| R24 | MDHI | 369E | N142MK | USA | 01/21/05 |
| R25 | Air Space Design | FH-1100 | N8171U | USA | 08/14/98 |
| R26 | MDHI | 369HS | N4278M | USA | 06/07/99 |
| R27 | Robinson | R22 | PT-YPB | Brazil | 03/10/15 |
| R28 | Bell | 407 | N457PH | USA | 05/02/17 |

In 1995, shortly after takeoff, the single-turbine powered rotorcraft of event **R21** lost the abrasion strip of one of the metallic TRBs, causing the tail rotor assembly to separate. An autorotation caused substantial structural damage but no injury to the three occupants. Mandated (ADs) daily inspections and rivets (secondary load path) did not prevent the failure. Despite signs of adhesion failure, the failure's cause could not be established [70]. The failure of the primary (bonding) and secondary (fasteners) load paths of other TRB parts caused similar accidents: (i) the single-turbine powered helicopter of event **R22** lost the tail rotor tip weight due to the installation of suspected unapproved TRB [71]; (ii) the 15-seat, twin-engine helicopter of event **R23** lost the TRB's tip weight due to manufacturing defects (poor bonding environmental resistance, larger rivets holes) [72]; and (iii) the single-turbine powered rotorcraft of event **R24** lost the TRB abrasion strip due to fatigue, poor bonding and inspections (visual only to detect disbond) [73].

In 1998, the four-seat, turbine-powered helicopter of event **R25** lost part of one of the two metallic TRBs during cruise, destroying the rotorcraft and killing the pilot. An irregular repair that replaced a bonded doubler caused this event. At that time, the OEM repair manual did not permit doubler replacement, and no other approved data supporting this repair was found [74].

In 1999, the single-turbine, powered rotorcraft of event **R26** started vibrating during cruise and lost the tail rotor assembly. The helicopter crashed, but the occupants suffered only minor injuries. During an unapproved repair, the TRBs' abrasion strip had been removed using direct heat, damaging a TRB's bond line. Some days before the event, the pilot (also a mechanic) had repaired a gap in the TRB tip cap with resin and had tap-tested the region. However, an SB explicitly required TRB replacement whenever detecting disbonds [75].

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 and no harm to the crew. The cause of the disbond remained undetermined, but the investigation suspected environmental degradation of the adhesive [76].

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. The tip block had been recently repaired, followed by pull-test, peel-test, and water test (leaking check). These post-repair tests were found to be inadequate to detect poor adhesive bonding. Later, the OEM revised the repair procedures to use only positive pressure instead of vacuum during the curing cycle and expand post-repair checks [77].

### *2.3.3 Other Than Rotor Blade Primary Failure*

Table 5 lists ten bond-related events involving rotorcraft that were not caused by blade failure.

Table 5. Bond-related occurrences involving rotorcraft (other than rotor blade primary 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 |
| 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** shuddered during cruise. The pilot made an autorotation and landed on a road. The helicopter was substantially damaged, but all four occupants were unhurt. A pylon isolation mount failure caused the vibration. This pylon mount comprised a center metallic plate connected to the upper and lower metallic plates by rubber damper elements (molded gasket). The upper plate disbonded from the rubber damper. Bond degradation (oil and grease) caused this disbond. The adhesive degradation that occurred over a long time had been undetected [78]. About 13 years later, poor surface preparation caused a similar event (**R30**) with another helicopter of the same model shortly after landing [79,80].

In 1993, the tail rotor drive shaft of the five-seat, turbine-powered rotorcraft of event **R31** failed during approach. The helicopter was substantially damaged, but all four occupants were unscathed. Following a previous tail strike, the same shaft had been reinstalled after inspections that used an unapproved paint stripping process, which introduced damages and stresses to the bond lines that already contained voids [81]. Later, a similar accident occurred during an external load operation (**R32**). An unapproved surface preparation method used during a repair had compromised the bonded joint protection, allowing fluid ingress, chemical attack, and adhesive degradation [82].

In 2007, the twin-engine transport rotorcraft of event **R33** shuddered while en route over water with 17 people aboard, prompting a successful emergency landing. A bearing retainer disbonded

from a flexible spar, leading to a TRB pivot detachment. This pivot comprised bonded elastomeric bearings connecting the composite blades' flexible spar to the torque tube. Inspections 53 flight hrs before this event had detected no anomaly. The disbonds' cause was undetermined. Later, the OEM reported 16 similar events and established more inspections [83]. About six years later, a failure close to the bonded TRB pivot bearings caused another event (**R34)** involving a different model. Though the failure's cause was undetermined, adhesion failure was disclosed [84].

In 2008, one of the three MRB spherical thrust bearings of the twin-engine helicopter of event **R35** failed shortly after taking off. The helicopter ended up substantially damaged while both occupants were unhurt. Pre-existing disbonds led to corrosion and adhesion failure. This bearing comprised elastomer blocks bonded to metallic parts and had a retirement life based only on flight hrs (on-condition elastomer and associated joints). The rotorcraft had been stored for 25 yrs. Four repair stations had inspected, and released to service, these bearings many times before this event [85].

In 2009, the tail boom of the twin-engine transport helicopter of event **R36** collapsed during taxi. All 14 occupants debarked unharmed. The tail boom sandwich panels (aluminum facings/Nomex honeycomb core) suffered widespread cohesive disbond caused by pre-existing core damage. After a tail strike, the tail had been repaired, and hammer tested, but no core damage was found. Similar in-service findings were reported, prompting additional NDIs (SBs/ADs) [86]. One year later, the tail boom of the single-turbine powered rotorcraft of event **R37** failed while hovering. All five occupants were uninjured, but the helicopter was substantially damaged. A fitting-to-longeron metallic (bonded and riveted) attachment failed. Interfaces showed signs of fretting, corrosion, and fatigue cracks. Bond failure or defects would permit relative movement and fluid ingress between these surfaces, but the exact cause of fatigue could not be established. No OEM fatigue substantiation for this fitting was found. The assessment of the impact of many supplemental type certificates (STCs) on this rotorcraft was also not located. Similar failures caused by excessive assembly loads (e.g., misalignment) were reported [87,88].

In 2012, an engine of the twin-engine transport rotorcraft of event **R38** failed when approaching a floating helipad. The pilot deployed the emergency flotation system and successfully ditched the helicopter. Both occupants disembarked safely. Soon after, the failure of an inflatable nose float bonded seam caused the rotorcraft to roll over and sink. Recurrent inspections had not detected bond degradation (adhesive cracks, failure, and understrength). Investigations concluded that limited inspections and lack of life limits posed a risk of float failure [89].

In 2019, during a post-maintenance flight, the door acrylic window separated from the eight-seat, twin-engine rotorcraft of event **R39**. The separation caused no secondary damage, and the helicopter landed uneventfully. Deviations from the OEM manual (insufficient adhesive, overly soapy solution to fit the seal, lack of staged independent inspection) caused the disbonds [90].

### 2.4 Engines

In relatively cold areas of engines, there are some structural bonding applications. Table 6 lists two bond-related events involving engines.

Table 6. Bond-related occurrences caused by engine failure.

| ID | Make (aircraft/engine) | Model (aircraft/engine) | Marks | State of registry | 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 |

In 2002, an engine failure caused substantial damage to wide-body airliner of event **E01**, but no harm to the 290 occupants. One compressor sandwich blade (two titanium plates separated by a metallic honeycomb) failed. A 'concessionally' accepted disbond (during production) had grown (from 12 to 22 mm) undetected (by the three different NDIs) in-service, leading to fatigue cracks. Later, the acceptance system was revised, and blades were removed from service (SBs) [91].

In 2004, the twin-jet regional airliner of event **E02** vibrated during approach. After an emergency off-airport landing, the airplane was severely damaged, and three of the 32 occupants were slightly injured. All ice impact panels from both engines disbonded (negating assumptions of the failure mode and effect analysis) and accumulated in the low-pressure compressors. Following an SB, two different repair stations (in the USA and the UK) had incorporated these composite sandwich panels long (5,000 flight hrs) before. Poor bonding instructions (e.g., many cross-references among manuals, editorial error, misleading text, undefined tools and consumables, inconsistent curing data) and unsuitable adhesive selection led to inadequate surface preparation, adhesive degradation (adhesion failure), (diffused) moisture cyclic freezing, and disbonds. Later AD led to the replacement of about 30% of the inspected panels. A similar event was later reported [92].

### 2.5 Propellers

There are numerous bonding applications in propellers, spanning from protective shields to primary hybrid joints [9]. Table 7 lists five bond-related events involving propellers.

Table 7. Bond-related occurrences caused by propeller failure.

| ID | Make (aircraft/propeller) | Model (aircraft/propeller) | Marks | State of registry | 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 |

In 1998, shortly after takeoff, a nickel erosion shield detached from a left composite propeller of the twin-turboprop commuter airplane of event **P01**. The plane was substantially damaged, but only one of the 15 occupants sustained minor injuries. One month earlier, all propellers had been overhauled and repaired by adhesive injection. Examination revealed adhesion failure and wrong adhesive mixing ratio in all propellers [93–95]. A similar event (**P02**) occurred with a twin-turboprop regional airliner during takeoff one year later. This shield bounced off the tarmac and hit one of the other engine's propellers. All engines were turned down, and all occupants debarked safely. Silicone from an adhesive tape used in the bond process contaminated the bond line [96].

In 2004, shortly after takeoff, the pilot of the ten-seat, three-piston airplane of event **P03** heard a bang. The plane landed safely with the two passengers injured. The de-icer boot of a left propeller disbonded and entered the cabin. During maintenance, a required sealant fillet had not been applied, allowing fluid ingress, creating peel stresses, and growing pre-existing disbonds. Later, about 100 propellers without the required sealant were identified [97]. Some months later, the same aircraft lost the de-icer boot from a right propeller (**P04**). This propeller had already been overhauled with the revised procedures to ensure the required sealant fillet. The use of an accepted, alternative boot and difference in the curing cycle between the propeller OEM's and the boots manufacturer's manuals led to fluid ingress, adhesive degradation, and adhesion failure [98].

In 2016, during takeoff, the two-seat, single-piston airplane of event **P05** lost the anti-erosion sheath from one of the composite propeller blades. The pilot completed an emergency landing uneventfully. Insufficient adhesive, excessive sanding during surface preparation, and improper cleaning before bonding caused the disbond [99].

# 3. RESULTS

The previous section summarizes 72 bond-related events. Each event's root causes (more than one might apply) were classified as design, production, operation, or maintenance. Table 8 shows that often (59 of 72) maintenance/production issues linked to bond process discrepancies (50 of 59) were contributing factors. As bonding is strong process-dependent, these discrepancies potentially represent shortfalls in type, production, or maintenance certifications.

Table 8. Classifications of bond-related occurrences

| Bond-related occurrences (%) | | | | | |
|---|---|---|---|---|---|
| Root cause group[i] | | Joint substrate material | | Aeronautic product | |
| Production | 51 | Metal | 44 | Rotorcraft | 54 |
| Maintenance | 36 | Composite | 24 | Transport airplane | 19 |
| Design | 19 | Hybrid[ii] | 7 | GA airplane | 17 |
| Operation | 3 | Other[iii] | 15 | Propeller | 7 |
| Undetermined | 8 | Unknown | 10 | Engine | 3 |

Notes: [i] Multiple causes might apply (total>100%); [ii]hybrid=composite-metal; [iii]other=wood, rubber, cloth, etc.

Events were also classified according to the joint substrate materials (see Table 8). Metallic joints represented about half (32 of 72) of the total cases, while composite joints were about one-fourth (17 of 72). Environmental degradation/adhesion failure (42 of 72) occurred in both metallic (21 of 32) and composite (7 of 17) joints. Table 8 also illustrates that bonded joints, the failure of which can contribute to aircraft accidents, exist in a wide range of aeronautical products.

The current certification policy [3] requires well-defined and controlled bonding processes. As localized understrength might yet occur, these policies include three choices of an additional layer 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 data suggest that no additional protection layer can alone ensure the required minimum level of safety in case of poor bonding. E.g.: (i) damage tolerance-based inspections or advanced NDI might not detect defects related to substandard bonding (e.g., **TA01**, **TA09**, **GA01**, **R28**, **R29**); (ii) load path redundancy or damage growth arrest features might not ensure the structural integrity in case of bond inferior processing (e.g., **R21** to **R24**); and (iii) environmental protection measures (e.g., sealant) might not prevent an inferior bonded joint from degrading over time (e.g., **P04**).

The data illustrate the adverse effects of substandard bonded joints on airframe integrity. Even in non 'critical structure' [3], poorly prepared bonding might lead to potentially unsafe conditions. E.g.: (i) the separation of doors (e.g., **R39**) and fairings (e.g., **TA03**, **TA05**) might lead to secondary impact damages; (ii) shield detachment might lead to vibration (e.g., **R21**, **R26**, **R24**, **P01**, **P02**, **P05**) or loss of engine power (e.g., **E02**), which might be risky depending on the phase of flight and severity; and (iii) failure of emergency floating devices (e.g., **R38**) might reduce

survivability. Moreover, bonding defects might also indirectly contribute to structural failures. E.g.: microcracks, interconnected voids, or porosity might permit fluid ingress, triggering corrosion and, ultimately, the nucleation of adherends' fatigue cracks that might grow undetected up to failure (e.g., **R05**, **R18**, **R19**, **R32**). The data also show that minor deviations to (e.g., **P04**), or inadequate instructions of (e.g., **E02**), the bonding process might impair the joint performance.

The severity of the aircraft damage and the highest level of injuries (among all injuries) per aircraft category (including the associated engines and propeller) are depicted in Figure 1 and Figure 2, respectively. The data suggest that more severe damage to the aircraft and injury to the occupants occur in bond-related events involving GA airplanes and rotorcraft than transport airplanes.

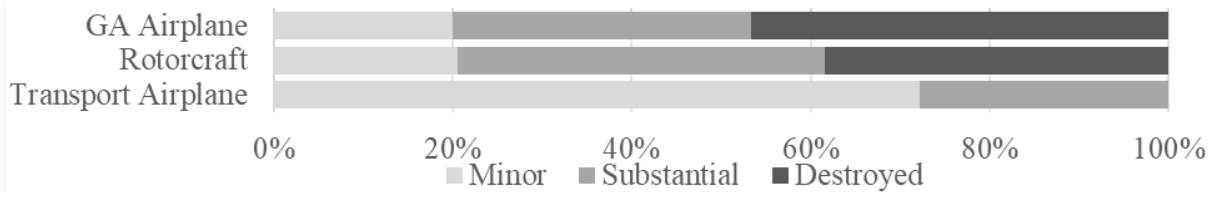


Figure 1. The severity of aircraft damage, per aircraft category (engine and propeller included)

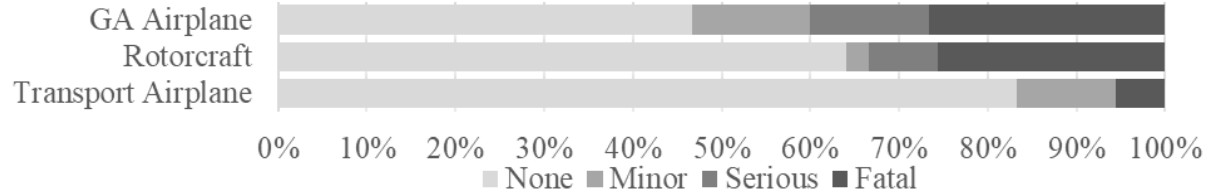


Figure 2. The highest level of injures per aircraft category (engine and propeller included)

The relationship between the number of events and the different aircraft categories was also examined. The number of events is likely correlated with the size of the fleet. Thus, each aircraft category's number of events was weighted, considering its proportion in the fleet [eq. 1].

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

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; [eq. 1]
$N_a^i$ = size of the fleet of the *i*-th aircraft category;
$N_a^t$ = total fleet of type-certified aircraft with valid registration.

The USA has the largest registered civil aircraft fleet globally, with over 232,000 type-certified aircraft with valid registration in 2019 [100]. Although this fleet has more than doubled in the previous decade, the proportion of rotorcraft, transport airplanes, and GA airplanes remained relatively stable (mean and standard deviation of 6 % ± 0.8 %, 8 % ± 0.4 %, and 84 % ± 0.4 %, respectively [100]. Assuming these proportions to the global fleet over the last decades, the weighted number of bond-related events involving rotorcraft, transport airplanes, and GA airplanes is about 630, 240, and 18, respectively. This result suggests that bond-related events have been occurring 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.

It is worthy to note that the level of investigation rigor varied among the reviewed events. Additional engineering data (e.g., NDIs, microscopy, chemical and mechanical tests, numerical simulations) complemented some investigations. Events with a higher degree of perceived

potential unsafe condition seemed to be investigated in more detail, e.g.: events involving many occupants (e.g., **TA06**, **R33**) or potentially affecting a significant part of the fleet (e.g., **R06** to **R08**). Other factors (e.g.: resources available for the investigation, public opinion) might also play a role in the investigation's rigor. A less thorough investigation might impact the proper identification of adhesives failure modes. Other aspects such as investigators' minimal exposure to bond-related investigations, which are relatively rare compared with other causes, and limited formal training on adhesive bond failure forensics might also impact this identification [4].

# 4. CONCLUSIONS

Over the last seven decades, the civil aircraft in-service experience has been documented worldwide in many aircraft event investigation reports and safety recommendations. From these documents, 72 bond-related events were reviewed here. The findings of the analysis follow:

- In most of the reviewed events (59 of 72), the investigators identified bonding process issues that originated during maintenance or production as contributing factors. These issues potentially represent shortfalls in type, production, or maintenance certifications;
- Environmental degradation/adhesion failures were often (42 of 72) observed in both metallic (21 of 32) and composite (7 of 17) joints;
- Bond-related events were found in all different categories of aeronautical products (rotorcraft, GA and transport airplanes, propellers, and engines);
- 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 related to transport airplanes;
- Bond-related events involving helicopters were observed more often than those involving GA or transport airplanes. In most cases (28 of 39), failures were in rotor blades;
- Substandard bonding in non-critical structures can also lead to potentially unsafe conditions (e.g., **TA03**, **TA05**, **R10**, **R20**, **R21**, **R26**, **R24**, **R38**, **R39**, **E02, P01** to **P05**);
- Bonding defects might also threaten the adherents' environmental protection and hence indirectly contribute to structural failures (e.g., **R05**, **R18**, **R32**); and
- The investigations' level of rigor varied among events, which might impact adhesive failure modes' identification.

These findings are consistent with the current certification policy [3] as it emphasizes the need for process control and durability substantiation to ensure bonded structures' long-term safe operation. This need is more evident in, but not restricted to, critical structures with limited load path redundancy (e.g., rotorcraft blades). 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 reliably guarantee the expected joint structural performance in case of substandard bonding.

# 5. RECOMMENDATION FOR FUTURE WORKS

This work was based on a limited number of events and could be complemented by additional investigation reports, service difficulty reports, or proprietary data (OEMs, operators, military). As the compiled data illustrates, 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 [5,15]. 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 (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.

## 6. DISCLAIMER

The opinions expressed herein are the authors' own and not necessarily their employers' view.

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