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Windshield Damage Analysis on ATR 42/72-600 Aircraft at PT. DEF

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Abstract. Windshield damage on ATR 42/72-600 aircraft at PT. DEF has caused operational disruptions, including flight delays, increased maintenance costs, and potential safety risks. Repeated damage to the Windshield is caused by various factors, namely inspection and maintenance errors, improper installation procedures, damage to the heating system or pressure distribution, glass material degradation, and exposure to extreme weather and UV rays. In this study, the analysis was carried out using a quantitative method with a fishbone diagram to identify the main causes of damage and appropriate mitigation steps. The results of the analysis showed that the main factors contributing to the damage were errors in inspection, installation errors, and material degradation. After implementing mitigation steps such as improving technician training, revising maintenance procedures, and improving material selection, there was a significant decrease in the frequency of Windshield damage. An indication of the success of these mitigation steps can be seen from the repairs carried out during January to June 2024 which succeeded in reducing damage and rejects on the Windshield by 40% compared to 2023, improving the quality of maintenance, inspection and material durability. In terms of maintenance costs for spare parts, there is a decrease in spending on purchasing spare windshields, namely USD 15,375 (PPG Inc.) x 10 units = USD 153,750 in 2023 to USD 21,915 (Saint Gobain) x 3 units = USD 65,745 in 2024 (June), which is 42% until mid-2024. This step increases operational reliability, cost efficiency, flight safety, and employee productivity, customer satisfaction also increases along with reduced flight delays and cancellations due to technical problems. Overall, the study succeeded in reducing Windshield damage and increasing the company's operational efficiency and reliability.

Keywords - Windshield; aircraft; ATR 42/72-600; fishbone diagram; damage mitigation

INTRODUCTION

The ATR 42/72-600 is a twin-turboprop commuter aircraft that is widely used for short-haul flights, especially in areas with airports that have limited runways. As an aircraft that prioritizes efficiency and comfort, the ATR 42/72-600 is highly relied upon in the aviation industry, especially in areas with challenging geographical conditions. Therefore, maintenance and repair of aircraft components, especially those related to aircraft safety and performance, are very important aspects [1] [2].

One of the important components of this aircraft is the Windshield (windshield), which has a crucial function in providing visibility for the pilot and maintaining the structural integrity of the aircraft during flight. Damage to the Windshield, whether caused by internal factors such as material fatigue, or external factors such as collision with a foreign object or sudden pressure changes, can have a direct impact on flight safety [3][4].
Windshield damage often occurs and can threaten flight safety. This problem can be caused by various factors, including drastic changes in air pressure, foreign object impacts, temperature fluctuations, and the quality of the material itself [5]. Damage to the windshield of the ATR 42/72-600 aircraft not only results in high repair costs, but can also cause flight delays and reduce passenger confidence in the airline [6].

PT. DEF, ATR 42/72-600 aircraft are the main fleet operating on various domestic routes. In several incidents, damage was found on the aircraft's Windshield, which requires in-depth analysis to determine the root cause and mitigation steps to prevent more serious system failures. Therefore, Windshield damage analysis is very important to ensure safe and optimal operations [7].

The phenomenon of Windshield damage on ATR 42/72-600 aircraft at PT. DEF has become one of the recurring problems and requires special attention. This damage generally appears in the form of cracks, condensation (fogging), and peeling of the glass layer (delamination) [8]. This phenomenon was detected after several incidents where pilots reported impaired visibility or vibrations originating from the Windshield during flight. Cracks often occur due to extreme air pressure, especially when the aircraft passes through areas of strong turbulence or experiences sudden changes in pressure [9]. Although these cracks appear small at first, the risk of further damage increases if not handled immediately. In addition, condensation between the glass layers is often reported by pilots after flights at low temperatures, which can interfere with visibility, especially when taking off or landing in areas with limited visibility.

This research aims to explore the thermal and mechanical properties of acrylic materials used in aircraft glass, as well as how these materials can be improved to provide better resistance to the various stress factors encountered during flight, such as drastic temperature changes and mechanical stress due to impact or vibration.

METHOD

Flowchart is an explanation of the flow of research or projects starting from the initial stage to the final stage. The research flowchart in Figure 1 shows the steps taken in a study. The process begins with the Literature Study stage, which is the collection of information from relevant library sources. This step is followed by Field Study, where primary data is collected directly from the field. After the data is obtained, the Data Processing stage is carried out to analyze the raw data into meaningful information. Data sources in research are a very important factor, because data sources will affect the quality of research results. Therefore, data sources are a consideration in determining data collection methods. Data sources consist of: primary data sources and secondary data.

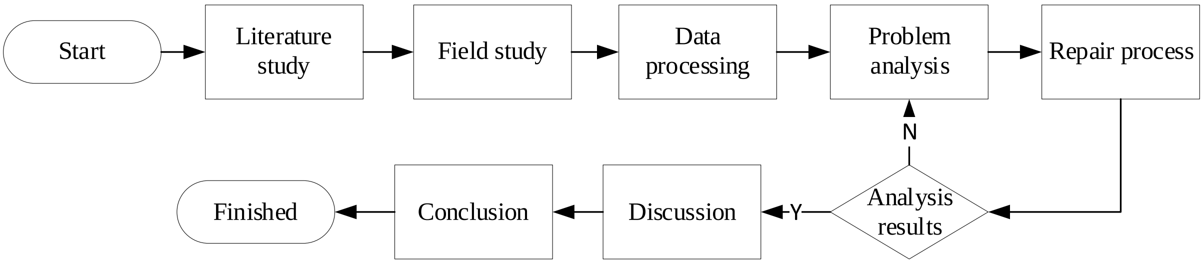

Figure 1. Research flowchart

Data collection technique

Data collection techniques are systematic and standard procedures for obtaining the data needed in research. Data collection is one of the most important parts in conducting research. This method is carried out directly in the aircraft maintenance workshop to directly see the inspection process, type of damage, severity of damage, repair and replacement of Windshield and testing of Windshield until the aircraft is ready to be used again. This observation technique provides visual data and technical data on how Windshield damage is diagnosed and repaired. The secondary data in question is statistical data on the frequency of windshield damage on ATR42/72-600 aircraft obtained from airline databases and maintenance workshops that have records of the types and amounts of damage that occur during a certain period. Data collection is carried out through literature reviews and document analysis related to aircraft Windshield maintenance and damage taken from the ATRnavx Aircraft Maintenance Manual (AMM), Service Bulletin (SB) and maintenance and incident reports to Windshield manufacturers and ATR aircraft factories.

RESULTS AND DISCUSSION

In identifying several cases of delamination, where the glass layer begins to peel off, especially on aircraft that have been in operation for more than five years. This delamination is caused by repeated exposure to temperature fluctuations and high humidity conditions that affect the integrity of the laminated glass on the Windshield.

Damage to the Windshield of an ATR 42/72-600 aircraft at PT. DEF has a significant impact on the company's operations. Whenever damage occurs, especially involving cracks or delamination, the aircraft must be immediately removed from flight service (grounded) to undergo additional safety inspections. This procedure, although important to ensure flight safety, causes flight delays and aircraft downtime, which directly impacts PT. DEF's daily operational schedule. As a result, scheduled routes must be postponed or diverted to other fleets, adding to the burden on an already busy flight schedule. The repair duration, which takes 2 to 4 days, further extends the aircraft downtime, creating disruptions in operational efficiency and domestic route service. This not only causes route delays for several days, but also has the potential to affect customer satisfaction and the company's cost efficiency [5].

Table 1. Damage level of ATR 42/72-600 windshield

Category Windshield Damage Level	Data
Number of aircraft with damage	4 out of 15 ATR 42/72-600 aircraft have experienced Windshield problems in the last 18 months.
Type of damage	3 out of 4 cases showed micro cracks detected during routine inspection.
Condensation	2 out of 4 aircraft experienced significant condensation during flights in low temperature conditions.
Incident Frequency	
Visibility impairment	5 reports from pilots regarding impaired visibility due to Windshield in bad weather conditions.
Delamination	Delamination incidents occur on average after 10,000 flight hours
Triggering factors for delamination	It often occurs on aircraft operating on tropical routes with high humidity
Repair Duration and Cost	
Repair duration	The average duration for repairing and replacing a windshield takes 2 to 4 days
Replacement cost	The cost of replacing a Windshield for ATR 42/72-600 ranges from USD 15,000 to USD 25,000
Additional cost	This cost does not include labor costs.

Table 1 shows the extent of damage to the windshield of ATR 42/72-600 aircraft over the past 18 months. Out of 15 aircraft, 4 experienced windshield problems. Of the 4 cases, 3 cases showed micro cracks that were only detected during routine inspections. In addition, 2 of the 4 aircraft experienced significant condensation during flight, especially in low temperature conditions. The frequency of incidents was also recorded, with 5 reports from pilots regarding impaired visibility due to the affected windshield in adverse weather conditions. Delamination was also a problem, usually occurring after the aircraft reached 10,000 flight hours. The main trigger for delamination is aircraft operation in tropical areas with high humidity. In terms of repair, the average duration of repair and replacement of the windshield takes about 5 to 7 days. The cost of replacing the windshield of ATR 42/72-600 aircraft ranges from USD 15,375 (PPG) to USD 21,914. 28 (SG).

Research analysis of damage types of ATR 42/72 - 600 Windshield

Based on data collected from airline operators and maintenance workshops, Windshield damage on ATR42/72-600 aircraft can be grouped into several general categories.

Cracks: Cracks are found on the outer and inner glass layers due to foreign object impacts or high air pressure. Cracks on the windshield (windshield) of the aircraft cockpit that has damage to the outer layer and possibly also the inner layer. These cracks can be caused by several factors. One of the main factors is the impact of foreign objects (FOD), such as birds or small debris, which can hit the glass at high speed. This impact puts great pressure on the glass structure, causing cracks. In addition, high air pressure at flying altitude is also a significant factor. The windshield is designed to withstand the pressure difference between the inside of the cockpit and the atmosphere outside the aircraft, but if there is a sudden fluctuation in air pressure, especially on glass that is already weakened, cracks can occur [10].

Extreme temperature changes can also affect the structure of an aircraft's glass. As an aircraft climbs to higher altitudes in colder temperatures or descends to warmer ones, the glass can expand or contract, causing additional stress on glass that may already have microcracks [11]. Additionally, material fatigue in aircraft glass, from the constant stress of operation, can make it susceptible to cracking, even in the absence of impacts or extreme pressure changes. The windshield's heating system, which prevents condensation or freezing, can also be a factor. If the heating system fails, overheating in some areas of the glass can lead to cracking [12]. To find out the exact cause of the crack, further inspection by a technician is required. They will check for physical signs, perform pressure testing, and evaluate maintenance or operating history to determine the factors that influence the damage to the windshield.

Delamination/Delamination: Delamination occurs when the layers between the glass begin to separate, often caused by extreme temperature changes or the quality of the Windshield material decreasing [13]. Delamination in materials, which is a condition where the layers of a material, such as glass or composite, begin to separate or peel away. This delamination can occur due to several factors, such as exposure to extreme temperatures, excess moisture, or mechanical damage. The delamination process usually begins with a small crack or gap in the outer layer, which can then widen over time. This condition reduces the structural integrity of the material, which can lead to weakness or even failure if not repaired promptly [14]. In the context of aviation or heavy industry, delamination of critical components such as aircraft windshields or structural composite parts can have serious implications for operational safety [15].

Bubbles: Bubbles are the appearance of air bubbles on the windshield between the glass layer and the interlayer layer. Discoloration: Discoloration is a change in color or the appearance of abnormal spots, usually caused by glass material degradation. Microflakes are conditions where the glass layer or polymer layer on the outer ply experiences small peeling in the form of micro flakes.

Scratches: Scratches are often caused by the use of wipers or dust rubbing against the glass surface during flight. Scratches on airplane glass, such as those commonly found on windshields, are surface defects that are generally caused by friction from hard objects, either directly or indirectly. One of the main causes of scratches is the use of wipers on dirty or dusty glass. As the wipers move over the glass, dust or dirt particles left on the surface can be dragged along and cause small to large scratches on the glass.

In addition, environmental factors also play a role. When the aircraft is flying at high altitudes, small particles such as dust, sand, or even ice can hit the glass at high speeds, causing surface damage. Although scratches may appear shallow, their effects can accumulate, reducing visual clarity and impairing the pilot's vision, especially when flying in poor weather conditions or at night. Unrepaired scratches can develop into cracks or more serious defects. Therefore, scratches on aircraft glass require regular care and maintenance to ensure the safety and functional effectiveness of the aircraft windshield.

Electrical defects: Electrical defects are divided into two, namely Arcing/sparks on the windshield that occur due to failure of the heating element/heating film cracking or electrical connection problems and damage to the temperature sensor, if this condition occurs, it can be moved from the main sensor to the spare sensor without having to replace the windshield. Some Windshield damage that occurs on the ATR 42/72-600 PT.DEF aircraft [16].

Windshield heater short circuit is a condition where there is a short circuit in the aircraft's windshield heating system, which causes the flow of electric current to flow directly without going through the proper path. The heating system on the aircraft's windshield is designed to generate heat through special heating elements in the glass layer, thereby preventing freezing and maintaining pilot visibility during high-altitude flights.

When a short circuit occurs, the electric current that flows exceeds the safe limit, causing excessive heat in the electrical components. This condition can trigger several problems, such as damage to the heating element itself, the glass becoming too hot, or even the failure of the entire heating system. As a result, the heating system may stop working, putting the windshield at risk of freezing at high altitudes and reducing visibility.

A short circuit in the windshield heater can be caused by several factors, including damage to the wiring, wear on the heating element, or even moisture entering the system and causing corrosion or insulation failure. This condition needs to be addressed immediately because it has the potential to compromise flight safety. Regular inspection and proper maintenance are essential to prevent these short circuits from occurring, as well as to ensure that the windshield heating system functions properly during flight.

Windshield heater short circuit is a condition where there is a short circuit in the windshield heater system of the aircraft. This heating system is important to prevent condensation (fogging) or ice formation on the windshield, especially when flying at altitudes with low temperatures [13].

When a short circuit occurs, the electrical flow is disrupted, which can cause several problems, such as: a) Damage to the heating system itself. b) Disturbance to pilot visibility because the windshield cannot be heated optimally. c) Potential safety risks if this problem is not addressed immediately. Indications of problems with the Windshield heater can be seen from warnings or fault messages in the cockpit, requiring immediate corrective action to prevent greater risks.

Windshield laminated layer Delamination is a condition in which the layers of laminated glass on the aircraft windshield experience adhesion failure or separation between one layer and another. In laminated aircraft glass, several layers of glass and plastic (usually PVB or polyvinyl butyral) are bonded together to provide strength and resistance to impact as well as protection against external factors such as extreme temperatures and pressure.

In Delamination, these layers no longer adhere properly. This can be caused by a variety of factors, such as excessive UV exposure, moisture entering the glass layer, damage due to drastic temperature changes, or suboptimal manufacturing processes. If de-bonding occurs, the separated area can appear as a bubble or a cloudy area on the glass.

This failure of windshield adhesion can have serious consequences, especially since aircraft windshields must withstand high air pressures and provide clear visibility for the pilot. Unaddressed de-bonding areas can grow larger over time, reducing the structural strength of the glass and potentially affecting the overall integrity of the glass.

Regular maintenance and inspection are required to detect and treat de-bonding at an early stage, so that the aircraft windshield remains safe and functional during flight. De-bonding of this layer occurs when the layers begin to separate or lose cohesion, which can be caused by various factors such as: Material fatigue due to extreme temperature changes, Continuous exposure to UV light and causing degradation of the adhesive, Environmental stress such as humidity or vibration during flight, Mechanical damage or impact.

This de-bonding effect can reduce the structural strength of the Windshield and potentially impair pilot visibility. This problem must be inspected and repaired immediately to maintain flight safety. Windshield crack in flight is a condition where the windshield of the aircraft cracks during flight. Aircraft windshields are designed to withstand extreme pressure and harsh environmental conditions, but there are several factors that can cause cracks in flight:

- Cabin Pressure: The difference in pressure between the cabin and the air outside the aircraft, especially at very high altitudes, can cause stress on the windshield. If the windshield already has weaknesses such as scratches or small imperfections, this stress can trigger cracks.
- Foreign Objects: Strikes from foreign objects such as birds or airborne debris (FOD) can cause damage to the glass, especially when the aircraft is flying at high speeds.
- Thermal Stress: Sudden temperature changes, such as transitions from extreme cold temperatures at high altitudes to warmer temperatures at low altitudes, can cause thermal stress that contributes to glass cracking.
- Windshield Heater Failure: Many aircraft are equipped with a Windshield heater to prevent ice formation. If the heating system fails, it can cause the glass to heat or cool unevenly, which can lead to cracking.
- Material Fatigue: Over time, the materials used in Windshields can fatigue due to repeated cycles of pressure and temperature, which makes the glass more susceptible to cracking.

If a crack in the Windshield occurs while the aircraft is in flight, there are several steps taken by the pilot: a) Lowering the altitude: Reducing the pressure difference between the cabin and outside the aircraft to reduce stress on the Windshield. b) Diverting the flight: If necessary, the pilot can divert the aircraft to the nearest airport for an emergency landing. c) Emergency Procedures: The aircraft is equipped with emergency procedures to deal with Windshield damage, including reducing the aircraft's speed and changing the flight path.

Windshield cracks rarely cause total structural failure because Windshields usually have several layers of safety. However, it is still a serious problem that requires immediate attention. Overall, the Windshield of ATR 42 PT. DEF aircraft must undergo routine inspections to ensure that there are no defects that affect its structural integrity or functional performance. Failure in any of these aspects requires immediate attention to maintain flight safety. In this study, some data has been collected regarding Windshield damage on ATR 42/72-600 aircraft.

Physical Inspection Data: a) Windshield has cracks on the outer layer of glass. b) There is visual distortion during flight due to moisture trapped between the laminated glass layers. c) Discoloration on several parts of the Windshield showing signs of oxidation or material degradation. d) Maintenance records indicate that there has been a history of Windshield replacement in the last few years.

Operational Data: a) Intensive use of the aircraft in extreme weather conditions, especially low temperatures and high pressures while flying at high altitudes that affect the durability of the Windshield. b) External temperature records during flight indicate that sudden temperature changes between parking and flight conditions may contribute to glass cracking.

Maintenance Data: a) Periodic maintenance procedures are in accordance with the maintenance manual, but some discrepancies were found in the routine inspection process on the Windshield. b) Use of cleaning materials that do not meet manufacturing standards, which can potentially damage the glass protective layer.

Data processing.

The results of data collection and collection that has been carried out at PT. DEF related to damage to the Windshield of the ATR 42/72-600 aircraft, this study only focuses on failures that occurred during the maintenance and use process in the last few months. The data collected includes the number of Windshields produced or installed and the number that experienced failure or damage.

Table 2. Number of windshield damages of ATR 42/72-600 aircraft at PT. DEF

Year	Number of windshields inspected and installed	Number of damages/rejects	Damage percentage (%)
2019	7	2	29%
2020	8	4	50%
2021	6	1	17%
2022	8	3	38%
2023	10	4	40%

Based on the data in Table 2 regarding damage to the ATR 42/72-600 aircraft Windshield at PT. DEF during the period 2019 to 2023, it can be seen that the percentage of Windshield damage varies from year to year. In 2019, out of 7 installed Windshields, there were 2 damages or rejects, which is equivalent to a 29% damage rate. This percentage increased significantly in 2020, where out of 8 installed Windshields, 4 were damaged, resulting in a damage percentage of 50%. 2020 recorded the highest figure during the period, indicating possible problems with material quality or maintenance procedures.

In 2021, there was a significant improvement with only 1 out of 6 Windshields damaged, giving a damage percentage of 17%, which is the lowest point in the last five years. However, this positive trend did not last long, because in 2022 the damage percentage increased again to 38% with 3 out of 8 Windshields damaged. In 2023, despite an increase in the number of Windshields installed to 10, the damage rate remained high with 4 damages or rejects, equivalent to a 40% damage rate.

These fluctuations indicate that there are factors that influence the Windshield failure rate, including material quality, maintenance methods, and aircraft operating conditions. Years with high failure rates, such as 2020 and 2023, require more in-depth analysis of the causes and more serious remedial actions to prevent future failures. Recommendations for improvement include improving the Windshield material quality, stricter installation procedures, and more thorough inspection of the Windshield heating and pressure distribution systems. This is important to reduce the failure rate and ensure the safety and reliability of aircraft operations.

Problem definition stage (define).

At this stage, it will be discussed about determining what process will be measured. The process stages that will significantly affect the performance of the aircraft need to be considered, because in the process of maintaining and using the Windshield, rejects or component failures are often found which are important considerations in determining the quality of the resulting maintenance. The process to be analyzed is the process of replacing and maintaining the Windshield of the ATR 42/72-600 aircraft. The end result is a Windshield that is installed and functioning properly to ensure the safety and operational efficiency of the aircraft.

Table 3. Total data of windshield damage of ATR 42/72-600 aircraft at PT. DEF

Year	Person	Environment	Machine	Material	Method
2019	2	-	-	-	-
2020	1	-	1	1	1
2021	-	1	-	-	-
2022	1	-	1	-	1
2023	1	1	1	1	-
Total	5	2	3	2	2

Based on Table 3 it can be explained that:

1. Human Factor (People): This factor is the most common cause with a total of 5 cases of failure during the five-year period from 2019 to 2023. Failures caused by humans can be errors in inspection, maintenance, or installation of the Windshield. This factor appears consistently every month, indicating the need for improvement in technician training or work procedures.
2. Environmental Factors: Environmental factors, such as extreme weather conditions or UV exposure, were noted as the cause of failure in 2 cases. Harsh environmental conditions can cause thermal stress on the Windshield, making it a significant cause.
3. Engine Factor: Failures caused by engine problems, such as failure of the Windshield heating system, were recorded 3 times. This shows that technical problems in the Windshield support equipment also make a significant contribution to the failure of this component.
4. Material Factor: Windshield material quality issues accounted for 2 cases of failure. This indicates that the Windshield material used may not have sufficient durability or may have degraded due to environmental exposure and prolonged use. The normal glass heating condition is around 35°C to 55°C (95°F to 131°F), depending on the aircraft type and the specific Windshield design.
5. Method Factor: Failures caused by improper procedures or methods were also recorded in 2 cases. This could be caused by installation or maintenance methods that do not comply with applicable operational standards.

Human factors were the most dominant cause with 8 failure cases, followed by material and method factors with 6 cases each. This indicates the need for improvement in technician training as well as checking the quality of materials used and maintenance methods applied. Environmental and machine factors also contributed to the total failure, although in lower numbers. Attention to all of these factors is essential to reduce the number of failures in the future. Human Factors (People) were recorded as the most dominant cause, with a total of 5 failure cases. This shows that human error, such as installation or inspection errors, is the biggest contributor to Windshield failures.

Environmental factors (e.g. extreme weather or UV exposure) and Mechanical factors (e.g. failure of the heating system or defogging regulator) each caused 2 cases of damage for the environment and 3 cases for the mechanical factors. These mechanical and technical factors play a significant role in the failure of the Windshield function.

Material factors (windshield material quality) and methods (improper installation or maintenance techniques) each contributed 2 cases of damage. The quality of the material and the working methods used are also important areas that need to be improved.

This diagram, it is clear that the human factor (People) plays a key role in Windshield failure, followed by other factors such as materials and working methods. To reduce the failure rate, there needs to be improvement in technician training as well as better material selection and implementation of more effective maintenance methods.

Problem analyzing stage (analyze)

In a study, conducting a cause and effect analysis of the problems that occur is a step that cannot be left out, considering that this is to find the real root of the problem so that it can later be used as a reference for improvement, so if the root cause analysis is correct, the improvement will also produce the right results.

However, on the other hand, if the root of the problem is not found correctly, then the determination of the repair solution will also be inappropriate, where later the repair results will not produce the appropriate results because the solution developed does not solve the problem that occurs. Therefore, for the analysis of the cause and effect of the problems that occur which are related to the cause analysis step, researchers will use a very popular method in finding the root of the problem, namely the fishbone method.

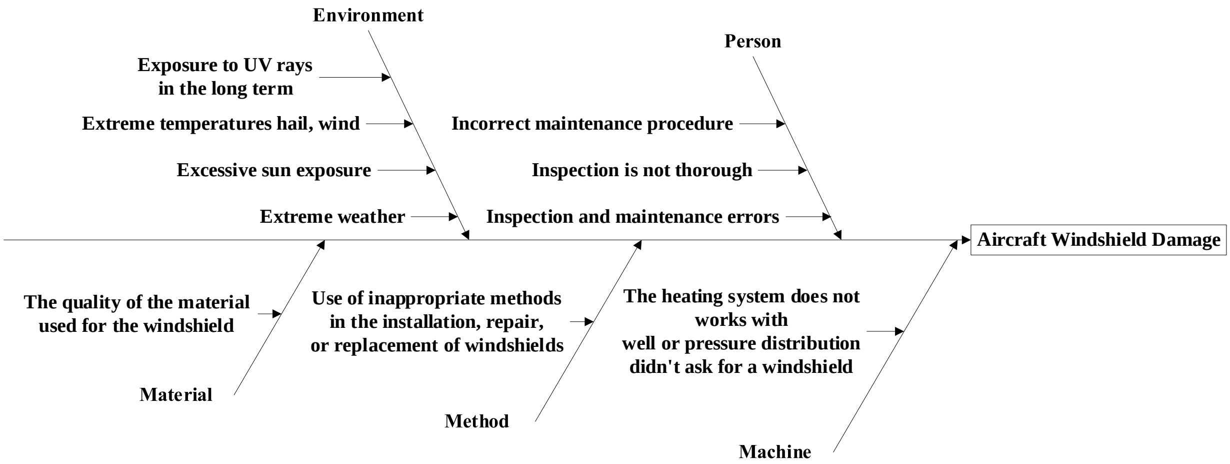

Figure 2. Fishbone diagram

Figure 2 explains the factors causing damage to aircraft windshields, based on the fishbone analysis shown in the diagram, which can be explained as follows:

- Human Factor (Inspection/Maintenance Errors): Mistakes made by technicians or maintenance staff in performing routine inspections and maintenance on the Windshield can be the cause of damage. For example, careless inspection or incorrect maintenance procedures can result in damage or failure to detect problems on the Windshield in a timely manner. Proper Repair and Maintenance include: a) Routine and Thorough Inspection: Aircraft Windshield maintenance requires routine inspections to detect potential damage. The application of visual and non-destructive methods (e.g., ultrasonic testing) is essential to find micro-cracks or material degradation that may not be visible to the naked eye. b) Technician Training: All technicians involved in Windshield maintenance must receive adequate training and certification. Procedural errors often occur due to lack of technical understanding, so periodic training is necessary to ensure compliance with applicable standards. c) Heating System: Periodic inspection of the heating system function is crucial. A heater that is not working optimally can cause the Windshield to experience thermal stress. Thermography or temperature sensor inspection can be used to ensure even heat distribution.
- Method Factors (Improper Procedure): Using an improper method in installing, repairing, or replacing the Windshield can cause damage. Incorrect handling procedures can create excessive stress, improper installation, or non-compliance with applicable safety standards. Proper Methods include: a) Windshield Replacement Procedure: Installation and replacement of the Windshield must follow standard procedures established by the aircraft manufacturer and aviation authorities. The use of proper tools (such as torque wrenches for tightening bolts) and testing after installation are mandatory steps to ensure that there is no excessive stress on the Windshield. b) Pressure and Temperature Measurement Standards: The use of accurate pressure and temperature

measuring devices during the installation of the Windshield will ensure that there is no significant pressure or temperature difference that can trigger damage

- Material Factors (Quality/Degradation): The quality of the material used for the Windshield, if inadequate or degraded over time, can affect its resistance to air pressure, extreme temperatures, or exposure to ultraviolet (UV) light. Materials that do not have high resistance to operating conditions can experience cracking or other damage. The Recommended Lifespan of Aircraft Windshield Materials is usually dependent on several factors, including material quality and operating conditions. However, in general: a) Laminated Windshield Glass: The average recommended life span is 4 to 5 years, depending on exposure to environmental factors such as UV light and extreme temperatures. b) Windshield Heating System: The heating components need to be checked and serviced regularly. The life span of the heating system is approximately 2 to 3 years, depending on usage and maintenance conditions. c) After this life span, a thorough inspection should be performed to ensure the structural integrity of the Windshield and replace if necessary.
- Engine Factors (Heating System/Pressure Distribution): Aircraft windshields are often equipped with a heating system to prevent dew or ice. If the heating system is not functioning properly or the pressure distribution is uneven on the Windshield, this can trigger damage, such as cracking or breaking due to changes in temperature or unbalanced pressure.
- Environmental Factors (Extreme Weather/UV Exposure): Extreme weather, such as excessive sun exposure, extreme temperatures, hail, or high winds, can accelerate the degradation of the Windshield material. Long-term exposure to UV rays can also damage the structure of the glass material, reducing its durability and increasing the risk of cracking. Environmental factors greatly affect the service life and condition of the Windshield material. Standards that need to be considered include: a) Operating Temperature: The Windshield must be able to withstand extreme temperature changes ranging from -50°C to 50°C. This refers to the temperature that can be experienced during flight, from low altitude to very high cruising altitude. b) UV Exposure: The Windshield must have high resistance to ultraviolet light exposure. The material is designed to protect against 99-100% of UV rays to reduce long-term degradation. c) Air Pressure: The windshield must be able to withstand a significant pressure difference between the cabin interior and outside the aircraft of up to 6.35 psid and the outside air pressure at an altitude of 25,000 feet is 10.91 psi (8,000 feet Cabin Altitude) approximately 30-40% of the air pressure at sea level which is 14.7 psi [17].

Each of these factors can contribute individually or simultaneously to causing damage to the aircraft Windshield, so it is important to evaluate each aspect in detail to determine the root cause of the problem. From the results of the cause and effect analysis with the fishbone diagram, an analysis of the causal factors was also carried out to be used as strategic steps in improvement (Improving Continuous) at the next stage of the process. presented in Table 4.

Table 4. Factors causing damage to the windshield of the ATR 42/72-600 aircraft at PT. DEF

No.	Factor	Dominant causes	Remarks	Fact
1.	Person	Inspection/maintenance error	Technician errors in checking or maintaining the Windshield cause damage not to be detected early.	Substandard maintenance reports were found, several errors in technician inspections were identified.
2.	Method	Improper installation/repair procedures	Using the wrong procedure in installing or repairing the Windshield can cause excessive stress.	The audit report showed that several installation procedures did not follow applicable SOPs, especially regarding pressure distribution during installation
3.	Machine	Damage to the heating system or pressure distribution	The Windshield heating system or pressure distribution does not function optimally, causing cracks in the glass.	There are records of damage to the Windshield heating system, with uneven heat distribution causing extreme temperature differences across the glass.
4.	Environment	Extreme weather and UV exposure	Extreme weather conditions and UV exposure cause glass	According to weather reports, aircraft are often exposed to extreme

			materials to degrade more quickly.	temperatures and high UV radiation in certain areas, accelerating the degradation of glass materials.
5.	Material	Degradation of glass material	The glass material used has low resistance to high pressure and temperature.	After laboratory analysis, it was found that the Windshield material experienced a decrease in mechanical strength after a certain period of use.

Table 4 provides an overview of the causal factors for Windshield damage, so the next step is to create a design to overcome the root cause, with the design structure using the 5W 1H method, as shown in Table 5.

Table 5. 5W 1H Method

No.	*What (The Problems is)*	*How? (Action Plan)*	*Why? (Effect)*	*When?*	*Where?*	*Who?*
1.	Inspection/maintenance error	Conduct technician retraining and regular evaluation of inspection procedures.	Damage was not detected in time so that the Windshield suffered more serious damage.	Every 3 months or after every critical flight.	Maintenance hangar and airfield.	Aircraft maintenance technicians and teams.
2.	Improper installation/repair procedures	Review of installation and repair SOPs, and re-certify technicians.	Improper installation causes excessive stress which can lead to cracks or damage to the Windshield.	After each new Windshield installation.	Windshield repair and replacement place.	Installation technician and maintenance manager.
3.	Damage to the heating system or pressure distribution	Perform heating and pressurization system checks before each flight.	Uneven heat distribution causes extreme temperature differences in the glass, triggering cracking or breaking.	Every pre-flight inspection.	In the cockpit and glass areas of the aircraft.	Electrical systems and parts technician.
4	Extreme weather and UV exposure	Using glass material that is resistant to extreme weather and UV, and provides additional protection.	Extreme weather and UV exposure accelerate glass degradation thereby reducing the life of the Windshield.	In extreme seasons/weather, especially on routes with high UV exposure.	Flight areas prone to extreme weather.	Pilots, engineers and flight planning team.
5	Degradation of glass material	Perform periodic replacement of glass materials and evaluation of material quality.	Material degradation causes the glass to become brittle and susceptible to extreme pressure and temperatures.	Material degradation causes the glass to become brittle and susceptible to extreme pressure and temperatures.	Material storage center and hangar.	Maintenance managers and material vendors.

Improvement Stage

In the improve stage, what will be done is to make a plan and implement improvements in order to reduce the number of failures in the relining process. This improvement is needed to fix potential problems that cause rejects.

Table 6. Implementation of Improvements

No	Causative factor	Implementation of Repairs
1.	Inspection/maintenance error	- Improve technician training to ensure inspections are performed to standards. - Create a more detailed inspection checklist that must be followed by technicians. - Introducing automated inspection technology (e.g., cameras or sensors) to assist technicians.
2.	Improper installation/repair procedures	- Revise SOP for installation and repair of Windshields, and provide retraining to technicians. - Ensure all procedures are followed with certification after installation. - Periodic audits to monitor the implementation of SOPs in the field.
3.	Damage to the heating system or pressure distribution	- Regular maintenance of the heating and pressure distribution system to prevent damage. - Calibration of heating and pressure distribution systems before flight. - Implementation of automatic monitoring of pressure and temperature distribution around the Windshield.
4	Extreme weather and UV exposure	- Using Windshield material that is more resistant to extreme weather and UV exposure. - Applying an additional protective layer to the glass to reduce the effects of UV. - Plan flight routes that avoid extreme weather, if possible.
5	Degradation of glass material	- Using materials with higher quality specifications that are durable. - Using materials with higher quality specifications that are durable. - Periodic material testing to ensure that the quality still meets standards.

Table 6 explains and provides details on how each improvement step is targeted to address the issues found on the aircraft Windshield, with a focus on improving the quality of inspection, maintenance, and the use of more durable materials. The extent of success after repairs were made, the damage to the aircraft windshield was then taken again from the aircraft windshield data after repairs were made for the period January to June 2024.

Table 7. Aircraft windshield damage data for the period January–June 2024

Month	Number of Windshields Inspected and Installed	Amount of Damage
Januari	2	0
Februari	-	0
Maret	-	0
April	1	0
Mei	-	0
Juni	-	0

Table 7 presents data on aircraft Windshield damage for the period January to June 2024, with information related to the number of Windshields installed and the number of damages or rejects. The following is an explanation of the table. Number of Windshields installed: a) January: A total of 2 Windshields were installed, and no damages were reported. b) February to June: There were no new Windshield installations in February, March, May, and June. In April, only one Windshield was installed. Number of Damages or Rejects: During the period February to June 2024, no damages or rejects were reported for the installed Windshields. This indicates that all installed Windshields are functioning normally without any defects that require replacement or repair.

Analysis

Maintenance Performance: The data shows positive results as there were no reports of damage or failures on the installed Windshields during this period. This could reflect the effectiveness of the Windshield maintenance and inspection procedures carried out by the maintenance team.

Installation Frequency: There was only one new Windshield installation in April and two in January, while no installations were seen in other months. This may indicate that new Windshield installations are carried out only when there is an urgent need (e.g., due to material age or previous damage), or that existing Windshields are still in good condition.

Recommendation: Even if no damage is reported, preventive maintenance and regular inspections should still be performed to ensure that the Windshield continues to function properly and does not show any signs of undetected degradation. Periodic Windshield performance evaluations will ensure that problems can be identified early before they cause further damage.

Table 8. Windshield damage data of ATR 42/72-600 Aircraft at PT. DEF after mitigation and analysis

Year	Number of Windshields inspected and installed	Number of damage/rejects	Damage percentage (%)
2019	7	2	29%
2020	8	4	50%
2021	6	1	17%
2022	8	3	38%
2023	10	4	40%
2024	3	0	0%

Table 8 the effectiveness of mitigation from the results of the Windshield maintenance improvement analysis at PT.DEF until June 2024 is a significant decrease in windshield damage by 40% compared to 2023. In terms of the amount of maintenance costs for spare windshields, there was a decrease in spending on purchasing spare windshields, namely USD 15,375 (PPG Inc.) x 10 units = USD 153,750 in 2023 to USD 21,915 (Saint Gobain) x 3 units = USD 65,745 in 2024 (June) which is 42% until mid-2024.

The impact of company operations after the improvement process

After making changes related to aircraft Windshield damage repair at PT DEF, several positive impacts on the company's operations can be identified. Increased Aircraft Operational Reliability: With reduced Windshield damage, aircraft experience fewer operational disruptions that require urgent repairs. This increases aircraft availability and reduces downtime, so flight schedules can be better maintained. Maintenance Cost Efficiency: Effective repairs have reduced the number of Windshield components that must be replaced. This lowers the material and labor costs for replacement or repair, as well as minimizing potential losses due to flight cancellations or delays. Increased Safety: A properly functioning Windshield is critical to flight safety, especially in the face of extreme air pressure and weather conditions. With reduced damage, operational risks related to safety also decrease, increasing confidence in the quality of aircraft maintenance. Employee Productivity: Training provided to technicians and improvements to inspection procedures help improve their skills and efficiency in handling Windshield maintenance. Employees can focus more on other tasks that also support daily operations. Customer Satisfaction: With reduced delays and cancellations due to technical problems with the Windshield, customer satisfaction levels (airlines or operators) increase. This has an impact on PT DEF's reputation as a reliable aircraft maintenance provider. Overall, the repairs related to the damage to the aircraft's Windshield have a significant impact on operational efficiency, flight safety, and the profitability of PT. DEF in the long term.

CONCLUSION

Repeated damage to the Windshield is caused by various factors, namely inspection errors, improper installation procedures, damage to the heating system and degradation of glass and seal materials. After implementing mitigation measures such as improving technician training, revising maintenance procedures, and improving material selection, there was a significant decrease in the frequency of Windshield damage. Evaluation of materials and components leads to a significant decrease in maintenance costs, selecting spare parts with higher prices but have good reliability is one solution in improving aircraft maintenance. If there is a material that often degrades, consider replacing it with a more durable material that is suitable for a particular aircraft type on the ATR42 / 72-600 aircraft, the selection of spare parts from the Pittsburgh Plate Glass (PPG Inc.) manufacturer switched to Saint Gobain. Damage Data Analysis must continue to be carried out in improving aircraft maintenance of other important components on the aircraft so that the maintenance process is more efficient and effective. Overall, this study has succeeded in achieving its objectives by reducing the number of Windshield damages and increasing the efficiency and reliability of the company's operations through improved procedures and technology

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