NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Aviation Engineering Division
Washington, DC 20594
June 21, 2019

STRUCTURES

STRUCTURES GROUP CHAIRMAN’S FACTUAL REPORT
DCA18MA142

1.0 Attachments

1) Cabin Pressurization System Description

2.0 Structures Group

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3.0 Summary

On April 17, 2018, at 1103 eastern daylight time, Southwest Airlines flight 1380, a Boeing 737-700, N772SW, experienced a left engine failure and loss of portions of the engine inlet and fan cowl during climb through flight level (FL) 320. Fragments from the engine inlet and fan cowl struck the wing and fuselage, followed by one cabin window departing the airplane and cabin depressurization. The flight crew conducted an emergency descent and diverted into Philadelphia International Airport (KPHL), Philadelphia, PA. Of the 144 passengers and five crewmembers onboard, one passenger received fatal injuries and eight passengers received minor injuries. The airplane sustained substantial damage. The regularly scheduled domestic passenger flight was operating under 14 Code of Federal Regulations Part 121 from LaGuardia Airport (KLGA), Queens, New York, to Dallas Love Field (KDAL), Dallas, Texas.

4.0 Accident Airplane Information

TABLE 1 provides airplane specifications and **FIGURE 1** provides a front, side, and top view of the airplane.

Operator:	Southwest Airlines, Flight 1380
Location:	Philadelphia, Pennsylvania
Registration Number:	N772SW
Airplane Serial Number:	27880
Airplane Category:	Transport
Airplane Manufacturer:	Boeing
Airplane Model:	737-700 (7H4)
Airplane Year:	2000
Airworthiness Certificate:	Standard
Approved Operations:	121
Aircraft Type:	Fixed Wing Multi-Engine
Maximum Takeoff Weight:	154,500 pounds
Total Time:	63,521 hours
Total Cycles:	37,021 cycles
Type Certificate:	A16WE Revision 61
Wing span (all versions):	112 feet 7 inches
Wing span (with winglets):	117 feet 5 inches
Wing chord at the root:	18 feet 9 inches
Wing chord at the tip:	4 feet 1¼ inches
Overall length (700):	110 feet 4 inches
Overall height (700):	41 feet 3 inches
Engine centerline distance:	31 feet 8 inches
Engine Type:	Turbofan
Number of Engines:	2
Engine Manufacturer/Model:	CFM International/CFM56-7B

Table 1 – Accident Airplane Information

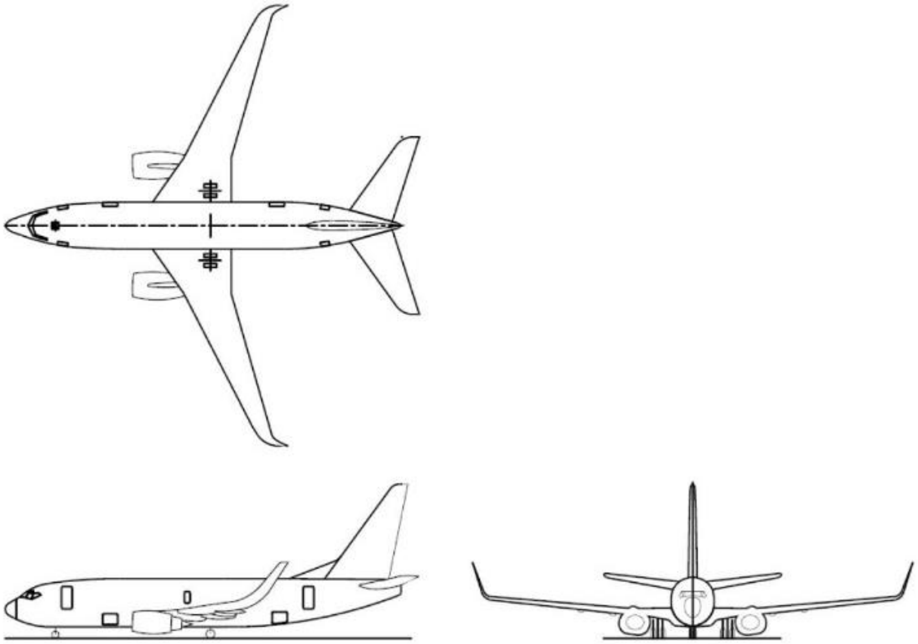


Figure 1 – 737 Three View

FIGURE COURTESY OF BOEING

5.0 Description of the Inlet and Fan Cowl Hardware

5.1 Inlet

The inlet is an aerodynamic fairing that guides air into and around the engine. It is attached to the front of the engine fan case (**FIGURE 2**).

Figure 2 – Engine Inlet Right Side View

FIGURE 3 provides a cross-section of the inlet that is representative of the inlet configuration and materials used at the time that the airplane was certificated and is typical of the fleet in-service configuration. The inlet consists of two concentric cylindrical structures, an inner and outer barrel, joined together by forward and aft bulkheads. The lip skin, which is at the front of the inlet, provides for both an aerodynamic flow surface at the front of the nacelle and a cavity for the passage of thermal anti-ice air.

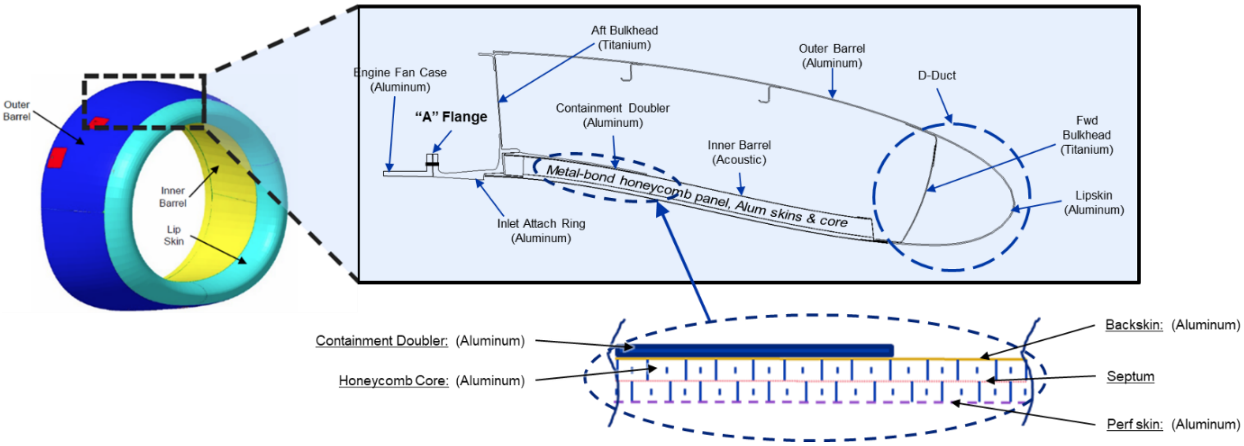


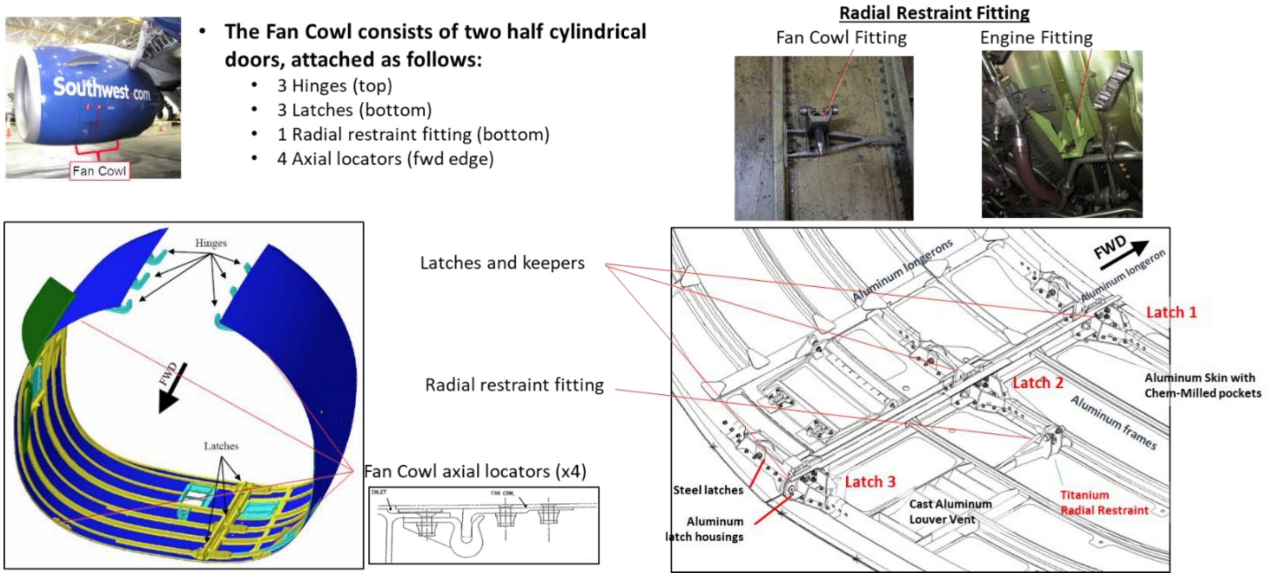
Figure 3 – Engine Inlet Hardware Overview

FIGURE COURTESY OF BOEING

5.2 Fan Cowl

The fan cowl is an aerodynamic fairing covering the engine fan case and fan frame. It consists of two half cylindrical doors attached by three hinges located at the top, three latches connecting the two halves at the bottom and one radial restraint fitting and pin at the bottom. At the forward edge of the fan cowls are axial locators that mate with interfacing fittings on the inlet aft bulkhead assembly. The aft edge of the fan cowl is supported by contact with the thrust reverser (**FIGURE 4**).

The 737-600/700/800/900 (also referred to as the 737 next generation, or 737NG) was a derivative of the original 737 airplane (737-100) that was certificated in the late 1960s with JT8D low bypass ratio engines installed under the airplane wing. As Boeing developed the 737-300 in the early 1980s it introduced the CFM56-3 engine; which was a high bypass ratio engine. This larger diameter engine made ground clearance an issue, which was solved by moving the engine ahead of the wing and moving engine accessories to the side of the engine rather than positioning them at the bottom. Consequently, the nacelle took on a non-round appearance with a flat bottom. The 737NG was developed in the 1990s and included the larger diameter CFM56-7B engine, which again required the non-round nacelle with a flat bottom.



- **The Fan Cowl consists of two half cylindrical doors, attached as follows:**
  - 3 Hinges (top)
  - 3 Latches (bottom)
  - 1 Radial restraint fitting (bottom)
  - 4 Axial locators (fwd edge)

Figure 4 – Fan Cowl Hardware Overview

FIGURE COURTESY OF BOEING

6.0 Accident Sequence of Events Overview

During climb through FL320, the left engine experienced a single fan blade separation at the blade root (**FIGURE 5 LEFT** – yellow arrow point to missing blade location). The separated fan blade impacted the engine fan case at about the 6:00 o'clock position and fractured into multiple fragments with some fragments traveling forward out of the engine and into the inlet with sufficient mass and energy to substantially damage the structural integrity of the inlet. The energy resulting from the impact of the separated fan blade with the fan case resulted in local deformation of the fan case, which started a high-energy displacement wave that propagated circumferentially around the fan case and inlet interface, causing additional damage to the inlet structure. The displacement wave also imparted significant load into the fan cowl through the fan case radial restraint pin located near the bottom of the fan cowl. The inlet damage created by the fan blade fragments and the displacement wave were substantial enough that the inlet could not sustain the flight loads; thus, the inlet lip, forward and aft bulkheads, outer barrel and portions of the inner barrel all departed the airplane (**FIGURE 5 MIDDLE**). The containment shield, portions of the inner barrel attached to it and the attach ring remained attached to the airplane.

The initial fan blade impact and subsequent displacement wave initiated cracks in the fan cowl which rapidly propagated and resulted in the separation of the fan cowl halves. The inboard aft latch assembly separated from the inboard cowl, and subsequently portions of both fan cowl halves liberated from the nacelle. Examination of the left side of the fuselage just forward and below where the cabin window was missing revealed evidence of impact including fan cowl grease transfer and witness marks consistent in size and shape with the recovered inboard aft latch assembly (**FIGURE 5 RIGHT**). The lack of any acrylic windowpane fragments and window frame material found inside the airplane was consistent with a rapid departure of the cabin window and subsequent depressurization of the cabin (See **ATTACHMENT 1** for description of the cabin pressurization system).

Figure 5 – Accident Sequence Overview

MIDDLE PHOTO COURTESY OF PASSENGER

7.0 Inlet and Fan Cowl Separation Sequence

The fan case, the inlet, and fan cowl were extensively examined and documented by UTAS (currently Collins), Boeing, CFM, and the NTSB for signs of fan blade impact marks, fan blade fragment orientation and trajectory scuff marks, fan blade material transfer, and fracture surface features such as overload, fatigue, bending, shear, material transfer, and yielding. Based on the physical evidence collected from the examinations conducted on the fan case, inlet, fan cowls, along with the recovered fan blade fragments, the following observations were made.

1) As the fan blade impacted the engine fan case, it fractured into several smaller fragments, some of which moved aft in the direction of the predominant air-stream motion, and some traveled forward into the inlet. Impact marks on the fan case and inlet along with the recovered fragments indicated that portions of the fan blade tip and mid panel exited the fan case and entered the inlet along a forward helical path (**FIGURE 6**). Although not recovered, the quantity and mass of the fan blade fragments that exited forward of the fan case in this accident are believed to be comparable to or greater than those observed during CFM56-7B engine fan blade out (FBO) rig tests and the engine FBO containment certification test (See the Powerplant Group Chairman's Factual Report in the docket for this accident for engine FBO testing and certification details). Due to the numerous impact and scuff marks in both the fan case and inlet and the unknown nature of the exact fragment orientation at the time the marks were created, there were various interpretations of how the marks were created. Therefore, the exact trajectory path of the departing blade tip and the mid span fragments could not be conclusively determined. The likely trajectory of the fragments in the accident event were considered to range from 15° to 30°. During the engine and nacelle development process, a fan blade tip exit trajectory of 15° was used. Midspan fragments were not defined during engine FBO certification.

Figure 6 – Possible Fan Blade Fragment Forward Helical Trajectory from Fan Case to Inlet

2) The inlet inner barrel forward of the containment shield exhibited through penetrations that were consistent with being created by the fan blade fragments; this type of damage was not observed during the engine FBO containment certification test. The engine FBO containment certification test reported that no fan blade fragments from the originally released fan blade penetrated the inner barrel and the inlet remained intact and securely attached to the fan case.

3) The displacement of the engine fan case transmitted deformations into the inlet A-flange and aft bulkhead, resulting in all the aft bulkhead-to-attach ring rivets to fail in shear, and the outer barrel skin to become cantilevered from the inlet forward bulkhead (See **FIGURES 21** and **22**).

4) Modeling indicated that the amount of damage to the inlet structure from a combination of fan blade fragment penetration and the displacement wave was sufficient to reduce the flight load carrying capability of the inlet. Portions of the inlet most likely departed no more than 0.5 second after the fan blade release.

5) During the engine FBO containment certification test, fan cowls were not installed to permit visibility for observation of the fan case and fan case-installed components during the engine test. Thus, the fan cowls were not physically tested but were certified by analysis. The fan cowls were designed to withstand the loads from the initial fan blade release and any subsequent damage and remain attached so that a safe landing could be accomplished. Modeling of the accident flight failure sequence as part of this investigation revealed the sensitivity of the fan cowl structure in relation to the fan case impact point. Specifically, the Boeing Progressive Failure Analysis Simulation (See SECTION 11), which used modern techniques unavailable at the time of design and certification, revealed that a fan blade impact with the fan case at or near the bottom (as in this event) where the fan cowl latches and the radial restraint fitting are located, presents the greatest challenge to the structural integrity and the greatest potential for the fan cowls to fracture and separate from the nacelle. During a previous CFM56-7B fan blade separation event (See NTSB docket DCA16FA217 for details), the fan blade fan case impact point was around the 3:00-4:00 o'clock position (aft looking forward), and the fan cowls remained attached. This was the only other CFM56-7B full span fan blade failure occurrence. Two other known partial span blade loss events did not result in inlet or fan cowl separation.

8.0 Inlet and Fan Cowl Structural Analysis

8.1 Definition and Description of Fan Blade Out

The release of an entire engine fan blade airfoil during flight is often referred to as a "Fan Blade Out" (FBO) event. During such an event, the airplane structure is subject to a series of loads. The description below summarizes the current knowledge and understanding of those loads. Industry knowledge and understanding of an FBO event has progressed since the Boeing 737NG airplane and CFM56-7B engine were developed and certified in the mid-1990s as new technologies and analytical methods have been developed that enhance the ability to both understand and model such an event. **FIGURE 7** depicts various phases and loads during the FBO event phases listed below:

1) Impact Phase - The impact phase occurs over the first 2 or 3 fan revolutions following fan blade release, approximately the first 0.02 second of the event. Within this time two independent conditions occur:

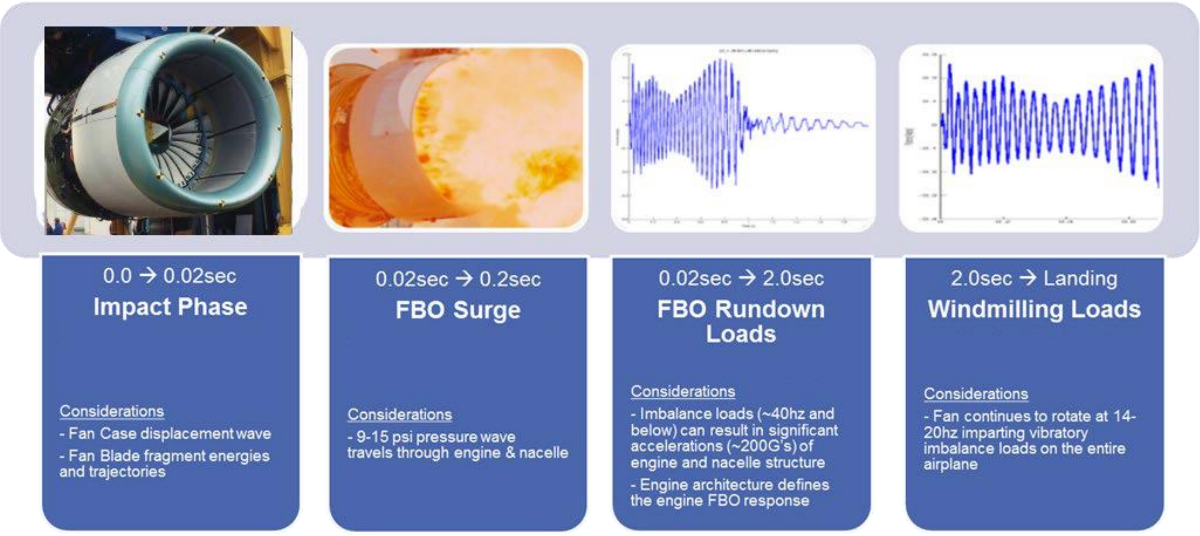
a. Displacement Wave - As an engine fan blade impacts the engine fan case, the fan case deforms locally over a short period of time. The deformation, referred to as the displacement wave, then travels both circumferentially and fore/aft. The high energy associated with the displacement wave peaks within the first few fan revolutions after the fan blade release, and the displacement wave continues until the impact energy dissipates. When the displacement wave reaches the attached airplane structure (e.g. the inlet attach flange), the local displacements can generate large loads and deformations in the structure that may result in local damage.

b. Fan Blade Fragments - As the engine fan blade impacts the fan case, it breaks into several fragments. In some cases, some of these fragments may travel forward into the inlet and cause local damage.

2) Engine Surge Phase - Following the fan blade release, the engine fan rotor is significantly imbalanced. The imbalanced fan rotor causes the fan blades to rub heavily on the fan case, resulting in rapid deceleration of the entire low pressure compressor system. This rapid deceleration along with the air flow disruption from the missing fan blade causes air flow voids in the forward section of the core. These voids cause the high-pressure flow in the aft section of the engine core to reverse direction and move forward to the lower pressure regions. This high-pressure air flow continues forward and exits the front of the engine. This is referred to as an engine surge, which typically occurs within approximately 0.2 second after the fan blade release. The surge pressure load affects both the fan case and the inlet.

3) Run Down Phase - After the release of the engine fan blade, the fan rotor decelerates. This deceleration or "run down" typically takes approximately 2 seconds. During this time the airplane experiences significant vibratory loading from the fan rotor deceleration, fan blade rubbing forces, and the imbalanced engine.

4) Windmill Phase - Windmill is the free spinning phase following engine shut down. After the engine has shut down, the fan is still subject to ram air pressure in flight. This pressure causes the imbalanced fan to continue to rotate through the remainder of the flight. The continued unpowered rotation of the imbalanced fan rotor generates a low level of sustained vibratory loading.



0.0 → 0.02sec
Impact Phase

Considerations
- Fan Case displacement wave
- Fan Blade fragment energies and trajectories

0.02sec → 0.2sec
FBO Surge

Considerations
- 9-15 psi pressure wave travels through engine & nacelle

0.02sec → 2.0sec
FBO Rundown Loads

Considerations
- Imbalance loads (~40hz and below) can result in significant accelerations (~200G's) of engine and nacelle structure
- Engine architecture defines the engine FBO response

2.0sec → Landing
Windmilling Loads

Considerations
- Fan continues to rotate at 14-20hz imparting vibratory imbalance loads on the entire airplane

Figure 7 – FBO Event Phases

FIGURE COURTESY OF BOEING

8.2 FBO Containment Design Development at the Time of Design and Certification

The CFM56-7B engine received certification from the Federal Aviation Administration (FAA) in December 1996 and the 737-700 received its FAA certification on November 7, 1997. The following subsections provide a high-level overview of the certification activities and data derived from them that were used to help validate the accident sequence of events. It is not intended to be a comprehensive summary of certification or the analyses and data that were developed as part of the certification process. In Section 6.0 of the Powerplant Group Chairman's Factual Report for this accident, titled Containment Requirements, there are detailed descriptions of how the CFM56-7B and Boeing 737-700 were designed, analyzed, tested, and certificated regarding engine FBO containment.

8.2.1 Inlet and Fan Cowl Design

The Boeing 737-700 inlet and fan cowl were developed between 1994 and 1997 with a design configuration and materials similar to previously certified Boeing models. Rohr (currently Collins) was responsible for the design and analysis of the inlet and fan cowl. Early fan blade development testing conducted by CFM for the CFM56-7B engine revealed that a high energy fan blade fragment could travel forward into the inlet during FBO, so the design for the inlet incorporated a metallic doubler (containment shield) to contain this fragment (See **FIGURE 3**).

8.2.2 Inlet and Fan Cowl FBO Structural Analysis

FBO analysis of the Boeing 737-700 inlet and fan cowl during the design and certification used the state-of-the-art methods available at that time. These methods involved generating a dynamic structural model (finite element model (FEM)) of the under-wing propulsion system, correlating the model to data measured during the engine FBO containment test, and using the model to generate structural loads that account for different fan blade release angles as well as the dynamic differences between the engine test stand and an on-wing engine. The FEM captured the global dynamic effects of the fan blade impact but did not fully account for the local loads resulting from the displacement wave. The inlet damage caused by the displacement wave was determined during certification by engine FBO test observation. The damaged inlet was assessed to assure structural capability for the remainder of the flight. The ability to analytically predict the local effects of the displacement wave during an FBO were not available until the development of a different aircraft model/engine combination in early 2000's.

During the design and certification process of the CFM56-7B and the Boeing 737-700 airplane, an engine "forcing function" was applied to the dynamic model which accounted for fan blade impact, torque, thrust decay, fan blade tip rub, and imbalance. Using the structural analysis methods available at the time that the airplane and engine were certified, the airplane was designed with the expectation that the inlet and fan cowl would remain attached during the FBO event and subsequent flight to enable a safe landing. A windmill analysis was performed on the inlet which accounted for the effects of reduced inlet stiffness due to the local damage sustained earlier in the event from the fan blade fragment and displacement wave induced damage, as observed in the CFM56-7B engine FBO testing. At the time of certification, the state-of-the-art FBO analysis methods did not fully account for the inlet local loading from the displacement wave.

8.2.3 Inlet and Fan Cowl FBO Structural Testing

A production-representative inlet was installed and tested during the engine FBO containment certification test conducted in April 1996. Fan cowls were not installed for the test since high speed film/video recording of the fan containment case was required and installation of the fan cowls would have obstructed the view of the fan case and the fan case mounted accessories.

The results of the engine FBO containment certification test regarding the inlet revealed that, after the initial FBO impact and subsequent engine surge: 1) the inlet remained attached, 2) the containment doubler worked as intended, (i.e. no penetrations), and 3) the inlet aft bulkhead inner attachment failed over 360° circumferentially.

Analysis of the damage from the displacement wave concluded that the inlet's ability to stay attached to the engine was not affected and this damage was considered as part of the windmilling analysis. As the FBO rig and engine FBO certifications tests were conducted under static conditions, aerodynamic effects could not be directly measured.

8.3 Inlet and Fan Cowl Structural Analysis Method Used for the Accident Event

Since an in-service engine does not have the high-fidelity data recording that is installed on a test rig, developing the detailed accident sequence of events required advanced modeling using current state-of-the-art methodologies. These methods included the ability to assess the effects of the displacement wave, the progressive failure of both the fan cowl and the inlet, and the interdependencies between the inlet and fan cowl failure sequences. As previously mentioned, these methods had not been developed at the time that the Boeing 737-700 airplane and CFM56-7B engine were certificated.

8.3.1 Inlet Structural Analysis Method Used for the Accident Event

Examination of the accident fan rotor, fan case, and inlet hardware indicated that impact damage from the fan blade fragments and displacement wave could have contributed to the inlet failure. As a result, a progressive failure analysis of the inlet was conducted using current state-of-the-art explicit finite element dynamic modeling methods (LS-DYNA). This analysis applied the loads from the fan blade impact displacement wave, damage from fan blade fragments, engine surge, and engine run down imbalance loads.

8.3.2 Fan Cowl Structural Analysis Method Used for the Accident Event

Examination of the accident fan cowl hardware indicated that displacement wave effects could have contributed to the fan cowl failure. As a result, progressive failure analysis of the fan cowl was conducted using current state-of-the-art explicit finite element dynamic modeling methods. This analysis applied the loads from the fan blade impact displacement wave, external aerodynamic pressures on the fan cowl, and internal pressures in the fan compartment. It also considered the effects of the inlet aft bulkhead damage from the displacement wave that occurred early in the event because the inlet aft bulkhead and the fan cowl leading edge contact each other and provide a load path.

9.0 Accident Inlet and Fan Cowl Damage Documentation

9.1 Inlet Damage Documentation

Visual observations and metallurgical analysis of the damage to the inlet was used to determine the contribution of damage due to the forward-traveling fan blade fragments. The damage caused by the fan blade fragments encompassed a range described in number of degrees around the circumference of the inlet.

The main observations of the accident inlet that led to the bracketing of the inlet damage ranges were the following:

1) Gouges and indentations in the inner barrel flow side attach ring, perforate skin, and honeycomb core
2) Fractures and deformations in the inner barrel containment doubler
3) Punctures in the outer barrel
4) Traces of titanium on inlet components
5) Inner barrel back skin fracture surface topography.

FIGURE 8 summarizes those observations used in defining the plausible range of inlet damage due to fan blade fragments; details of the accident hardware observations are provided in the **REPORT FROM PARTIES – COLLINS, AND REPORT FROM PARTIES – CFM**. A plausible level of damage attributed to fan blade fragments used for the Boeing Progressive Failure Analysis included 150° of damage to the inner barrel perforate skin as well as 70° of damage through the inner barrel back skin forward of the containment doubler.

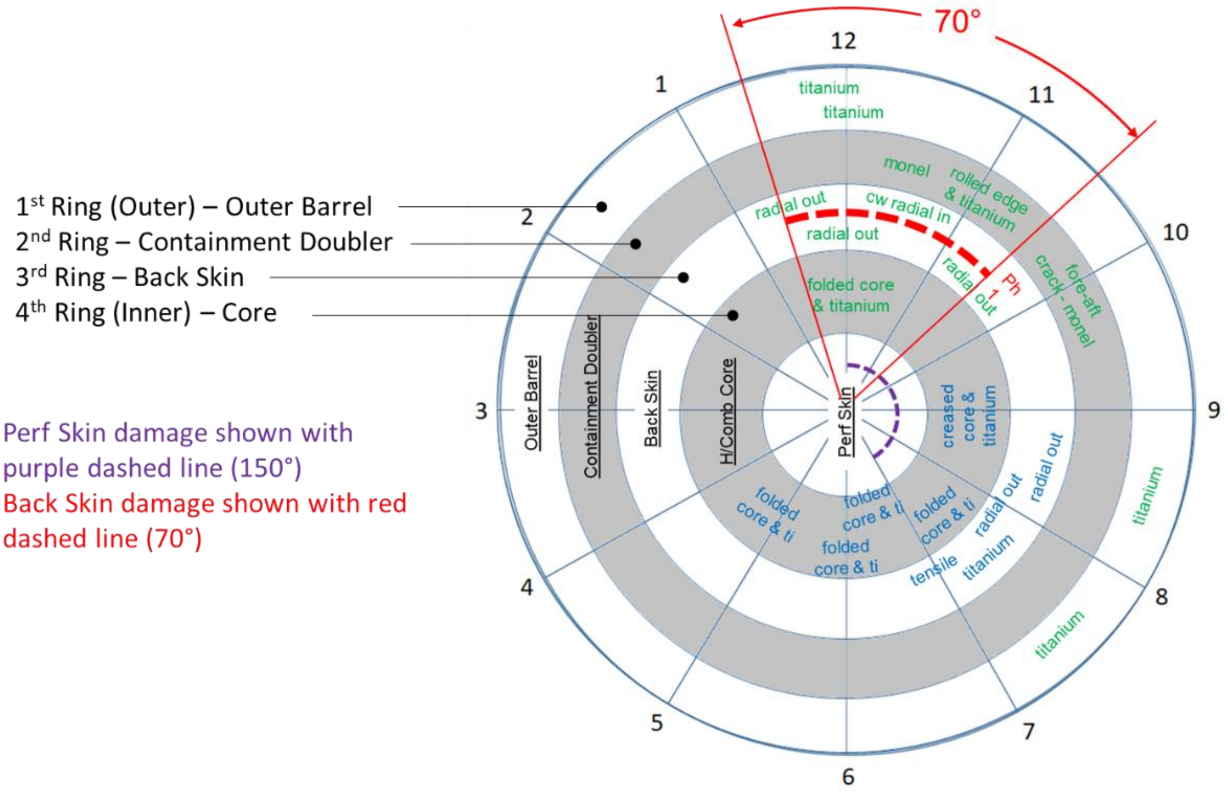
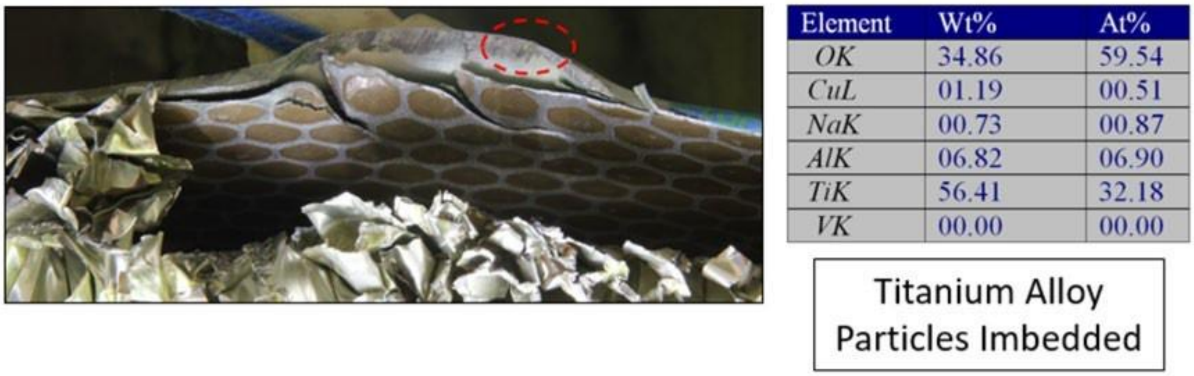


Figure 8 – Inlet Damage Due to Fan Blade Fragment Assessment

FIGURE COURTESY OF BOEING

Two main findings supporting inlet damage due to the fan blade fragments are shown in **FIGURES 9** and **10**.

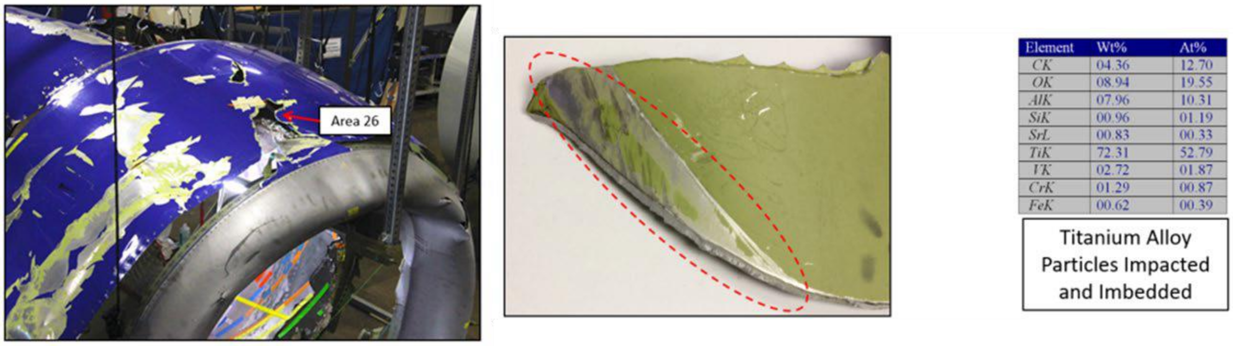


Element	Wt%	At%
OK	34.86	59.54
CuL	01.19	00.51
NaK	00.73	00.87
AlK	06.82	06.90
TiK	56.41	32.18
VK	00.00	00.00

Titanium Alloy Particles Imbedded

Figure 9 – Inlet Containment Doubler Forward Edge with Evidence of Titanium Transfer

FIGURE COURTESY OF COLLINS



Element	Wt%	At%
CK	04.36	12.70
OK	08.94	19.55
AlK	07.96	10.31
SiK	00.96	01.19
SrL	00.83	00.33
TiK	72.31	52.79
VK	02.72	01.87
CrK	01.29	00.87
FeK	00.62	00.39

Titanium Alloy Particles Impacted and Imbedded

Figure 10 – Inlet Outer Barrel Penetration with Evidence of Titanium Transfer

FIGURE COURTESY OF COLLINS

A comparison of the accident inlet damage created by the fan blade fragments with the damage observed and documented on the production-representative inlets used during the FBO rig test and the CFM56-7B engine FBO containment certification test indicated that, for the accident event, fan blade fragments entered the inlet along a helical path with fragment quantity, total mass, and trajectory angles similar, but in excess of those defined at the time of the engine FBO containment certification test. The resultant inlet damage was significantly greater than the damage level observed and analyzed at the time of inlet certification.

Visual observation of the recovered inlet hardware indicated that all the fasteners that connect the aft bulkhead to the attach ring fitting failed, consistent with damage expected from the displacement wave.

9.2 Fan Cowl Damage Documentation

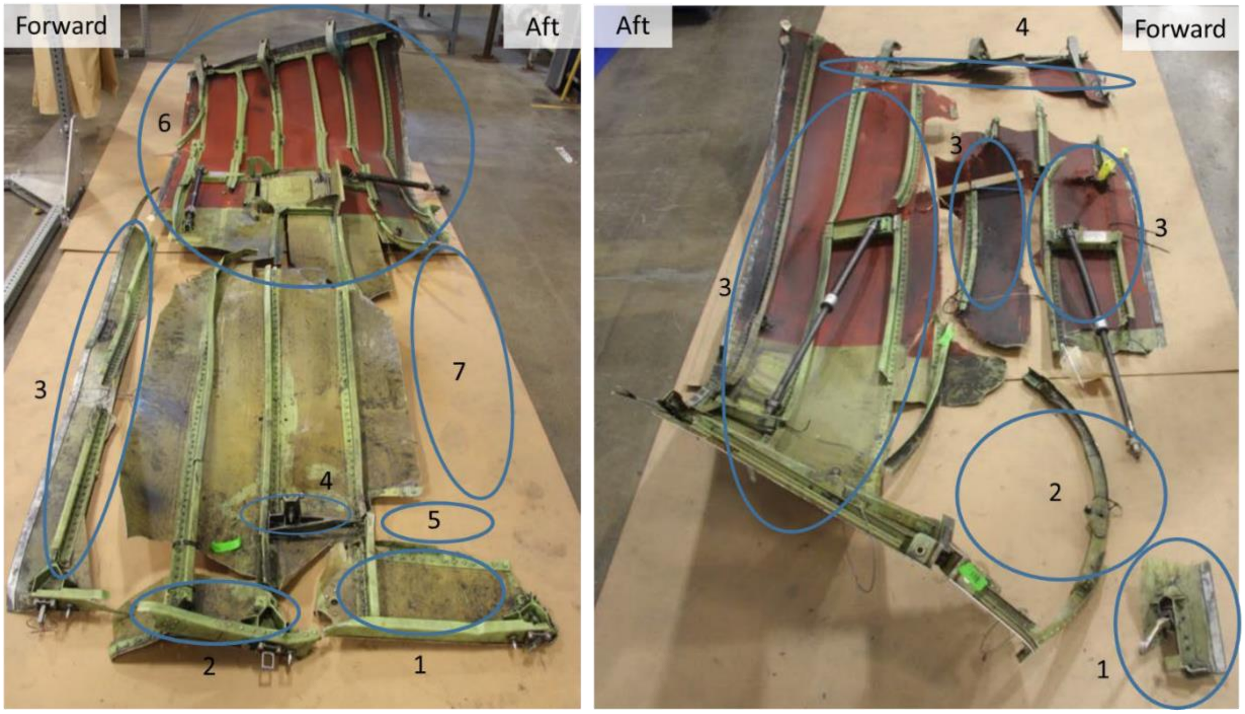
The following were observations from the departed fan cowl pieces that were recovered and those pieces that still remained attached to the airplane. The main observations are listed below for each of the two fan cowl halves, and the numbers associated with each observation are labeled in **FIGURE 11**.

Inboard Fan Cowl (Right Side)

1) Small skin panel with latch 3/aft keeper fitting separated – appears to have hit fuselage
2) Small skin panel with latch 2/mid keeper fitting separated
3) Long narrow skin panel with latch 1/forward keeper fitting separated
4) Radial restraint bracket shows significant damage at attachments to cowl frames
5) Cast starter vent mostly missing, but remaining attach flanges show fast fracture failures
6) Upper cowl panel remained attached to airplane via three hinges
7) Aft lower cowl panel was not recovered

Outboard Fan Cowl (Left Side)

1) Small skin panel with latch 1 and fitting separated from cowl
2) Forward lower cowl panel was not recovered
3) Multiple cowl panel sections separated
4) Small remnants of fan cowl panel attached to hinges remained attached to airplane



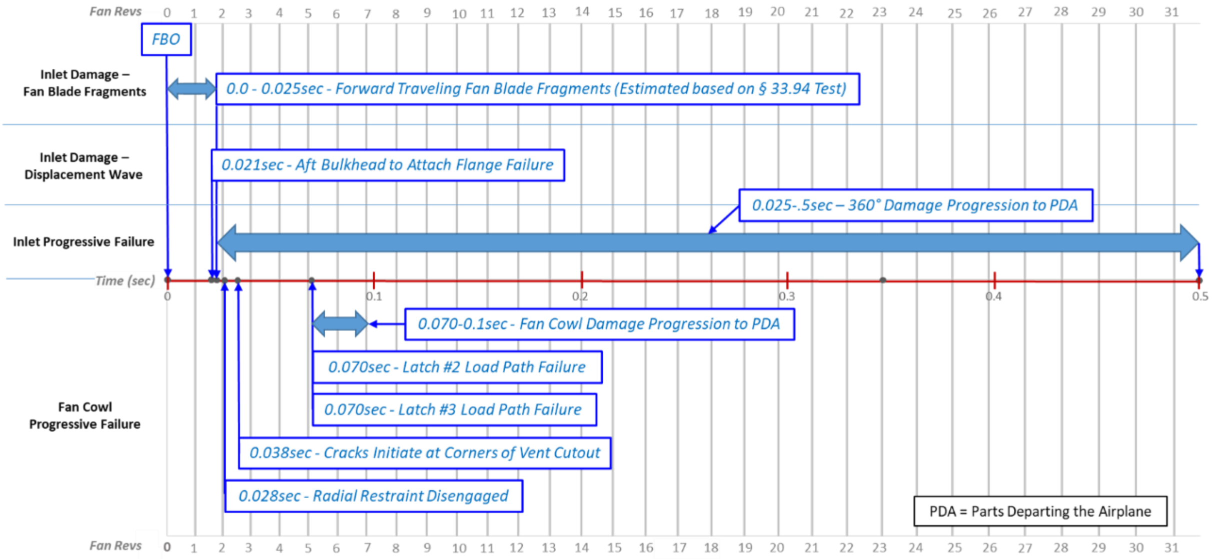
Right Side (Inboard) Fan Cowl Left Side (Outboard) Fan Cowl

Figure 11 – Accident Fan Cowl Damage Locations and Observations

FIGURE COURTESY OF BOEING/COLLINS

10.0 Accident Failure Sequence Modelling

After the accident, Boeing and CFM together developed analytic models to predict the behaviour of the engine and airplane structure during a 737-700/CFM56-7B FBO event and correlated those models with the accident inlet and fan cowl hardware damage documentation, the CFM56-7B engine FBO containment certification test results, and flight data recorder (FDR) and cockpit voice recorder (CVR) data. The models were determined to be sufficiently accurate to determine the extent and timing of the damage sustained by the accident inlet. **FIGURE 12** provides a composite timeline based on the available data.



Fan cowl PDA timeline (0.070-0.1 sec) is within NTSB PDA timeline correlated with airplane depressurization timeline (0.0-3.0 sec).
Assuming the least amount Fragment Damage, and based on Fan Cowl PDA timeline, Inlet PDA timeline is 0.070-0.5 sec.

Figure 12 – Fan Cowl and Inlet Failure Sequence Event Timeline

FIGURE COURTESY OF BOEING

10.1 Inlet Failure Sequence

The predicted results of the accident event analysis were consistent with the inlet experiencing initial structural damage during the displacement wave and fan blade fragmentation, which then propagated during the engine run down, resulting in large portions of the inlet departing the aircraft. The analysis predicted, and the accident hardware examination confirmed, that the aft bulkhead-to-attach ring joint failed 360° circumferentially due to fastener shear caused by the displacement wave.

Additionally, the displacement wave resulted in localized failures of the inner barrel-to-forward bulkhead interface at the 3:00 o'clock and 9:00 o'clock locations, consistent with the axial splices of the inner barrel. The inner barrel, which was initially damaged by fan blade fragment impact, sustained additional damage from the imbalance loading during run down.

After the initial damage, the critical remaining inlet structural element was the 0.020 inch thick aluminum inner barrel back skin just forward of the containment doubler. During the run down, the remaining inner barrel, with the exception of the reinforced 3:00 and 9:00 o'clock splices, experienced a 360° circumferential failure allowing separation from the rest of the inner barrel.

Figure 13 and **Table 2** summarize an inlet damage scenario that is consistent with the structural analysis[1], including approximate time from fan blade release, until the parts of the inlet departed the airplane. The numbers referenced in **Figure 13** correspond to the numbers referenced in **Table 2**.

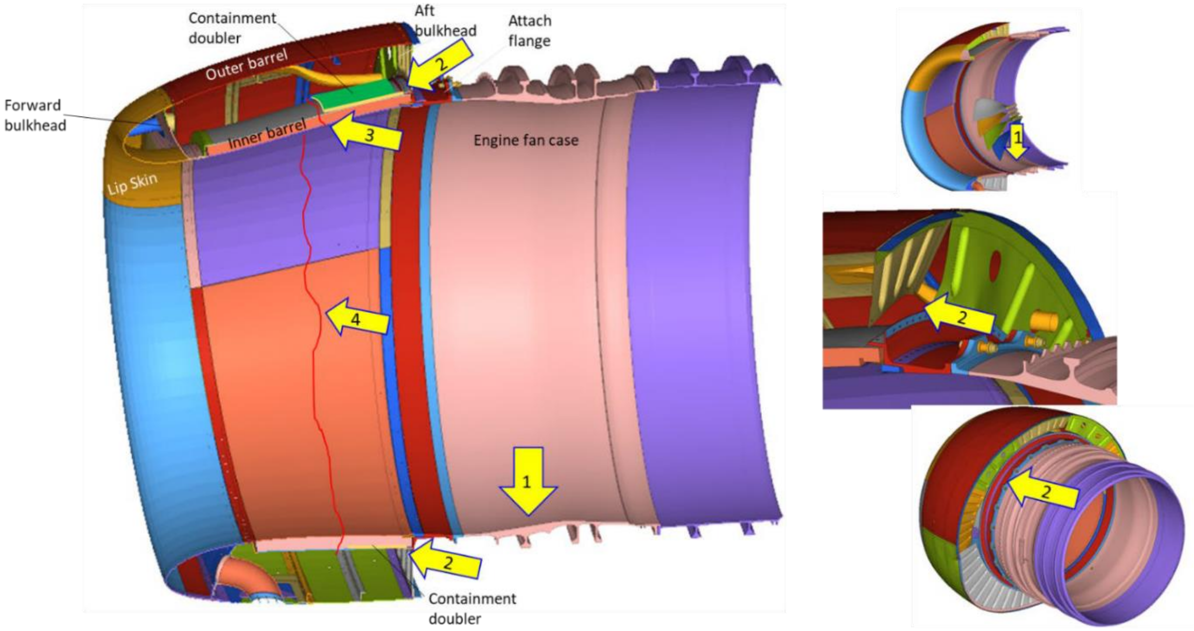


Figure 13 – Predicted Inlet Failure Sequence

FIGURE COURTESY OF BOEING

Sequence	Inlet Departure Scenario Consistent with Analysis	Time after blade release (second)
1	Fan blade impacts fan case	0.005
2	360° failure of aft bulkhead joint (due to displacement wave)	0.021
3	70° through crack in inner barrel (due to blade fragments)	0.025
4	360° through crack in inner barrel (due to run down loads)	<0.500

Table 2 – Predicted Inlet Failure Timeline

10.2 Fan Cowl Failure Sequence

The predicted results of the accident event analysis were consistent with the observed damage in the fan cowl near the radial restraint fitting near the bottom of the fan cowls. This damage was caused by the fan case displacement wave transmitting load through the radial restraint fitting. This load caused cracks to form in the fan cowl skin and frames near the radial restraint fitting. This damage then propagated forward and aft, severing all three latch assembly load paths,

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[1] The accident event structural analysis included variables such as different inlet backskin aluminium alloy tempers (the alloy temper for the event inlet - Al2024 T81 - was different than the alloy temper defined at certification - Al2024 T62) and the presence of the fan cowl (the analysis was run for both a fan cowl present and a fan cowl missing). The predicted results from the accident event structural analysis demonstrated that these variables did not materially influence the inlet failure sequence.

culminating in large portions of the lower part of each fan cowl half separating and departing the airplane. The observed fan cowl damage was consistent with the predicted results. **FIGURE 14** and **TABLE 3** summarize the failure sequence in this scenario. The numbers referenced in **FIGURE 14** correspond to the numbers referenced in **TABLE 3**.

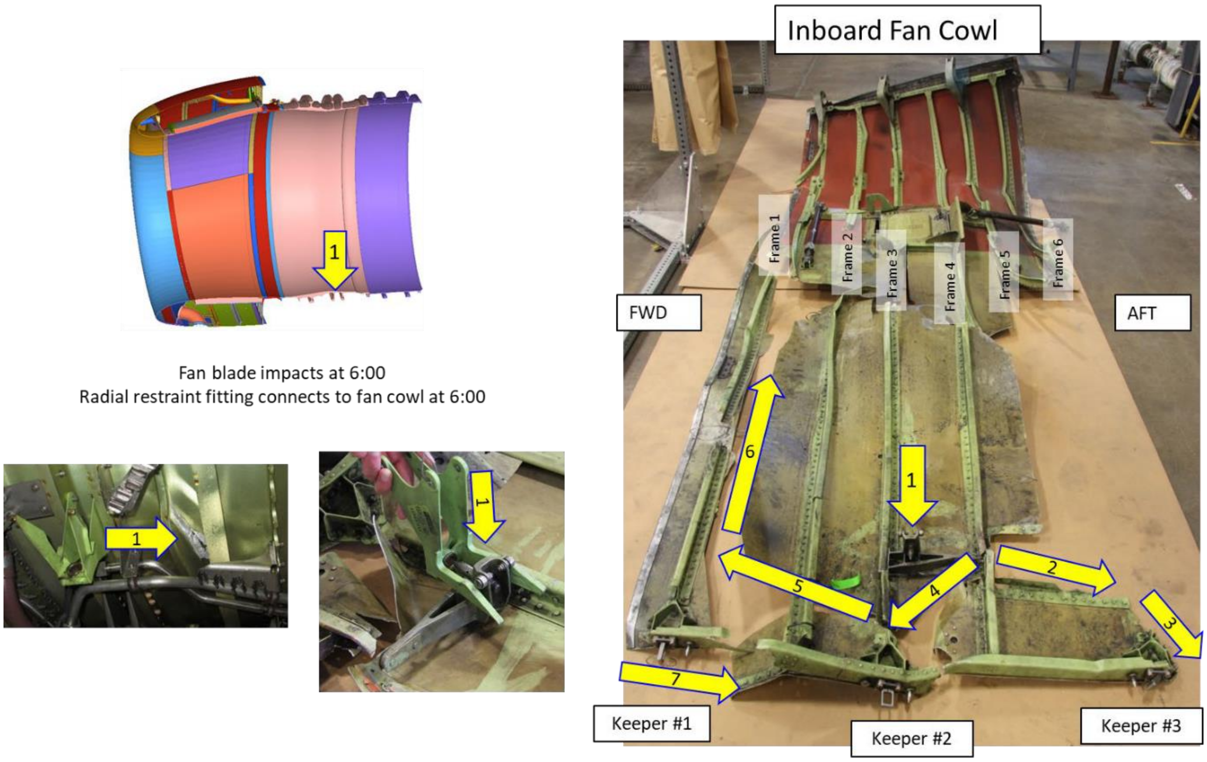

Figure 14 – Predicted Fan Cowl Failure Sequence
FIGURE COURTESY OF BOEING

Sequence	Fan Cowl Departure Scenario Consistent with Analysis	Time after blade release (second)
1	Radial restraint fitting transmits load into cowl and then disengages. Multiple cracks in cast starter vent fitting initiate	0.028
2	Cracks initiate at corners of vent	0.038
3	Cracks run in skin to aft edge of fan cowl	0.062
4	Latch 3 load fails skin between frames 4 and 3	0.070
5	Skin crack runs from under frames 2 to 1	0.070
6	Crack turns and runs in chemical-mill step aft of frame 1	>0.070
7	Side load on latch 1 fails latch fitting	>0.070

Table 3 – Predicted Fan Cowl Failure Timeline

10.3 Passenger Window Departure Timeline

The NTSB performed a failure sequence timeline to determine the timeframe when a portion of the fan cowl could have departed the airplane and struck the fuselage, followed by the window departure and cabin depressurization.

For the accident flight, Boeing calculated that the cabin pressure would have been 5,773 feet as the airplane was climbing through an altitude of 32,600 feet.[2] Among the information that the active cabin pressure controller logged was a 10,000 feet cabin altitude status message at 32,610 feet and a 13,500 feet cabin altitude status message at 32,554 feet, indicating that the cabin altitude was increasing as the airplane's altitude was decreasing.

The cabin altitude at the time of the 10,000 feet cabin altitude status message was recorded by the cabin pressure controller at 10,661 feet. The FDR data showed that the cabin altitude warning parameter, which was sampled once per second, transitioned from NO WARNING to WARNING between 1103:37.6 and 1103:38.6 (**FIGURE 15**).[3] The CVR recorded the sound of the cabin altitude warning horn at 1103:39. Based on the CVR and FDR data for the cabin pressure warning and the FBO event, the fan cowl structure likely impacted the fuselage in the area of the passenger window between 0.00 and 3.17 seconds after the FBO (**FIGURE 16**), followed by the window departing the airplane creating an opening through which pressurized cabin air could escape and the cabin altitude warning to trigger; the maximum time from FBO to cabin altitude warning trigger was estimated to be 5.4 seconds.

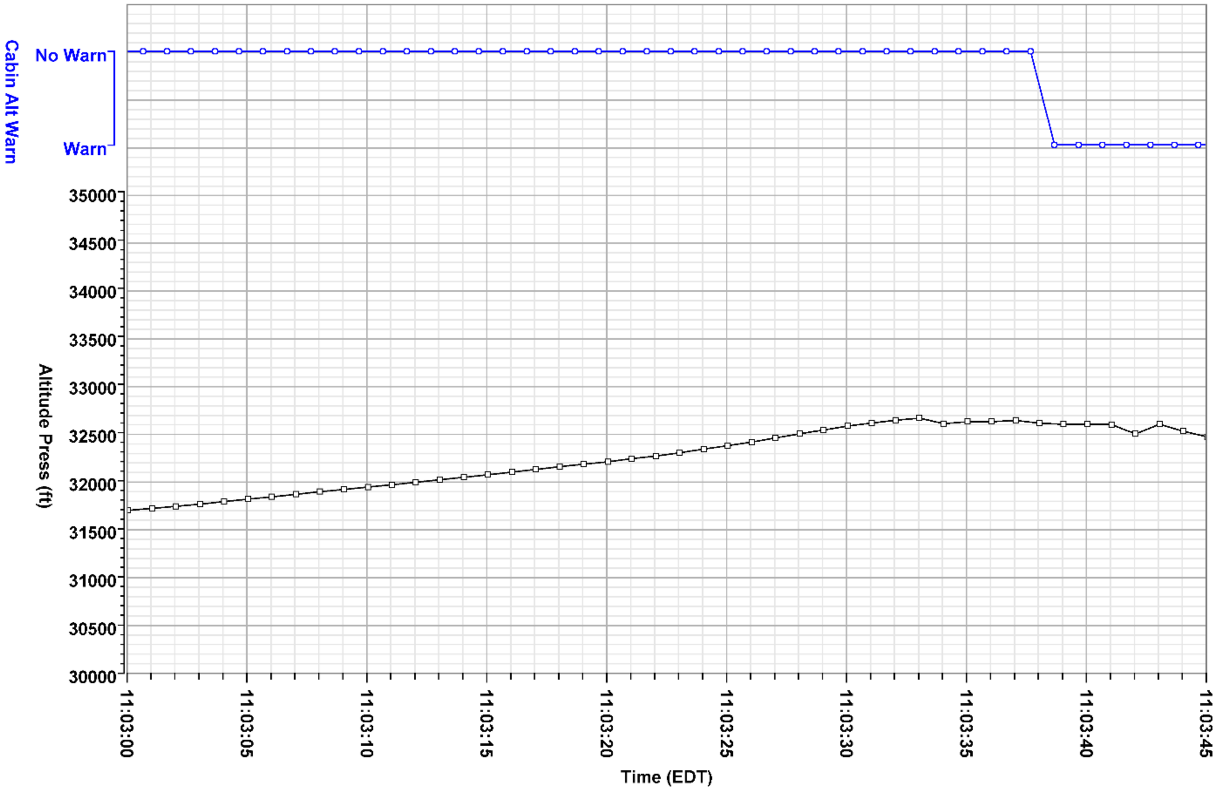

Figure 15 – FDR Data of Cabin Pressure Altitude Warning and Altitude Pressure Versus Time

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[2] Neither the FDR nor the cabin pressurization control system continuously records cabin altitude, so it was calculated assuming normal bleed and air conditioning system operation and nominal fuselage leakage.

[3] All times listed are local.

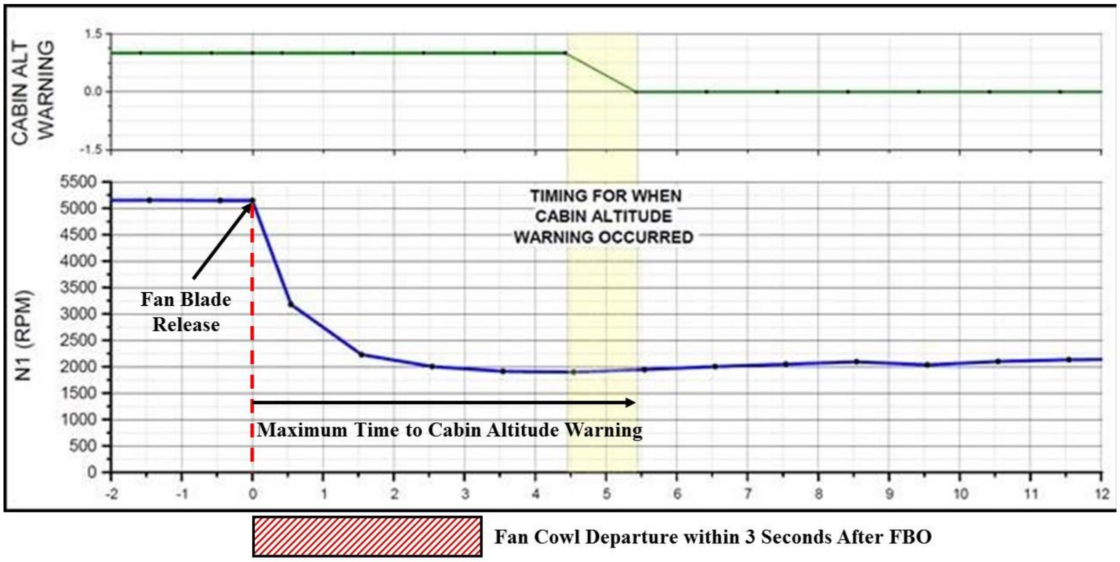


Figure 16 – Fan Cowl Departure and Cabin Depressurization Timing Based on FDR Data

The cabin altitude at the time of the 13,500 feet cabin altitude status message was recorded by the cabin pressure controller at 14,067 feet. The flight attendant and passenger oxygen masks were designed to deploy automatically when the cabin altitude reached 14,000 feet. The FDR does not record when oxygen masks are donned; however, the Master Caution alert is set when the cabin masks are deployed. During the accident, the Master Caution alert had previously activated due to the FBO event; thus, the timing of this alert could not be used to determine when the oxygen masks deployed.

11.0 Progressive Failure Analysis Simulation

11.1 Inlet Progressive Failure Analysis Method and Results

11.1.1 <u>Progressive Failure Analysis Methodology</u>

Boeing performed a progressive failure analysis of the inlet using the multi-step approach listed below. Boeing used advanced progressive failure analysis methods beyond their typical 20 to 30 milliseconds for FBO displacement wave and bird strike impact analysis. For the accident investigation, the progressive failure analysis was run for 2.0 seconds (2000 milliseconds) in order to capture all the details of the event. Based on current impact analysis methodology, the criteria were based on strain-to-failure criteria. Included in this analysis were the effects of cyclic loading. The strain-to-failure criteria was validated with independent fracture mechanics (crack propagation theory) hand calculations. The material properties used for the strain-to-failure were based on published tension ultimate stress values and stress versus strain curves for the actual constituent materials used in the manufacturing of the structure. The strain rate effects were negligible and not included in the analysis. Additionally, the models mesh density was small enough to account for local stress concentrations during the cyclic loading. The results of the analysis were correlated against recorded and observed test data, independent fracture mechanics theory, and physical documentation of the accident events. **FIGURE 17** provides an overview of the inlet analysis method and below are listed the steps used in the analysis.

1) Current state-of-the-art explicit finite element dynamic modeling methods, not developed at the time of original certification, were used to simulate the extent of inlet damage resulting from the fan blade impact displacement wave.

2) Examination of the inlet hardware was used to establish the level of inlet damage from forward traveling fan blade fragments. Note that this examination resulted in a wide range of possible damage levels. See Section 9.1 titled INLET DAMAGE DOCUMENTATION of this report for details.

3) Static strength analysis was conducted with engine surge pressures provided by CFM to determine if the inlet damage from Steps 1 and 2 would propagate during the surge phase.

4) A separate analysis model of the entire propulsion system was used to determine the inlet load and deflections experienced during the run down phase. This analysis method was similar to the one used during certification. The displacement wave damage from Step 1 and the fan blade fragment damage from Step 2 were mapped onto an inlet model compatible with the run down analysis method. An engine forcing function model for the event was developed in coordination with CFM and applied in this model.

5) Engine fan case deflections from Step 4 were then applied to an explicit finite element model of the inlet and fan case which had the damage from displacement wave (Step 1) and fan blade fragments (Step 2) represented. This model was used to simulate damage growth during the run down phase.

6) Inlet loads from Step 4 were also used in a fracture mechanics book form solution, as a form of validation. The fracture mechanics formulations predicted that the residual strength of the inner barrel would be overcome early in the engine run down phase, correlating with the results of the explicit FEM in Step 5.

All analyses run for the accident hardware and conditions were also run for the 1996 FBO engine containment certification test in an attempt to verify the analysis simulation methods by confirming results agreed with test-recorded data and observations.

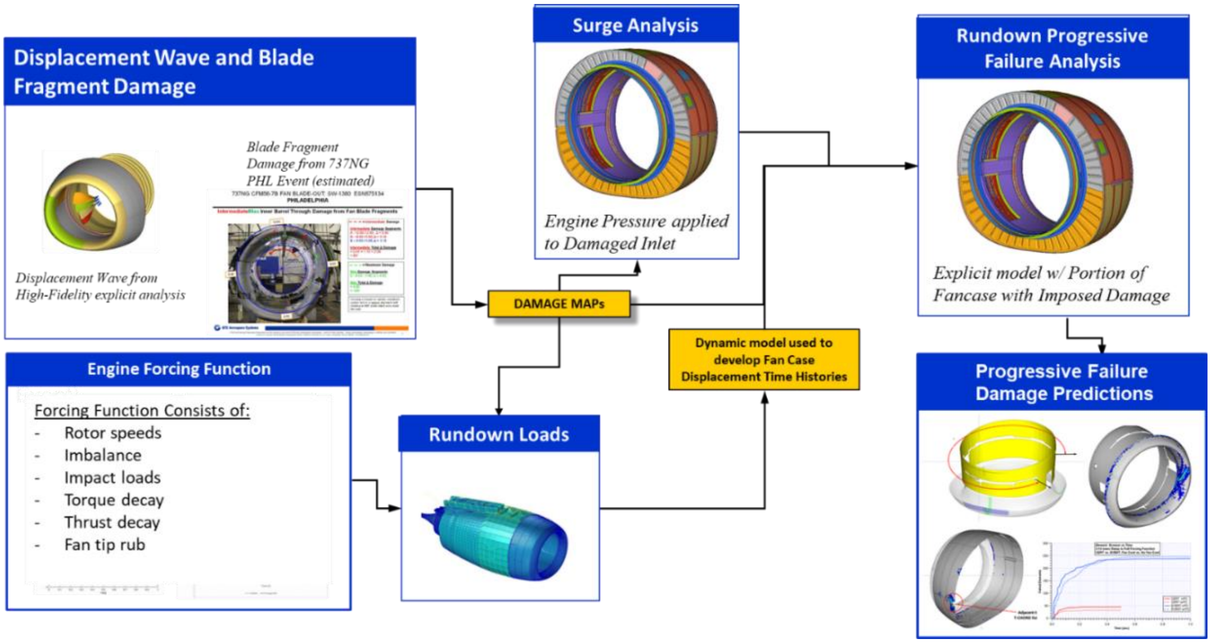


Figure 17 – FBO Inlet Analysis Methods

FIGURE COURTESY OF BOEING

11.1.2 Inlet Analysis Results from the Displacement Wave Only

The results of the structural analysis used to simulate the event fan blade release and displacement wave were consistent with the high speed video observations of structural damage occurring to the inlet within two fan revolutions (approximately 25 milliseconds) following the fan blade release during the 1996 engine FBO certification test. **FIGURES 18** and **19** illustrate the simulated results which were consistent with both the CFM56-7B engine FBO containment certification test results (**FIGURE 20**) and the accident inlet damage visual assessment (**FIGURES 21** and **22**); the aft bulkhead damage simulated results are as follows:

1) 360° circumferential failure of the aft bulkhead to the inlet attach ring due to fastener shear
2) Full failure of 5 of the 7 aft bulkhead circumferential splices
3) Two areas of about 40° inner lip skin-to-forward bulkhead joint failure

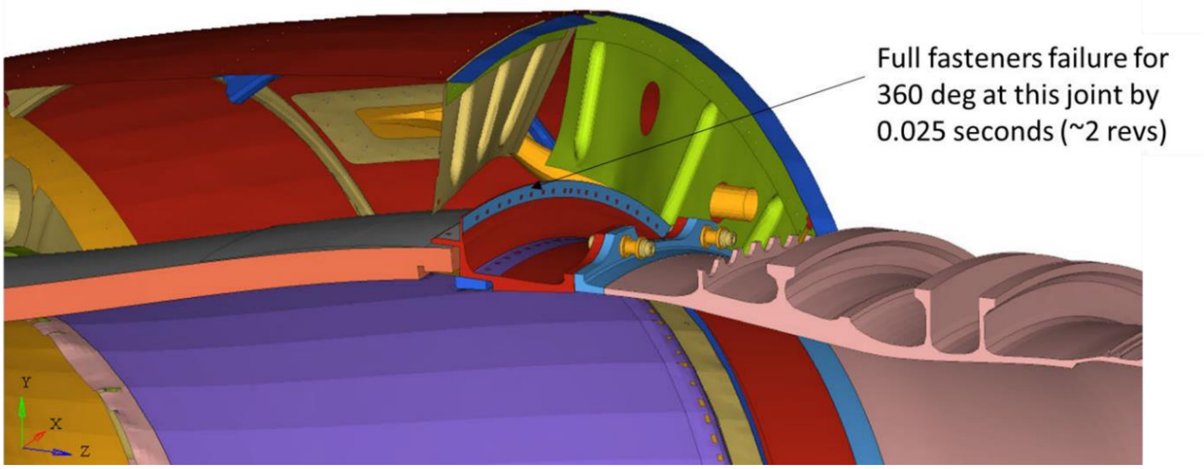


Figure 18 – Simulation Result of Aft Bulkhead-to-Attach Flange Joint Failure

FIGURE COURTESY OF BOEING

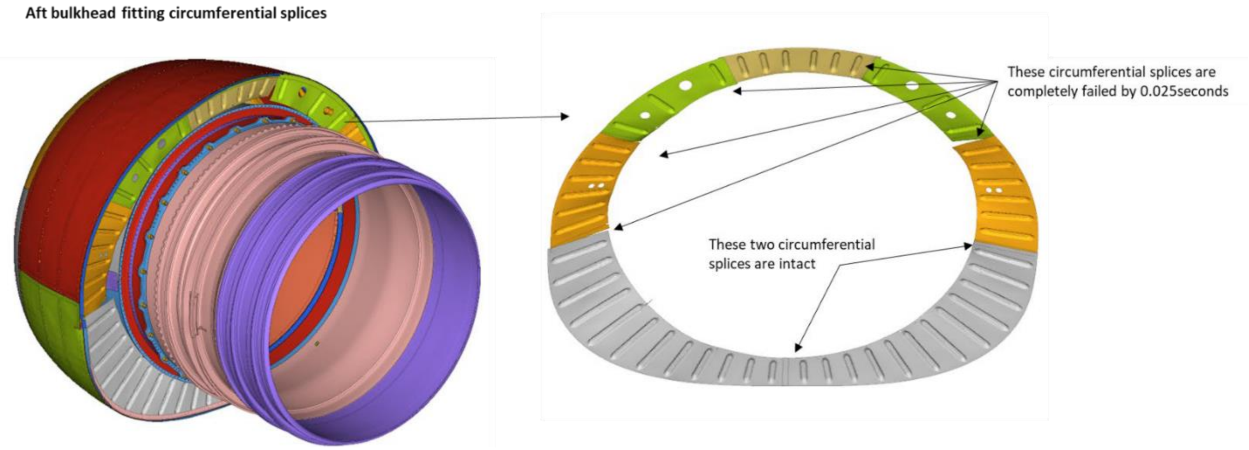


Figure 19 – Simulation Result of Aft Bulkhead Splice Joint Failure

FIGURE COURTESY OF BOEING

Review of the high speed camera footage from the CFM56-7B engine FBO containment certification test, which included a production-representative inlet installed but no fan cowls, showed that in the first 2-3 fan revolutions following the blade release (about 25-40 milliseconds) all the aft bulkhead-to-attach ring joint fasteners had failed, together with several aft bulkhead web panel-to-panel joint fasteners failures (**FIGURE 20**) which correlates well with the simulation results discussed above and depicted in **FIGURES 18** and **19**. For a more comprehensive discussion of the CFM56-7B engine FBO containment certification test results, refer to the NTSB Powerplant Group Chairman's Factual Report for this accident.

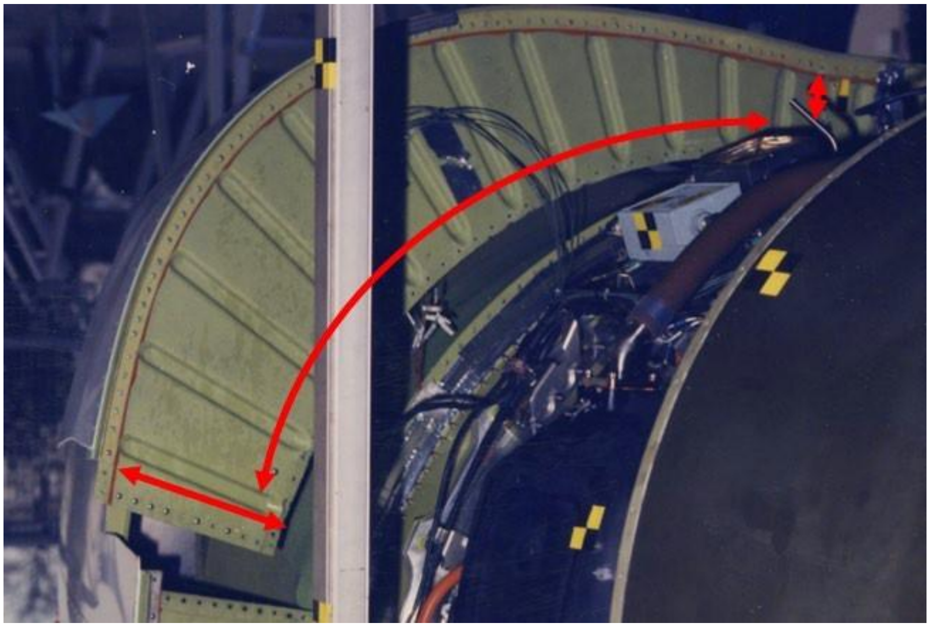


Figure 20 – Engine FBO Containment Certification Test – Inlet Aft Bulkhead Damage

Figure Courtesy of CFM

Inlet hardware that departed the airplane and was later recovered on the ground was reconstructed together with hardware remaining on the airplane to enable observations of accident event damage. Similar to the engine FBO containment certification test, the accident hardware exhibited a full 360° circumferential fastener shear failure in the aft bulkhead-to-attach ring joint (**Figures 21** and **22**). The aft bulkhead web panel splice joints failed also by fastener shear. Based on the engine FBO containment certification test observations, and structural analysis in support of the accident investigation, the accident inlet hardware observations were, for purposes of the structural analysis, attributed to the displacement wave loading.

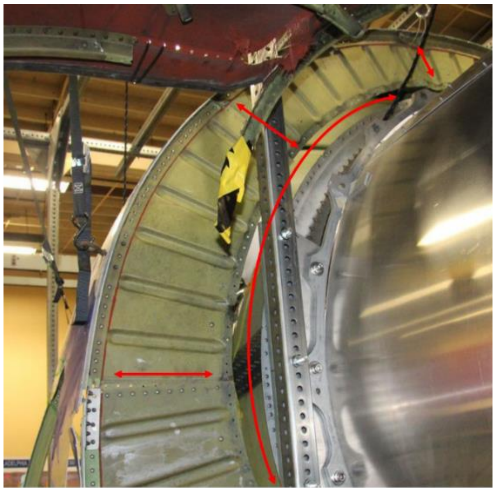


Figure 21 – Aft Bulkhead Joint Failure – Accident hardware Left Hand View (Aft Looking Forward)

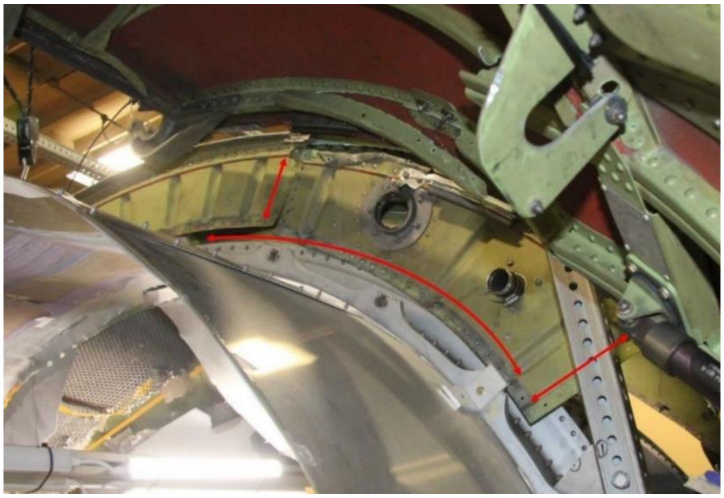
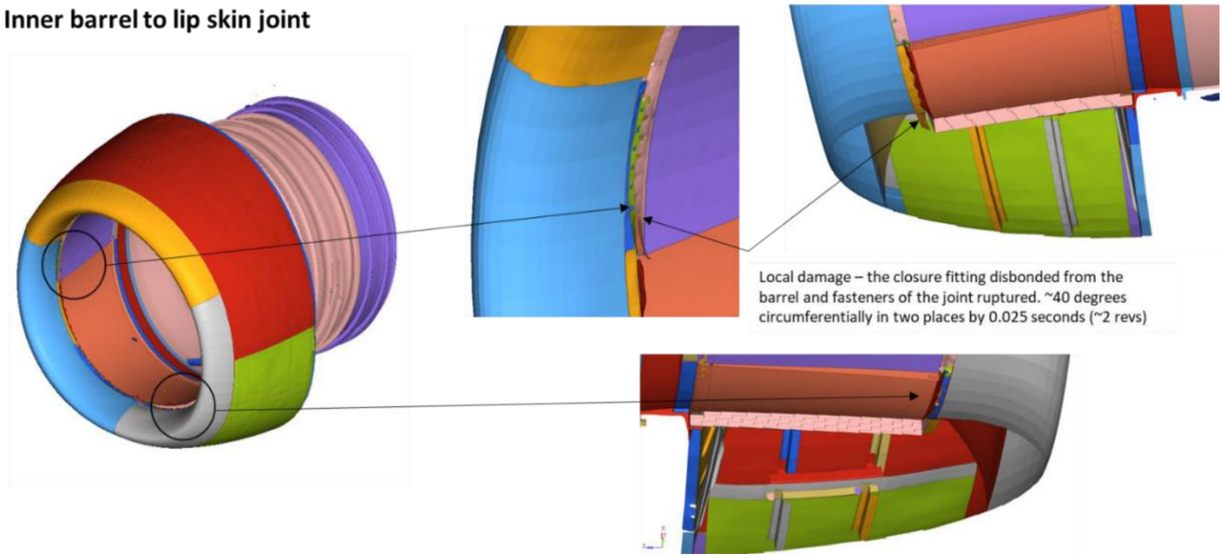


Figure 22 – Aft Bulkhead Joint Failure – Accident hardware Right Hand View (Aft Looking Forward)

Figures Courtesy of Boeing

FIGURE 23 illustrates the simulation results related to the inner barrel-to-lip skin joint. The simulation results were consistent with the lip skin joint failure; however, lip skin joint failure does not appreciably contribute to the inlet separation.


Inner barrel to lip skin joint

Local damage – the closure fitting disbonded from the barrel and fasteners of the joint ruptured. ~40 degrees circumferentially in two places by 0.025 seconds (~2 revs)

Figure 23 – Simulation Result of Lip Skin-to-Inner Barrel Damage

FIGURE COURTESY OF BOEING

Additional event hardware damage was evident, including the inlet lip skin, forward bulkhead, inner and outer barrel. That damage was, for purposes of the structural analysis, attributed to fragment damage, airframe, or ground impact damage, or undetermined forces.

11.1.3 Inlet Analysis Results from Surge Pressure

Results from a structural analysis performed by Collins with the defined event surge pressures provided from CFM for the accident altitude and engine conditions indicated that the surge pressure did not contribute to any damage progression.

11.1.4 Inlet Analysis Results from Run Down Loads

Accounting for potential inlet damage caused by the displacement wave loading, and an estimate of the minimum amount of damage caused by forward traveling fan blade fragments, a progressive failure analysis was performed on the inlet using loading based on the actual accident event run down conditions based in part from FDR data and correlated with data from the CFM56-7B engine FBO containment certification test.

FIGURE 24 shows the inlet model that was used for the progressive failure analysis during the run down phase of the accident event and it shows the starting condition state that included the damage to the inlet from fan blade fragments and displacement wave loading (See **FIGURE 8**). The run down simulation was consistent with damage propagating within 0.5 seconds after fan blade release and the damage propagation was sufficient to separate the forward portion of the inlet.

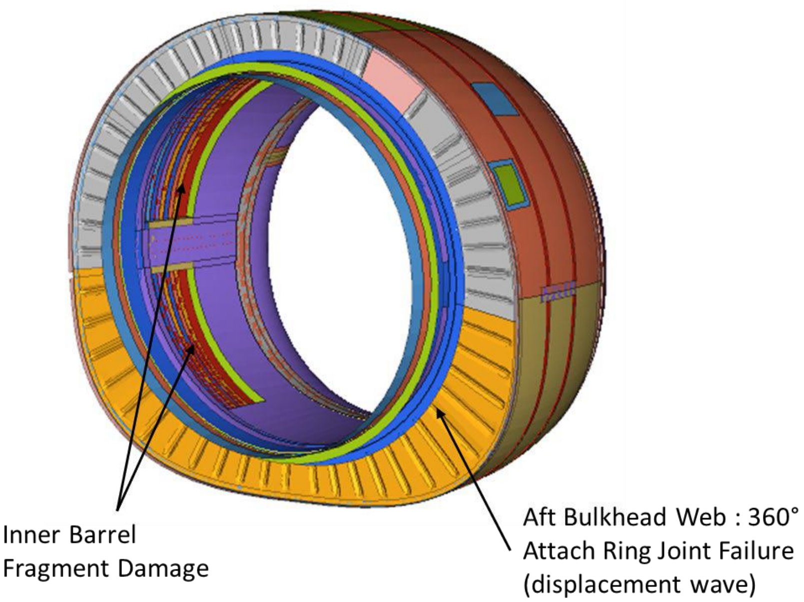


Figure 24 – Simulation Model for the Run Down Analysis with Displacement Wave and Fan Blade Fragment Damage Conditions Applied

FIGURE COURTESY OF BOEING

FIGURE 25 shows the state of the inlet mid simulation, which illustrates damage propagation in the inlet inner barrel as well as damage accumulation at the aft bulkhead to outer barrel joints.

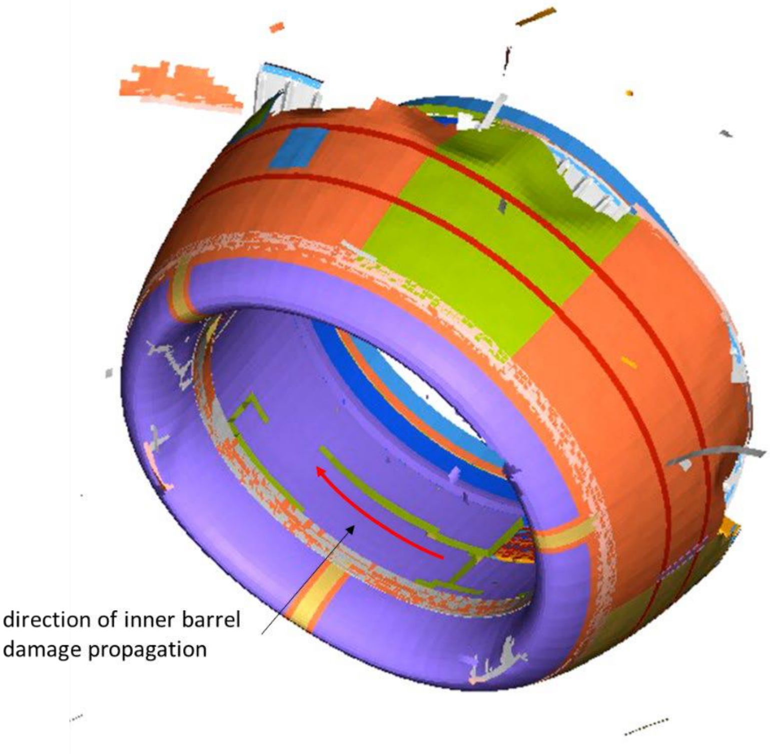


Figure 25 – Simulation Run Down Progressive Failure Analysis at Mid-State – Inlet Still Attached

FIGURE COURTESY OF BOEING

Figure 26 shows the state of the inlet at the end of the simulation. The only structure that remained attached to the engine was the attach ring, the aft part of the inner barrel (including containment doubler), and the 3:00 and 9:00 o'clock inner barrel splices; this is all consistent with the accident inlet hardware in the as-landed condition.

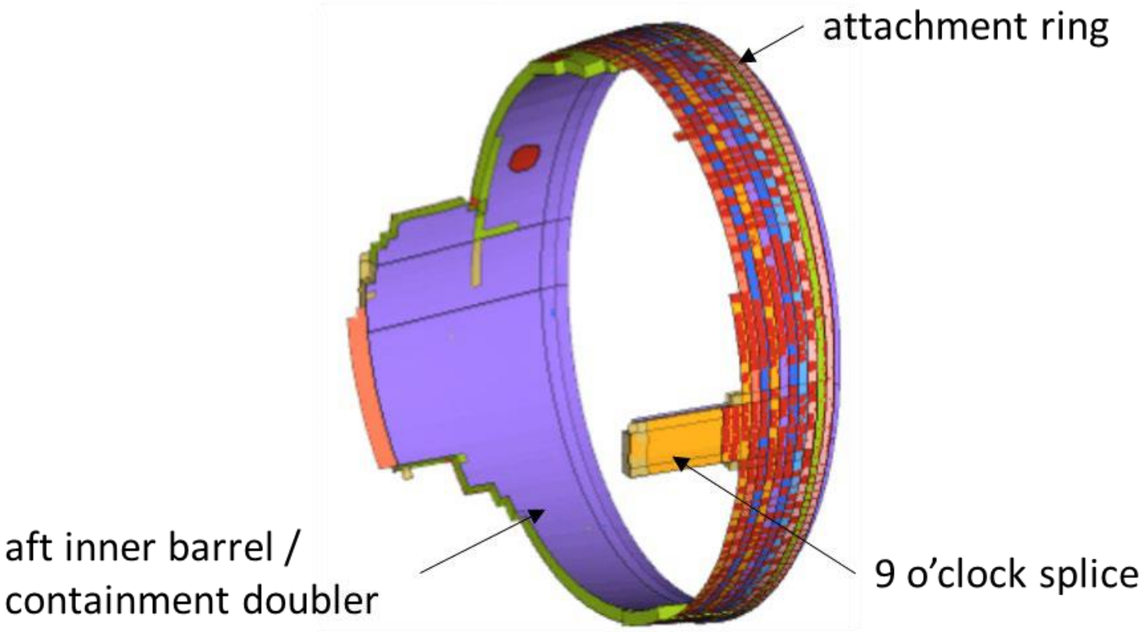


Figure 26 – Inlet Progressive Failure Analysis Simulation – Final State

FIGURE COURTESY OF BOEING

During the CFM56-7B engine FBO containment certification testing, the fan spooled down at a rate that was influenced by fan imbalance, resulting in the fan blade tips rubbing against the fan case, mechanical bearing friction, and fuel flow. The engine control unit was damaged during the engine FBO containment certification test that resulted in a shutdown in fuel flow and hence a quicker spool down rate than the accident event. As part of the engine FBO containment certification test procedures, the engine is purposely allowed to run for 15 seconds before an attempt is made to shut the engine down. The ability to shutdown the engine is one of the acceptance criteria for a successful the engine FBO containment certification test. The production-representative inlet installed during engine FBO containment certification test sustained damage from the displacement wave and from fan blade fragments but remained attached to the engine after surge and run down.

As previously mentioned, the displacement wave caused the aft bulkhead joint to fail; thus, the only remaining inlet mechanical load path was through the inner barrel perforate and backskins. The backside skin of the accident event inlet was visually inspected under magnification to look for signs of static or fatigue type of failure. The inspection found that there were no signs of fatigue striations (**REPORTS FROM PARTIES - COLLINS**). The lack of fatigue striations was consistent with a fast fracture failure mode, indicating that the inner barrel skin damage initially caused by fan blade fragments propagated rapidly and overloaded it beyond its residual fracture strength capability.

The FDR for the accident flight indicated that the No. 1 engine fan speed continued to run at 40% of the maximum (redline) speed for 35 seconds until the fuel was commanded off by the pilot (See Flight Data Recorder Specialist's Factual Report for this accident for details). The accident analysis simulations used the actual No. 1 engine run down fan speeds with its 'power on' condition. The run down rate used for the analysis was derived from FDR data and was determined not to be a significant contributor to inlet separation.

FIGURE 27 shows the side-by-side comparison of the accident event inlet (**FIGURE 27 LEFT**) in the as-landed condition and final state of the inlet progressive failure analysis simulation for the load conditions previous discussed (**FIGURE 27 RIGHT**). The simulation model correlated well with the accident event inlet.

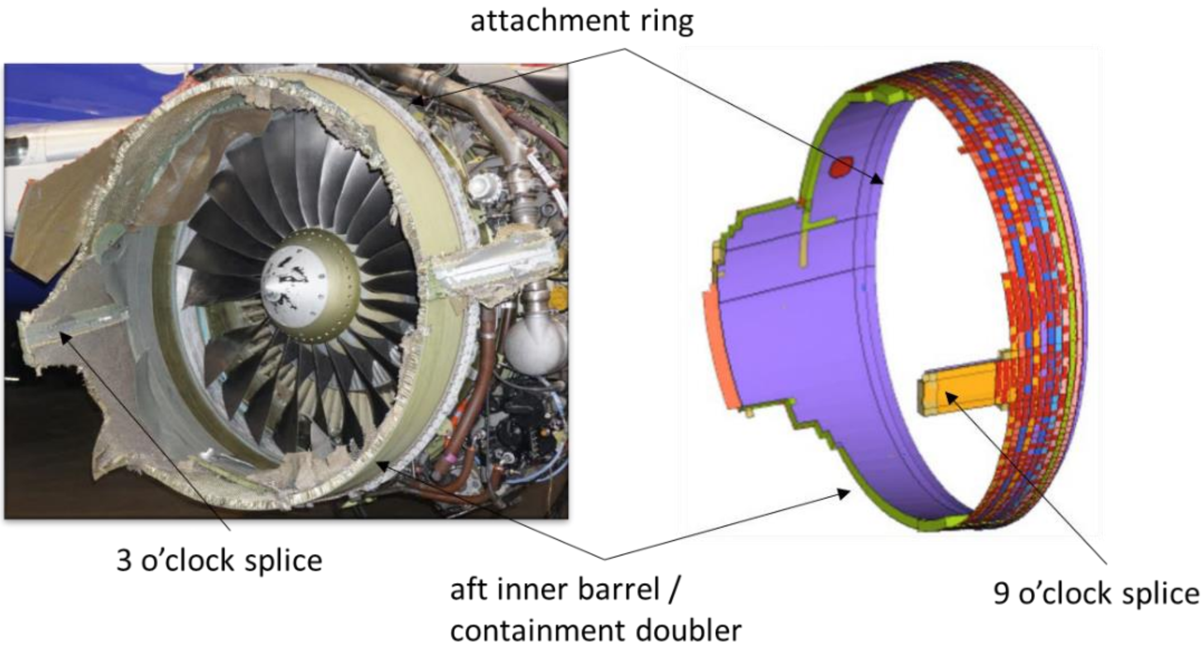


Figure 27 – Inlet Simulation Result (right) Versus Accident Event Inlet Condition (left)

SIMULATION FIGURE COURTESY OF BOEING

11.2 Fan Cowl Progressive Failure Analysis Method and Results

11.2.1 Progressive Failure Analysis Methodology

The analysis performed to simulate the accident event fan cowl damage failure progression used the same modern explicit finite element modeling methods not available at the time of certification as the inlet displacement wave analysis. The fan cowl simulation included only the displacement wave from the fan blade initial impact near the 6:00 o'clock position and the external aerodynamic pressures on the fan cowl. The simulation did not use run down loads which would have increased the internal loads in the structure. **FIGURE 28** provides the 3-step analysis process (model generation, fan blade release and displacement wave definition, and progressive failure of fan cowl structure) used by Boeing to simulate the damage.

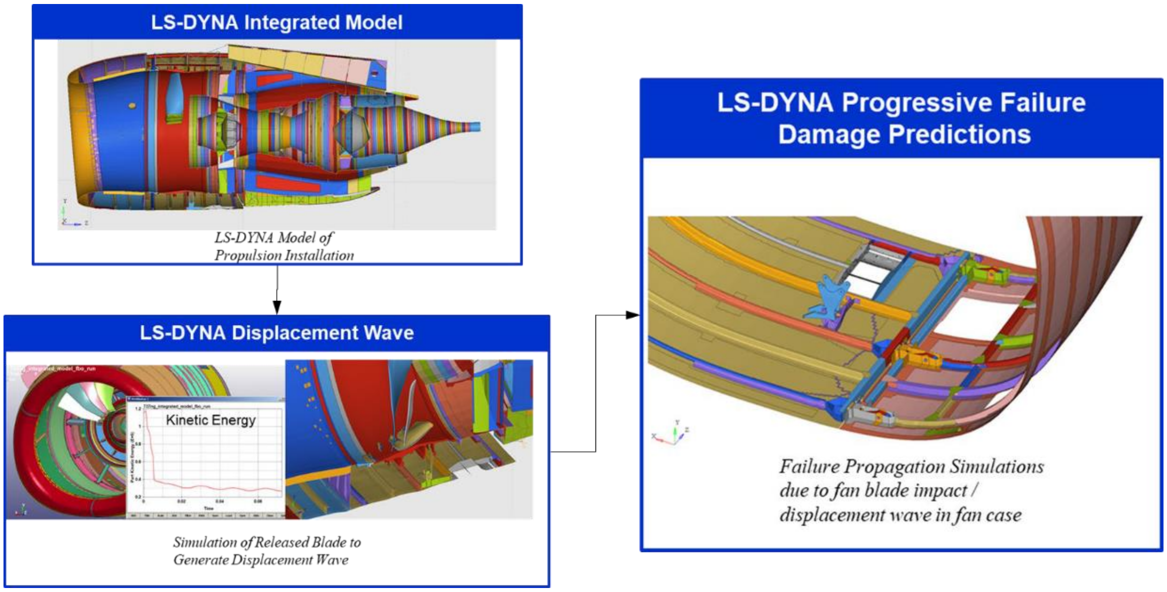


Figure 28 – Fan Cowl Progressive Failure Analysis Methodology

FIGURE COURTESY OF BOEING

11.2.2 Fan Cowl Progressive Fracture Analysis Results

FIGURE 29 shows the location of fan blade root fragment impacting the fan case at 6:00 o'clock; the engine fan case has been removed from the figure so that the correlation between the fan blade impact location and radial restraint can be more easily observed. This impact location was identified by examination of the hard impact marks in the fan case, assessing which parts of the released fan blade created which marks, and correlating that with FBO rig and FBO engine containment certification results. Fan blade fragment impact at the 6:00 o'clock position of the fan case in close proximity to the fan cowl radial restraint fitting and is the start of the fan cowl analysis simulation.

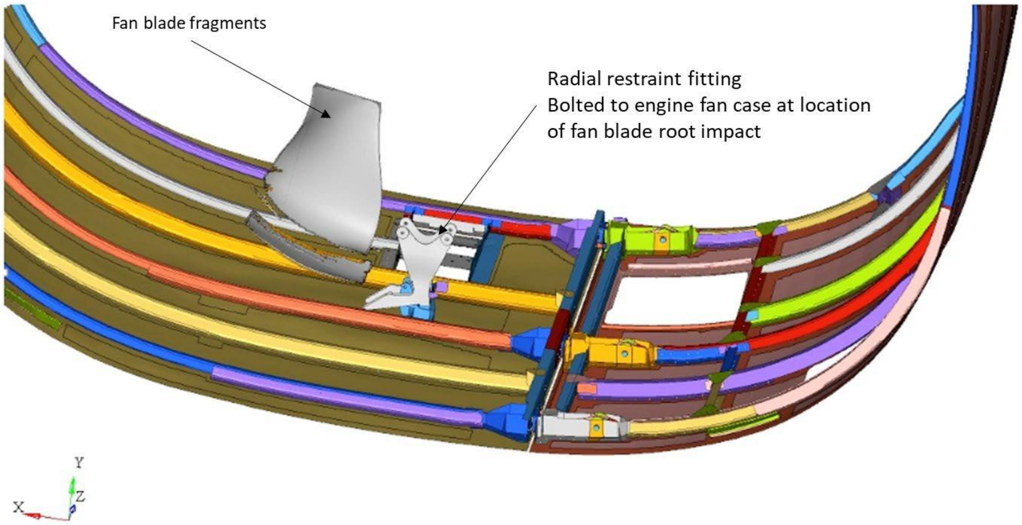


Figure 29 – Fan Cowl Simulation Model for Fan Blade Impact at 6:00 o'clock Position

FIGURE COURTESY OF BOEING

Following the fan blade release, the impact and the displacement wave loads were transmitted through the radial restraint fitting into the fan cowl. The fan cowl experienced significant displacements that resulted in the radial restraint fitting shear pin becoming disengaged and the failure of frame 3 to start. The energy from the FBO introduced into the fan cowl allowed cracks to initiate in the corners of the vent starter cut-out (**FIGURE 30**). Disengagement of the radial restraint fitting occurred at about 28 milliseconds after fan blade release.

In the original loading assumptions used at the time of the engine and airplane certification, it was assumed that the radial restraint fitting failed immediately, prior to transmitting loads to the fan cowl. The remaining structure was assessed and the cowls were predicted to sustain the FBO loading without departure.

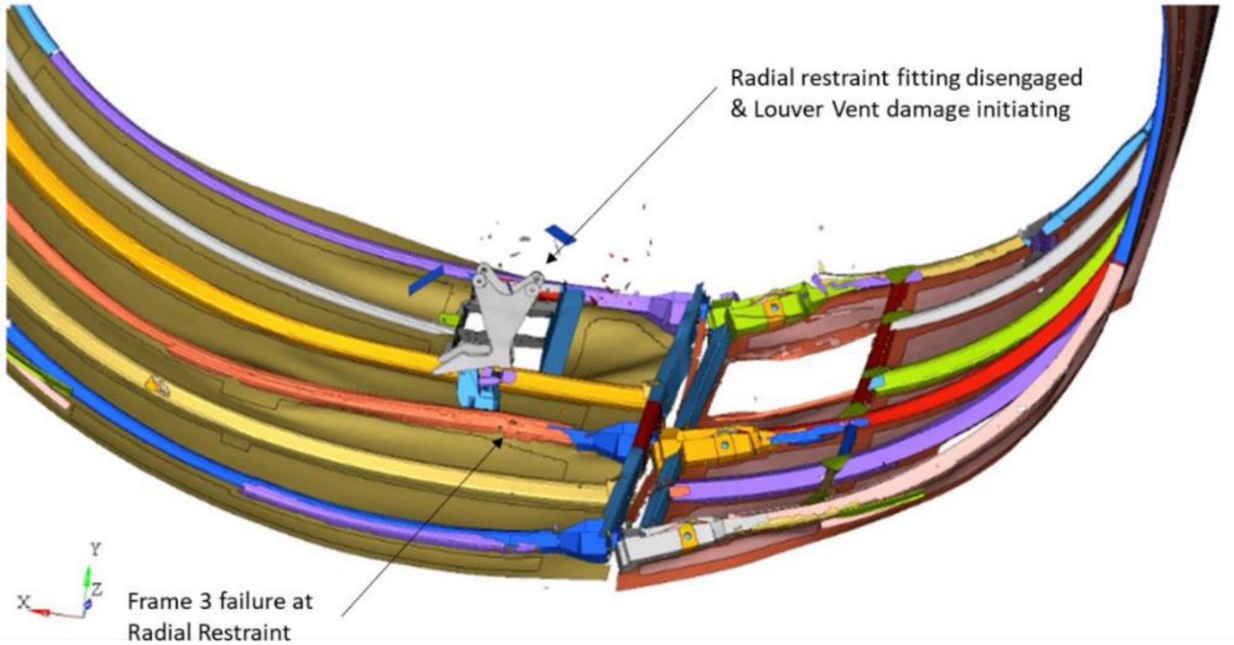


Figure 30 – Fan Cowl Progressive Failure Analysis
Radial Restraint Disengages and Fan Cowl Damage Initiates

FIGURE COURTESY OF BOEING

FIGURE 31 shows the total load path failure around the aft keeper (keeper 3) fitting and the separation of the louver vent from the fan cowl due to failures at the joint locations. The impact loads and external aerodynamic pressure loads resulted in further crack propagation and the opening of the fan cowl. The structural failures lead to a progressive total fan cowl failure with latch 2 and then latch 1 connections failing. All latch load paths failed leading to fan cowl opening and partial separation from the airplane by approximately 0.070 seconds after fan blade release. The results of the simulation were consistent with the documented damage on the accident event fan cowls (See **FIGURES 11** and **14**).

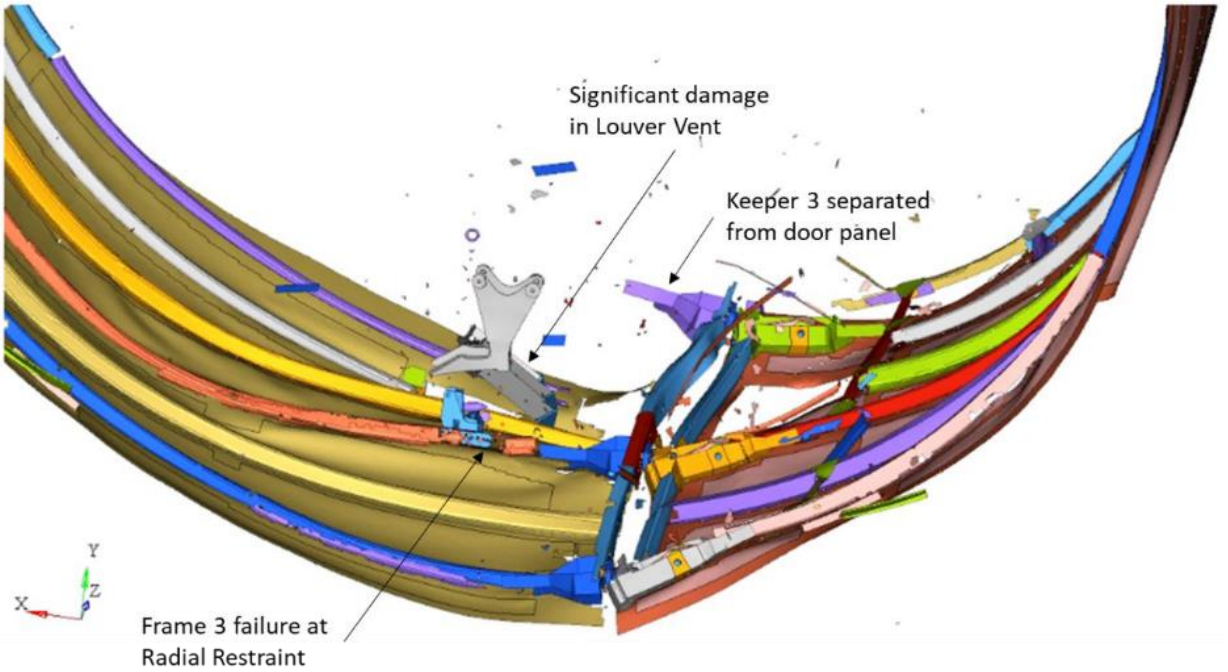


Figure 31 – Fan Cowl Progressive Failure Analysis – Louver Vent and Aft Latch Keeper Failure

FIGURE COURTESY OF BOEING

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Aircraft Structures