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8:05 a.m.

CHAIRMAN CARMODY: Alright, Ms. Ward, would you proceed with the next witness, please?

MS. WARD: I'd like to call Dr. James Reeder. Whereupon,

DR. JAMES REEDER

was called as a witness, and first having been duly sworn, was examined and testified as follows:

BY MS. WARD:

Q Please have a seat. Dr. Reeder, would you please state your full name, your present employer, and your business address?

A Dr. James Reeder --

Q Mike, please?

A That on?

Q Yes.

A Dr. James Reeder. I work for NASA Langley Research Center. You asked for address? 2 West Reed Street, Hampton, VA.

Q What is your current position and how long have you been in that position?

A I am a research engineer. I have been in that position for 15 years. I do research into the failure mechanics and testing of composite materials.

1 Q Do you have any additional duties and
2 responsibilities that you're responsible for, and can
3 you also list any education and training that you
4 required for this position?

5 A Research has been my responsibility for that
6 15 years. I have multiple degrees in mechanical
7 engineering. My final degree was a Ph.D. from Texas
8 A & M University.

9 Q Thank you, Dr. Reeder.

10 Madam Chairman, I qualify this witness and
11 now pass over to Dr. Matthew Fox for questioning.

12 CHAIRMAN CARMODY: Thank you. Please go
13 ahead.

14 BY DR. FOX:

15 Q Good morning, Dr. Reeder. I'd like to
16 discuss some of the fractography that was done on the
17 vertical stabilizer attached lugs, and I understand
18 that you have a general presentation regarding overall,
19 general fractography of composites.

20 A Yes, I do. If you would put up my
21 presentation. Is there a problem putting up the
22 presentation that is on my computer? We had that up
23 earlier. There it is.

24 PRESENTATION BY DR. REEDER

25 Composite fractures complex. That is, it's

1 generally messy and interpreting fracture surfaces is
2 not an exact science. The way this generally works is
3 researchers go into the laboratory and create a
4 fracture surface under a very controlled situation,
5 look at the fracture surface and try and look for
6 unique features on that fracture surface that they then
7 identify with that form of failure.

8 You then go to a failure where you don't know
9 the failure events and compare to try to make educated
10 assumptions of what took place in the failure.

11 I put this presentation together to give you
12 an idea of some of the features that we look for on
13 fracture surface. The type of fracture surface that
14 you generate is dependent on many different factors.
15 In composites, it depends on whether you're breaking
16 fibers or whether you're breaking matrix. It depends
17 on which failure plane you're working on or fracture
18 plane you're working on, whether you're in a
19 translaminal plane or you're breaking across the ply,
20 therefore breaking fibers. You can also break in the
21 intralaminar plane, which is still breaking across the
22 ply, but you're going along the fibers so you're no
23 longer have to break them, and you see primarily matrix
24 failure.

25 There is also interlaminar fracture. This is

1 fracture between the planes. This is commonly called
2 delamination, and I'll try and use delamination so that
3 I don't confuse you or me with -- between interlaminar
4 and intralaminar -- these terms are awfully similar.

5 The fracture surfaces that are generated also
6 depend on the type of loading. Are you pulling the
7 structure in tension, pushing it in compression? Are
8 you shearing the structure? Are you bending the
9 structure?

10 And finally, the nature of loading. Was the
11 fracture surface generated in one loading event or was
12 the fracture surface generated incrementally with
13 repeated loadings of fatigue?

14 To go through this, I will look at different
15 combinations of these factors. For instance, the first
16 fracture surface I will look at is fiber failure in the
17 translaminar direction under tensile loading and a
18 static failure. This type of failure is generally
19 characterized by radial markings on the fracture
20 surface of the fiber. When a fiber fails in tension,
21 it is often initiated by a surface imperfection. The
22 crack then grows across the fiber, across the fiber,
23 leaving faint radial markings. And this directionality
24 to the fracture is a very good indication of the
25 fracture direction on that fiber, but it may not be a

1 good indication of the overall fracture direction
2 because these failures are often heavily influenced by
3 where the imperfection happened to be around the
4 circumference of the fiber.

5 To get a better idea of the overall growth
6 direction, when you look at a fracture surface, often
7 one failure will lead to another, and you can track
8 this as you -- from one fiber to another, and this
9 provides a better indication of growth direction.

10 Also, in the randomness of the radial
11 markings, there can sometimes be some directionality
12 that you can pick up, and this is also an indication of
13 the larger growth direction.

14 Translaminar tension failure of fibers also
15 generally occurs on many different planes as you can
16 see in this lower picture. And because of that, when
17 you look at that type of fracture optically, it's
18 generally a very dull, non-reflective surface.

19 Same type of failure, but we've changed the
20 loading. We load the fibers in compression. This type
21 of fracture is often characterized by chalk marks, that
22 is, these lines on the fiber surface. These lines on
23 the surface are created because when we push on a fiber
24 in compression, the fiber doesn't actually fail in
25 compression, it fails in buckling. When the fiber

1 buckles, as you can see in these pictures, this
2 picture, it bends. When the fiber bends, one surface
3 of the fiber will go into tension, the other side of
4 the fiber will go into compression. The change from
5 tension to compression creates the line on the fracture
6 surface.

7 Compression failures tend to be much more
8 planar, occurring microscopically on a flat surface.
9 And because of that, these can -- optically these
10 surfaces can appear slightly more reflective.

11 If we take the same fracture plane and load
12 the structure in shear, you might think we would get
13 shear failures on the fibers. But we rarely see shear
14 failures of a fiber. It's very -- the weaker matrix
15 generally cannot load the fiber in shear enough to fail
16 it. The fiber in shear -- so that if you put one ply
17 in shear, generally the matrix would collapse, allowing
18 the fibers to rotate.

19 If you have a structure such as this and you
20 place the structure in shear, fibers in one direction
21 will generally pick up tension loading, fibers in
22 another direction will pick up compression loading, so
23 you would see tension and compression loadings --
24 tension and compression failures on the planes.

25 On the same fracture surface, still failing

1 fibers, but if you put the structure in bending, just
2 as with the fiber, one side went into tension, one side
3 went into compression. The same thing happens in the
4 structure, and so you can see a compression failure on
5 one side, a tension failure on the other, and you see
6 this line between in this transition from tension to
7 compression. It's characteristic of a bending failure.

8 If we go back to the translaminar tension
9 direction, and we look for evidence of fatigue, there
10 may not be a lot of evidence of fatigue on the fiber
11 itself, but the fiber failure could fail the matrix
12 around it and on the matrix failure around the fiber we
13 can sometimes pick up these very faint markings on the
14 surface that we call striations, and these striations
15 mark where the crack advanced with each increment of
16 loading, and as an indication of fatigue.

17 If we change planes. We're now in the
18 intralaminar plane, that is still breaking through the
19 ply, but this time we're going along the fibers so we
20 don't need to break fibers. So the fracture plane is
21 primarily matrix. On these -- this plane is
22 characterized by two different failure morphologies or
23 features, and they can easily be confused, and they
24 indicate growth in opposite directions. So I put them
25 together so they can be compared.

1 The first one is river markings. River
2 markings are created because when a fracture initiates,
3 it will initiate on many different planes and as the
4 fracture grows, these planes try to join up, creating
5 these types of features that have been described as
6 small streams growing towards larger river, and thus
7 the term, river markings.

8 If the planes do not join up as the crack
9 grows, the crack front normally spreads out and
10 therefore these lines will spread out and the spreading
11 of the lines on the surface is a feature called
12 feathering. It is often apparent at a lower
13 magnification. And as you can see, the growth
14 directions are marked on the graph.

15 Changing planes once again. This is
16 delamination. This is interlaminar fracture, so we are
17 breaking the composite between the layers of the plies.

18 To make things a little more complicated, usually when
19 we talk delamination, we no longer talk tension and
20 shear, we talk mode I and mode II, that is a fracture
21 mechanics terminology. Mode I is analogous to tension.

22 You're pulling the crack faces open. Mode II is a
23 shearing type action, where you're shearing the faces
24 over each other and Mode III is also a shearing type
25 action, but it is a scissoring action.

1 Generally, in composite failures, we're most
2 concerned with mode I and mode II. The mode I fracture
3 surface, again, shows very little evidence of the
4 fibers underneath the surface. It's a fairly flat
5 surface and you may see signs of river markings and
6 feathering on the surfaces as well.

7 The mode II surface is rougher. You see
8 either fibers or indentations of fibers on the surface,
9 and you see these structures which are called hackles -
10 - and I'll talk more about these hackles.

11 The hackles are formed because you are
12 putting the matrix between two plies in shear. When
13 you put the matrix in shear ahead of the crack tip,
14 small matrix cracks will open up in a tension
15 direction. These matrix cracks cannot grow easily into
16 the ply because they're stopped by the fiber, so with
17 increased load, a new matrix crack will open up, and
18 another matrix crack. With continued loading, these
19 matrix cracks will finally join up and they'll join up
20 generally close to one fiber or another, and finally
21 you can grow this crack all the way across the
22 structure. If you open up the structure and look at
23 the face, you're therefore left seeing these platelets
24 of fibers which have been compared to shingles on a
25 roof, existing between impressions of fibers. These

1 plates of matrix are what we call the hackle, and they
2 generally indicate a shearing force on the surface,
3 opposite to the direction of the lean of the hackles.

4 Many researchers have tried to also interpret
5 the growth direction from the hackles, but this is very
6 difficult to do reliably because mating surfaces will
7 have hackles in different directions, and so depending
8 on which surface you look at, you might predict growth
9 in different directions. And so predicting the growth
10 direction is difficult.

11 Hackles often have a tendency to form
12 perpendicular to the fiber direction. I talk about
13 these hackles as a mode II fracture surface, but on a
14 general fracture surface we wouldn't have just mode II,
15 we would have just mode I, we would have some
16 combination of mode I and mode II loading, and from
17 this picture you see the mode I being very flat; mode
18 II having all the hackles, but already at 50 percent
19 mode II loading, we already have hackles that are well
20 established. At just 20 percent mode II the fracture
21 surfaces become rougher and so the presence of hackles
22 is not an indication that you did not have opening mode
23 on a fracture surface.

24 We also can look at -- for evidence of
25 fatigue on these delamination fracture surfaces, and

1 that can come in many different forms. The first one,
2 we call matrix rollers. These features are caused by
3 rubbing of the surfaces. When you rub the surface, the
4 hackles can break off and can be rubbed down into these
5 cigar shaped features that are called matrix rollers.

6 Another type of evidence of fatigue is that
7 all of the sharp hackles that exist on a static
8 fracture surface can be rubbed away, basically sanded
9 down to the surface where the fibers exist, so the
10 surface looks much -- shows much less feature --
11 flatter, sanded.

12 A final indication of fatigue that can be
13 seen on mode II fracture surfaces -- again, striation
14 marks, but in this case the striation marks look
15 different, they're generally seen in the smooth areas
16 where fibers have pulled out, and again these striation
17 marks are generally associated where the crack stopped
18 after increments of loading.

19 I'd like to describe one last fracture
20 feature. This is called matrix granularity, and this
21 type of feature is generally associated with a marred
22 surface, something scratched or rubbed, or abraded the
23 surface. And so it's breaking up the matrix into
24 pieces. This is generally also associated with
25 failures of the fracture -- failures of the fiber on

1 the fracture surface.

2 As I described earlier, all these pictures
3 are made possible by researchers who have run careful
4 experiments to create fracture surfaces under well-
5 controlled conditions, and here is a list of work that
6 I've referred to, and a final page of that.

7 DR. FOX: Thank you, Dr. Reeder, for that
8 comprehensive overview, and should give us a good basis
9 for the following discussion. Also, Dr. Shultheis (ph)
10 and I would like to express our appreciation for your
11 consultation and advice provided during the
12 examination, as well as your direct participation in a
13 portion of the interlaminar fracture examination.

14 BY DR. FOX:

15 Q So I guess moving to the fractographic
16 examination of the accident vertical stabilizer, I'd
17 like to address some questions regarding the
18 longitudinal attached lugs examination. Selected
19 photos from the fractographic examination are shown in
20 Exhibit 15C.

21 So I guess for stepping through, first I'd
22 like to discuss the fractures through the thickness,
23 across the fiber layers on the right side of the
24 vertical stabilizer. So, in your review of the
25 fractographic examination of these longitudinal

1 attachment lugs, could you describe the general
2 features observed on the translaminar fracture surfaces
3 on the right side?

4 A On the right side, when we looked at
5 translaminar fractures, that is breaking through the
6 plies, breaking fibers, we saw lots of evidence of
7 radial markings, indicating tension loading and in
8 these translaminar fractures occurred in different
9 places on each of the lugs on the right hand side. If
10 you look at Figure 4 of Exhibit 15C, that's on page
11 three, you see that the translaminar fractures were
12 created as a wedge of material was broken out, allowing
13 the lug bolt to escape.

14 A delamination occurred between the
15 translaminar fracture allowing the wedge of the front
16 of the lug to occur at slightly different planes than
17 the lug on the back of the -- of the lug. But both
18 were about 90 degree wedges, and looking at the
19 fracture surfaces, the general direction of growth
20 seemed to be from the inside of the lug outward.

21 In the center lug, the -- that can be seen on
22 Figure 9 on page five of Exhibit 15C -- here the
23 translaminar fracture occurred above the outside lug
24 buildup area, along the line which is marked by the RC2
25 and RC1 specimen that were cut away. This is where the

1 fracture cut through the skin of the aircraft.

2 In this failure, again, we saw lots of
3 evidence of tension failure and generally the crack
4 growth direction in these two spots that we looked at,
5 RC2 and RC1, appeared to be towards the back -- excuse
6 me, towards the front of the aircraft.

7 Q So the crack growth direction generally from
8 aft to forward?

9 A From aft to forward. On the front lug, that
10 is seen in Figure 14, page seven, again we have a wedge
11 of material that has been broken out, creating -- the
12 breakout was due to translaminar fracture, breaking
13 across fibers. The -- it is not apparent from Figure
14 14, but the fracture surface marked by RF1 is an
15 extremely planar fracture for a composite fracture,
16 with only a few plies sticking up above the fracture
17 surface, and you can see -- and it is those plies that
18 you can see sticking below the paint line.

19 Again, looking at the fracture surfaces we
20 see radial markings on the fibers indicating tension
21 failure and general direction of growth on the -- in
22 the RF1 area was from the inside the bolt outward.

23 The fracture on the rear side of this lug,
24 that is the area marked by RF2(a) was slightly more
25 complex. You have translaminar fracture happening at

1 several different planes due to thickness, and these
2 planes were connected by delaminations to make a
3 complete fracture path.

4 Again, looking at this fracture surface,
5 radial markings indicting tension failure and the
6 general direction of growth was from inside of the lug
7 outward.

8 Q Thank you. Let's see, I guess the next area
9 to look at would be on the left side of the vertical
10 stabilizer. Once again, looking at the same fracture
11 plane through the thickness, across the layers. So in
12 your review of the fractographic examination for these
13 longitudinal attachment lugs, could you describe the
14 general features observed on the translaminar fracture
15 surfaces on the left side?

16 A The fracture surfaces on the left side were
17 much more complicated, in general, much more of a
18 tortuous path through the thickness. The translaminar
19 fracture on the right rear -- excuse me, left rear --
20 this fracture surface is shown in Figure 25 and 26 on
21 page 11. The translaminar fracture, certainly of the
22 skin layers, occurred at a row of bolts that attached
23 rib one. Looking at the translaminar fracture, we
24 again saw radial markings and they were generally from
25 the front of the aircraft, rear.

1 On the center lug, you see this fracture --
2 page 19, Figure 41 -- this was a much cleaner fracture.

3 It again failed, translaminar fracture, cutting
4 fibers, and again this failure occurred at the row of
5 rib one fastener bolts, and the general direction of
6 growth was from the front towards the rear. This
7 translaminar fracture also had an area of compression
8 near the outboard side, which could indicate a bending
9 on this lug. You will notice that this lug was the one
10 that had been repaired during the manufacturing
11 process, so you might be able to see all the additional
12 fasteners above and below the rib one fastener, but the
13 fracture occurred through the rib one fastener bolts.

14 Translaminar fracture on the front left --
15 this fracture surface is shown in Figure 45. Again,
16 the translaminar fracture in this case was fairly
17 complicated with the translaminar fracture happening on
18 many different planes as you step through the thickness
19 of this lug. The direction of growth from the radial
20 markings on the fracture surface tended to be from the
21 inside of the lug outward.

22 Q Which page should we be referring to for the
23 --

24 A Page 21, Figure 45. There you go. Again, a
25 wedge of material became detached in the lower section

1 on the left front lug created by the translaminar
2 fracture.

3 Q And the black arrow in the figure? What is
4 that pointing to?

5 A The black arrow in the figure points to a
6 bearing failure that occurred on the surface. This
7 corresponded to the outer lug clevis of attachment,
8 where the lug was attached to the tail of the aircraft,
9 and so a surface bearing type failure. Compression.

10 Q Okay, I guess the next feature to discuss
11 would be looking at the inner laminar fractures, or the
12 fractures between layers. So again, looking at the
13 left side, based on your participation and review of
14 the fractographic examination on the inner laminar
15 fractures of the left aft and left forward lug
16 positions, could you describe the fracture locations
17 within the stacking sequence and the general appearance
18 of these fracture surfaces?

19 A I'll start with the left rear, and I think
20 I'd better draw this. Let me see if I can bring that
21 Exhibit up on my computer here, because it was a fairly
22 tortuous path of delaminations working its way through
23 the structure. I'll describe it from the inside of the
24 structure outward, but the actual directions of growth
25 and failure sequence was unclear.

1 This fracture started toward -- near the rib
2 one flange, breaking the flange and working its way
3 along the stringer outer flange, which was made up of
4 zero degree fibers. It works its way up that plane, up
5 above the lug buildup area, which is the wedge that you
6 see here, and continued on up into the skin of the
7 aircraft, or skin of the tail. The delamination also
8 turned and ran down next to the skin. It actually ran
9 inside the lug region, but in the first plies of this
10 wedge of material next to the skin, and it ran down to
11 the -- to the row of fastener bolts for rib one which
12 occurred around here. At this point, it broke across
13 the skin plies which are the light plies, that is the
14 translaminal fracture I described earlier. When it hit
15 the outside lug buildup area, this outer wedge, it
16 again turned, became OD lamination and ran up the skin
17 before finally exiting, allowing a complete fracture
18 path and the two parts to separate.

19 Q And again, that's not necessarily the crack
20 direction --

21 A That is not necessarily the crack direction,
22 but was the --

23 Q -- or necessarily the order of --

24 A Yes, right.

25 Q But it's the easiest way to describe the

1 fracture path, --

2 A Which is very complicated.

3 Q -- that allows that to completely separate.

4 A Yes.

5 Q Okay.

6 A The fracture surfaces on -- to examine these
7 fracture surfaces we had to -- to examine the fracture
8 surfaces inside this wedge that was created by the lug
9 region pulling out, we had to section the skin layers
10 away to look at that fracture surface. You can see in
11 Figure 27, page 12, where we cut away the skin layers,
12 and you can see that that delamination was of
13 considerable size.

14 Examining the fracture surface, we saw lots
15 of hackle formations, indicating shear on the fracture
16 surface, and the direction of the hackles was generally
17 consistent with the lug region pulling downward.

18 On the left front lug, it is not apparent
19 from the figure, shown in Figure 45, but these failures
20 were associated with considerable delaminations and
21 they happened in several different places. Excuse me,
22 page 21. Delaminations occurred in several different
23 places. Down in the lug region, that's in the region
24 marked by LF3(c) and LF 3(b) -- those pictures are on
25 the next page, page 22, you can see that particularly

1 on the outboard side, there are considerable
2 delaminations near those complex fracture planes.

3 Q Can we pull up the lower figure?

4 A A lot of damage in this lug region. In
5 addition to these delaminations, if you look above the
6 lug region, there was a large delamination that can be
7 seen once pieces had been cut away to reveal the
8 delamination, you can see the surfaces in Figure 54 on
9 page 25. So again, the delaminations in the bottom lug
10 appeared -- that I showed earlier, near the bottom of
11 the lug, appeared to be limited to the lug region.
12 This delamination, which occurred generally between --
13 again between the stringer outer flange layers which is
14 the zero degree tape layer near the inboard surface and
15 grew up from the line of rivets, the line of fasteners
16 that attach rib one, and these delaminations grew well
17 up into the structure.

18 In general, the delaminations, particularly
19 these larger delaminations, wherever we found them,
20 almost always occurred at an interface between the zero
21 degree tape and a plus or minus 45 degree weave layer.

22 Those interfaces occurred at different points through
23 the thickness of the structure, and the delamination
24 almost always found one of those interfaces to run
25 along.

1 Where growth could be determined on the
2 delamination shown in Figure 54, it, in general,
3 appeared to be growth upwards. This delamination
4 fracture surface differed from the one we saw in the
5 previous lug because there was more evidence of some
6 mode I being on the fracture surface, on the
7 delamination fracture surface, so it had more evidence
8 of river markings that we could use to try to determine
9 the fracture direction.

10 Q I guess you've described some of the
11 microscopic features -- hackles and river markings.
12 Were there -- can you describe some of the other
13 microscopic features that you observed on the
14 interlaminar fracture surfaces?

15 A On the interlaminar fracture surfaces, as I
16 said, they almost always occurred between a zero degree
17 tape fly and a 45 degree weave. When you looked at the
18 weave -- the weave side, where you had fibers running
19 over each other -- get a picture of that -- say, Figure
20 58 on page 27 -- where you have fibers running over and
21 under each other, you naturally develop pockets of
22 resins in those regions.

23 What we did notice on the delamination
24 fracture surface is that optically, in these areas,
25 there tended to be -- they appeared to be tan or deep

1 red in color in these pockets, and sometimes these --
2 that coloration was more prevalent than in other
3 places, particularly higher on the lugs, particularly
4 the left front lug -- this tannish color in these
5 pockets became more evident.

6 When you look at this type of thing under the
7 microscope -- Figure 57 down on the bottom corner,
8 where it says matrix porosity -- these tan regions
9 generally looked like they were porous, something like
10 coral, in those regions along the fracture path.

11 Q Does that -- is that a common feature that
12 you see in structures such as this?

13 A I haven't dealt a lot with this particular
14 material, and so I cannot say whether it is common to
15 this material or not, but it was just a feature that --
16 that we did note as being something different on the
17 fracture surface.

18 Q Okay. I guess in a complex structure such as
19 this, what other techniques in addition to the
20 fractography, are generally used to fully understand
21 the fracture process?

22 A As I said, fractography is not an exact
23 science. It does not provide definite answers. It
24 provides clues. To back up the clues that we form by
25 looking at the fracture surface, we generally would

1 want to do mechanical analysis, structural analysis, to
2 make sure that the types of failures that seem to be
3 indicated by the fracture surface actually make sense
4 for the structure, for the material.

5 Q So I guess generally speaking, throughout all
6 the interlaminar and translaminar fracture surfaces
7 examined at each of the lower attached lug positions,
8 were there any indications of fatigue?

9 A As we look at all of these fracture surfaces,
10 we were watching for fatigue. We were looking for
11 striations or roller pins, matrix rollers, or abrasion.
12 We never saw any features that we identified as being
13 an indication of fatigue.

14 Q I guess one final question, for composites in
15 general, is it possible to have a preexisting defect
16 without producing fatigue features, or features that
17 would indicate fatigue?

18 A Yes, this is not an exact science and we
19 interpret what we see. You would think that a large,
20 preexisting flaw -- a significant preexisting flaw
21 would give some sign, but that's not definite.

22 DR. FOX: Okay, thank you. No further
23 questions.

24 CHAIRMAN CARMODY: Is there anything else
25 from the technical panel? Any questions? Alright.

1 We'll move then to the parties. Pardon me? Dr.
2 Kushner.

3 BY DR. KUSHNER:

4 Q Just if you could clarify a little bit. In
5 talking about your examination on the large
6 delamination surfaces on the left side, the front and
7 rear, you made some references on the rear to direction
8 of motion, and on the front a little bit. We tend to
9 try to think of these in terms of primarily tension or
10 bending loads or whatever. Is there any implication,
11 in terms of what you talked about, in terms of
12 interpreting the loading that took place?

13 A I didn't understand the question. Could you
14 restate?

15 Q The motions that you thought were implied by
16 the patterns on the delamination surfaces, would they
17 have been associated with the lugs and tension or
18 compression or some combination with bending -- can you
19 make a judgement on that?

20 A Sure. Generally, the delaminations we looked
21 at on the left rear lugs were on the back side and had
22 to do with the large wedge of lug build up area
23 becoming, breaking free. In that area, the direction
24 of the hackles gave us the indication that that lug
25 region would have been moving down, the direction of

1 shear would have been associated with that lug region
2 moving down.

3 Particularly in the left side, the fractures
4 are very complicated and are not classic. I do believe
5 that there are, on the center left lug, there's an
6 indication of bending, and I think on the front left,
7 the multiple delaminations along the outside surface of
8 the -- in the lug region could also be an indication of
9 bending.

10 CHAIRMAN CARMODY: Alright, moving to the
11 parties. I would start with the FAA and then go to
12 Allied Pilots, Airbus, and American. FAA, are there
13 any questions of the witness?

14 MR. DONNER: No questions, thank you, ma'am.

15 CHAIRMAN CARMODY: Alright, Allied Pilots,
16 Captain Pitts?

17 BY CAPTAIN PITTS:

18 Q Thank you, ma'am. Dr. Reeder you mentioned
19 the fractures on the left side were not classic. Had
20 you ever seen that combination of fractures before in
21 any of your research?

22 A Each failure event is different, and so
23 that's a relative term. I'm not sure how to answer it.
24 These were complex failures and you take the different
25 parts as best you can. Certainly I've seen areas where

1 you create multiple delaminations that -- when you put
2 something in compression, and a bending would have put
3 that side into compression.

4 Q In your experience with these materials,
5 would you say that what you observed in the failure
6 mode of this left side has established a new benchmark
7 in failure modes, or at least another new example of
8 failure modes?

9 A No, I wouldn't say that. I'd say it's a
10 complex fracture, so the failure events are complex.

11 CAPTAIN PITTS: Thank you sir. I have no
12 further questions.

13 CHAIRMAN CARMODY: Alright, Airbus. Dr.
14 Lauber?

15 DR. LAUBER: Airbus has no questions for Dr.
16 Reeder, thank you, Madam Chairman.

17 CHAIRMAN CARMODY: American. Mr. Ahearn.

18 MR. AHEARN: Madam Chairman, no questions.
19 Dr. Reeder, thank you for your time.

20 CHAIRMAN CARMODY: It was an excellent
21 presentation. Going now to the Board. Member
22 Hammerschmidt? Member Goglia? Member Black?

23 MEMBER BLACK: Just a couple, thank you.
24 Certainly one of the best presentations we've seen. I
25 wish you were teaching somewhere, you have the flair

1 for it, and conveying information.

2 BY MEMBER BLACK:

3 Q Was your work complicated any by we were
4 missing some of the pieces of the lugs, they were never
5 recovered. Do you think that would have helped you
6 any? You had one side, but you don't have the other
7 side of the fracture?

8 A You always want all the information you can
9 get.

10 Q You always want everything, yes.

11 A I don't think of a place where that seemed
12 crucial. There was never a place that there was the
13 feeling that if we only had that other piece.

14 Q That's what I was looking for. Did you -- a
15 number of the witness statements indicated that
16 something struck the fin in the process and caused it
17 to fail. You wouldn't know that, you'd have to read
18 500 witness statements to see it, but there were enough
19 of them to the point of where it would cause me to ask
20 the question if you found any contact damage that might
21 have been indicative of some projectile or some object
22 striking the fin before or after it left the fuselage?

23 A The fracture examination of the fin is --
24 you're talking about the fin --

25 CHAIRMAN CARMODY: Dr. Reeder, the

1 microphone, please.

2 THE WITNESS: Sorry, thank you. The
3 examination that we have performed are really down in
4 the lug region and there's nothing in that region that
5 would have indicated an impact. There were places
6 where we saw matrix granularity, but that -- some of
7 those places could have been damaged after the fact.
8 Matrix granularity is associated with -- generally with
9 a surface being rubbed or marred.

10 BY MEMBER BLACK:

11 Q Okay, thank you. I noticed on Figure 41 that
12 the failure seemed to be along a fastener row. Is that
13 any indication of -- is that a problem or is that just
14 an observation?

15 A That is an observation. I think that more of
16 the designers -- designers' realm to decide whether
17 that would have been a problem. A fastener -- a row of
18 fasteners, certainly, is a place where stresses become
19 concentrated and so that would not be unusual.

20 Q Based on your work, and might say since it
21 was sort of localized to the fracture areas, do you see
22 any sort of a design issue with using lugs versus some
23 other means of transferring the load from the fin into
24 the fuselage?

25 A Again, that's in the design realms, and I

1 wouldn't be comfortable speaking to it.

2 MEMBER BLACK: Fair enough. Thank you very
3 much.

4 CHAIRMAN CARMODY: Alright, are there any
5 more questions from the technical panel or anything
6 from the parties? And I see heads shaking. Well,
7 thank you, Dr. Reeder, for your testimony and your
8 time. We do appreciate your contribution to the
9 investigation.

10 THE WITNESS: Thank you.

11 (The witness was excused.)

12 CHAIRMAN CARMODY: And Ms. Ward, why don't we
13 proceed.

14 MS. WARD: I'd like to go ahead and call Dr.
15 Jim Starnes.

16 Whereupon,

17 DR. JAMES STARNES

18 was called as a witness, and first having been duly
19 sworn, was examined and testified as follows:

20 BY MS. WARD:

21 Q Please have a seat. Dr. Starnes, could you
22 please state your full name, your present employer, and
23 your business address?

24 A My name is James Herbert Starnes, Jr. I work
25 for the NASA Langley Research Center in Hampton,

1 Virginia 23681.

2 Q What is your present position and how long
3 have you been in that position?

4 A I am currently the chief engineer for
5 structures and materials, which is also known as the
6 senior engineer for structure and materials competency.

7 I have been in that position for a little over years.

8 I'm sorry, did you have another question?

9 Q Yes, I was wondering if we could move the
10 mike. And what are your duties and responsibilities
11 and the education and training that you received to
12 qualify you for your current position?

13 A Well, my current responsibilities are to
14 integrate across seven research branches and one
15 technician branch, to form, direct, plan, advocate
16 research programs that require more than one
17 subspecialty. In our competency we have seven research
18 branches, each focusing on a particular aspect or
19 subdiscipline of structure and material. My job is to
20 integrate those into larger scale, more strategic
21 programs than might be executed down at the branch
22 level.

23 My educational background is I have a
24 Bachelor of Science degree in engineering mechanics,
25 and a Master of Science degree in engineering mechanics

1 from Georgia Institute of Technology, also known as
2 Georgia Tech. I also have a Ph.D. in aeronautics,
3 structural mechanics option from the California
4 Institute of Technology, also known as Cal Tech.

5 I've been at NASA Langley for 32 years. The
6 entire period of time I've worked across personal
7 research level up through division level and branch
8 level management -- all in the structures discipline --
9 structural mechanics discipline. Prior to my current
10 position I was the head of the structural mechanics
11 branch and aircraft structures branch over an 18 year
12 period.

13 Q Thank you, Dr. Starnes.

14 Madam Chairman, I find this witness qualified
15 and now pass over to Mr. Brian Murphy for
16 questioning.

17 CHAIRMAN CARMODY: Please continue.

18 BY MR. MURPHY:

19 Q Good morning, Dr. Starnes. I'd like to
20 discuss the following topics with you today: briefly,
21 the historical perspectives in the application of
22 composites; the use of fault tree analysis for failure
23 investigation; the FEM evaluations that have taken
24 place to date; and the structural testing that has
25 taken place or will take place.

1 Could you give me a brief description of
2 NASA's involvement in the development and
3 implementation of composite materials in transport
4 aircraft structures?

5 A Our research in composite structures and
6 materials started in 1968 when a couple of our research
7 scientists returned from graduate school having
8 developed the background in that field. Within a very
9 short period of time we recognized that composite
10 material systems as applied to composite structures
11 offered up performance advantages extremely desirable
12 from an aircraft design point of view. So we began
13 programs, both at a basic research level, which would
14 be executed in some of our research branches, as well
15 what we call more focused programs where we would have
16 many branches and industry and some university
17 involvement, trying to develop a more mature
18 application of some of the basic research findings that
19 we developed.

20 This led to, in the very early 70's, a period
21 of time where we would begin to think about how to
22 introduce composite structures into transport category
23 aircraft. The way we began that was to begin studying
24 the application of these material systems for things
25 like ferrings, control surfaces, what we typically

1 thought of as secondary structures. We would work with
2 industry to develop the design for whichever these
3 components were interested in, do ground tests, flight
4 tests, gain practical experience in service with
5 airline operators.

6 These applications were followed by what we
7 at that time called our medium primary structural
8 applications, which could be things like horizontal
9 stabilizers and vertical fins. That particular
10 program, known as the ACEE or Aircraft Energy
11 Efficiency program started in the mid to early 70's,
12 where we began to try to scale up from primary --
13 secondary structures to primary structures. We worked
14 with companies like Boeing and Douglas at that time,
15 and Lockheed, to develop three empennage class
16 structures, that we had one horizontal stabilizer that
17 we studied with Boeing; we had a vertical fin at
18 Douglas, and we had a vertical fin at Lockheed.

19 Applications were 737 horizontal stabilizer,
20 the L-1011 vertical fin and the DC-10 vertical fin.
21 All of these aircraft parts were fabricated, designed,
22 analyzed, tested and certified by the FAA, put into a
23 flight service program where we operated these across
24 several aircraft operators, including the Air Force, to
25 gain in service experience.

1 This was then followed in the late 80's to
2 mid 90's with a program that focused on primary
3 structures that involved wing structure as well as
4 fuselage structure. We call that our ACT program, our
5 Aircraft -- I'm sorry, our Advanced Composite
6 Technology program. At that time we had 15 different
7 participants across the industry, as well as
8 universities. The activity was culminated in a full
9 scale wing box for a generic narrow-body transport
10 class aircraft, as well as a fairly decent start on
11 some fuselage panels at Douglas.

12 That fuselage program was terminated about
13 half way through because of budget restrictions. We
14 elected to go ahead and take the wing structure all the
15 way through to full scale s...span ground test, and at
16 that point, NASA terminated the activity. That was
17 with first Douglas Aircraft and then McDonnell Douglas
18 Aircraft, and then Boeing as the company changed its
19 affiliation.

20 We've since then had activities in more
21 advanced concepts in dealing with tailored structure,
22 which is our current activities, but it's from a
23 practical, full-scale, aircraft point of view. I would
24 say the wing box activity that we finished about two
25 and a half years ago was probably the most significant.

1 Q We've heard the composites witness testify to
2 using the building block approach. Has that same
3 approach been applied with the NASA prototype programs?

4 A Oh, absolutely. That's the way we gain
5 confidence in our design is we start from the coupon
6 level, item, where we're understanding material
7 properties, mechanical properties, some of the simpler
8 phenomena associated with local discontinuities like an
9 open hole, up to the structural element where you're
10 now changing the dimensional scale of the problem and
11 some of the complexities associated with interactions
12 between small structural pieces and the effect of some
13 of the more complicated discontinuity phenomena like
14 eccentricity and things of that nature.

15 Then as you step up to the next dimensional
16 scale, say at the panel, you have additional
17 interaction issues and the next scale, say a
18 subcomponent, it's even more complex in the sense that
19 you have multiple load paths and you have to understand
20 the interaction of all of those pieces as they come
21 together in a part because they begin to interact with
22 one another.

23 And then finally we get up to the component
24 level where we're dealing with a lot more complex
25 interaction issues.

1 When we first started our research in the
2 development of primary structures for transports, we
3 went into this with the notion that you might be able
4 to design these parts pretty much the same way you
5 would metallic parts. Well, the first thing we learned
6 is you cannot do that. There are different failure
7 mechanisms that you have to be aware of. There are
8 different damage tolerance issues, such as low speed
9 impact damage that you have to account for, none of
10 which you would have to be significantly concerned
11 about in metallic structure.

12 I mentioned having two strings of research
13 activities, one basic research, one focused on
14 technology research -- it's more applied. It was in
15 one of our early basic research programs that we became
16 involved with the notion of the effect of low speed
17 impact damage on compression strength. That's one of
18 these phenomena where we wondered what would happen if
19 we imposed a constraint that we had not seen before,
20 what it would do to the structural integrity of a part.

21 So the mental exercise that went on is what would
22 happen if one of these aileron surfaces we were
23 concerned about in our very early days, would be struck
24 by foreign object damage or some sort of runway debris
25 that was spun up by tires or engine exhaust blast. And

1 we learned early on, in fact, that low speed impact
2 damage could degrade the compression strength of a
3 phenyl-all (ph) sandwich structure, quite
4 significantly.

5 With that experience, we began to apply that
6 same concern to some of our other design technology
7 activities where we were at the time working on big,
8 stiffened cover panels for compression applications on
9 wing spans and we indeed discovered there were a
10 significant reduction in compression strength as a
11 result of this particular phenomenon. So there's an
12 example of our basic research leading us to an understanding
13 of a unique phenomenon to a particular material system that
14 led to the development of an entire new design constraint
15 that's now widely used throughout the industry and the
16 government. I've gotten off your point there, but --

17 Q No, it's fine.

18 A -- you got me started.

19 Q Could you briefly comment on the importance
20 of subcomponent and large scale tests in the
21 substantiating of static strength and damage tolerance?

22 A My experience and my belief is that there are
23 many phenomena that you simply cannot address at a
24 lower scale. If you're working at the coupon scale,
25 you will see some failure mechanisms that are

1 particular to that kind of loading system at that
2 geometry, and when you get up to the more complicated
3 structures, such as a wing box, where you have
4 interaction between cover panels and ribs and spars and
5 so on, you can't see that phenomena, that interaction
6 phenomena at coupon level. You have to go to the
7 larger scale structure to see that.

8 Usually what happens when we progress from
9 the coupon to the element, to the panel, to the -- and
10 so on up, we're addressing the failure mechanisms and
11 the response phenomena that occur at those lower
12 dimension scales. Try to understand those and come to
13 a point where we believe we understand that particular
14 behavior at that dimensional scale, that we try to
15 apply that at the next complex dimensional scale, look
16 for the interactions that occur at elements and coupon
17 level pieces; gain the confidence that we understand
18 the phenomena -- response phenomena or failure
19 mechanisms that might occur at that next level of
20 complexity before we step up to the still higher level
21 of complexity where there's even more complicated
22 interactions.

23 And the reason you want to do this is because
24 it's a whole lot less expensive to learn about a
25 failure mechanism at a smaller scale than to go ahead

1 and build your entire final component part and
2 discover, oops, got a little problem down in this little
3 detail. So the try you address the failure mechanisms,
4 the response phenomena at the smallest scale you
5 possibly can, to integrate a whole lot of confidence,
6 to get up to the next, more expensive scale.

7 So I believe in it. In fact I don't think
8 you can come up with a complex design without doing
9 that.

10 Q Thank you.

11 MR. MURPHY: Madam Chairman, Dr. Starnes has
12 also prepared some overview material on these topics
13 which basically will summarize what NASA Langley has
14 provided to the structure group, so if he could work
15 through that at this time. It's Exhibit 7-HH, Mr.
16 Goldberg.

17 PRESENTATION BY DR. STARNES

18 You want to go to the next chart, please?
19 This is a list of some of the topics that are currently
20 ongoing in our activities, and I'll describe these
21 activities in a summary overview fashion. The very
22 last item on that list represents some of the other
23 activities that some of my colleagues who have come
24 before me have addressed, but I will give you a summary
25 list of the other activities as well.

1 The fault tree analysis process is a device
2 or process that we use quite frequently within NASA
3 when we have a significant failure or problem with a
4 given prototype design and we want to try to come up
5 with the way to understand what that failure might have
6 been caused by, so we can understand it better.

7 I'll talk about a global vertical fin and
8 rudder analysis that we're doing, and the purpose here
9 is given the external loads that come to us in any
10 given state of the flight profile, in particular during
11 the eight seconds of the accident, what would be the
12 external forces that would cause the fin and rudder to
13 deform in such a way that we would perhaps see
14 something that we had not anticipate in the design.

15 The local vertical fin lug analyses is a
16 specific local detail feature that we're all concerned
17 might have played a significant role in the failure of
18 the accident aircraft, so we're trying to take the
19 information from the global structural analysis, feed
20 that as the loading conditions and banner conditions
21 into the local analysis and try and get a much higher
22 fidelity understanding of what might have happened in
23 that set of lugs.

24 We're pursuing flutter analyses because when
25 we started thinking about building or populating the

1 fault tree, we realized that there could have been an
2 aeroelastic instability that one of our colleagues at
3 Langley turns out to be a flutter expert, so of course
4 he looks for flutter problems. But in the process of
5 interrogating what he saw, it seemed logical that we
6 would want to consider that.

7 The computational fluid dynamics, or CFD
8 analyses was an attempt on my part to make sure we had
9 as accurate a cord-wise pressure distribution at any
10 point along the span of the fin, so that from a
11 structural point of view, when we applied whatever that
12 pressure distribution might be for whatever attitude
13 the aircraft was in at any given time, we could
14 determine if the center of pressure was moving forward
15 or aft of the elastic axis of the fin which would then
16 affect the way the fin itself would deform.

17 Structural tests we're conducting or planning
18 to conduct in order to support our hypotheses having to
19 do with how things might have failed. So we have a
20 number of notions, all of us collectively, of what
21 might have happened, and we're going to depend on our
22 analytical tools and our experimental methodologies to
23 confirm or deny that some event did in fact occur the
24 way we thought.

25 May I have the next chart, please? This is a

1 very high level form of the fault tree analysis that we
2 put together for this particular investigation. The
3 notion is that the vertical fin failed. The question
4 is why? On the left hand side of this figure, we have
5 a -- is there a pointer that I could use --

6 MR. MURPHY: Maybe under the piece of paper
7 there. I thought there was a silver pointer. Somebody
8 had used it the other day.

9 DR. STARNES: Is that what this is?

10 MR. CLARK: We either need to bring it up on
11 his computer --

12 DR. STARNES: Will it work off that screen?

13 MR. CLARK: Whichever one it works to.

14 MR. MURPHY: Is there someone who can tell
15 us?

16 DR. STARNES: Well, I'll just speak it this
17 way. If you look at the line right below the vertical
18 fin figure, there are two boxes there. One says fin
19 capabilities less than expected. Then the
20 corresponding box on the right would be fin loads
21 greater than expected. These are two logical
22 conditions that we feel could have led to this event.

23 Now once you get into one of these higher
24 level boxes on a fault tree, recognize that under these
25 there are several tiers of additional types of

1 questions that would lead to trying to understand what
2 might have happened that would be associated with the
3 fin being less than expected, or the fin loads being
4 greater than expected.

5 So what you see here is really that high
6 level branch of a tree, now think about a second level
7 below that and another level below that, and there
8 might be ten to 20 lower level questions that we're
9 pursuing for each of the boxes that you see on this
10 chart. Now the way that the chart came about was I was
11 asked by the NTSB to introduce some of the NASA fault
12 tree analysis technology into the investigation, and
13 when I explained how we went about doing, using such a
14 tool to Mr. Murphy and Dr. Ilcevice, they both came up
15 with what they thought would be a good way to start
16 thinking about it, and after the three of us got into a
17 discussion about it and we got to a straw man,
18 primarily put together by Dr. Ilcevice, we shared that
19 with the NTSB structures group where all the parties
20 involved were represented -- American Airlines had
21 people there, Airbus did, and we started in our own
22 group, began to think, well, what could have happened
23 here? What could have happened there? What would we
24 have to do to answer the question did this or that
25 occur?

1 As a result we ended up with that very large
2 number of issues that we each agreed had to be
3 addressed in some fashion. Now some of them are not
4 quite so complicated. In this particular application,
5 the column on the left there, fin capability less than
6 expected, is something that we at NASA have to address
7 quite often in our advanced vehicle prototype
8 developments. Quite often these are one of a kind type
9 vehicles. They were not fabricated and assembled using
10 production line methodologies, whereas in an aircraft
11 like the flight 587 vehicle, that was one that had been
12 in production for a while and there was a basis for
13 believing that Airbus, indeed, knew what the material
14 properties were, indeed they knew how to process the
15 material. That's not always true with some of the NASA
16 experiences.

17 Nonetheless, we went through that same
18 logical process of addressing each one of these kinds
19 of questions and at some point in time there will be a
20 definitive statement that says this box is closed or
21 disposed of because of this objective study that was
22 done by some number of people within the structures
23 group.

24 Now there are interfaces between what we do
25 in the structures group, the flight data recorder

1 group, the systems people, the human factors folks, the
2 performance group, so what this represents is just the
3 piece that we felt was important to study the
4 structure's activity.

5 If this were in color you would see that
6 there 's some green things here and here, which tend to
7 have to do with how was the vehicle maintained. Was
8 there anything that had been discovered in service that
9 would, in some fashion, affect the way the structure
10 might perform? Well, that would be a task more suited
11 for American Airlines, since they maintained the
12 aircraft.

13 There were other activities, such as the wake
14 vortex or turbulence box here where we would depend on
15 people like Dr. Proctor, whom you heard the other day,
16 to provide for us some of the non-structures related
17 activities. Dr. Proctor comes from an aerodynamics
18 community where they deal with wake vortices and those
19 kinds of questions, and then we would then look upon
20 that as some kind of effect on the external loads.

21 Rather than going over each -- did you want
22 me to go over each one of these boxes?

23 MR. MURPHY: No, that's not necessary, Dr.
24 Starnes..

25 DR. STARNES: There's a definite link between

1 what happens in stability and control, but we would
2 need input from another group working on the
3 investigation to tell us whether or not there would be
4 some influence on what happened to the structure. This
5 would then lead us to an anticipation of understanding
6 how the loads might have been greater than expected, if
7 in fact that's what we come to.

8 I mentioned flutter earlier. When our
9 aeroelastician looked at the failed parts, it was a
10 particular signature that he recognized as something
11 that's representative of a certain kind of aeroelastic
12 phenomenon, so we added it to the box and it will be up
13 to Dr. Edwards at Langley to say I can't justify that
14 there was a flutter problem, or there is. So there's a
15 way we go through this rational process.

16 May I have the next chart please? This is a
17 summary of the activities that we're doing in our
18 global fin and rudder structural analysis. Now the
19 first thing we did was to try to get an understanding
20 internal to NASA of what Airbus did to certify the
21 part. How was the structure designed in the sense that
22 if you compare any of the local stresses, let's say,
23 with what you might, in the United States, might refer
24 to as a design allowable stress, how much margin of
25 safety, or in the Airbus language, what is the reserve

1 factor that would be associated with any of these
2 critical points in the structure under given loading
3 conditions?

4 So we went through all the drawings. We were
5 fortunate in that we were able to obtain the Airbus
6 finite element (ph) model, so we were using the exact
7 geometry that Airbus used in their design and in the
8 studies they're performing under the investigation. We
9 went through the process of understanding the
10 assumptions that were made to put together the finite
11 element model. We contrasted that with what we saw in
12 the strength justification documents, and we started
13 using that model as modified by us to suit our
14 interests, to start to look at the full scale test
15 correlation documents as well as the other response
16 phenomena we were concerned of.

17 So after we had gained an understanding of
18 the model, the way Airbus designed the aircraft, the
19 reserve factors that were part of it, the correlation
20 between the certification tests and what we were able
21 to interpret from the analytical methods, we began to
22 wonder what would happen if we would take that model
23 that we now believe we understand, and use that model
24 to begin to interrogate what would happen if some
25 feature had a failure initiation event that eventually

1 propagated in such a fashion that we would have a
2 sequence of events, say lug -- the right rear lugs
3 failed, perhaps, that led to the failure of the center
4 lug, that led to the failure of the forward lug. So we
5 would go through a process of studying these sequences
6 that would then let us understand which failure
7 scenarios we think we can support as most likely have
8 happened.

9 There were a number of failure scenarios that
10 were developed by the structures group as we were
11 putting together the fault tree, so now the question
12 is, can we support or dismiss any of those scenarios as
13 being most likely to have occurred? And we'll use
14 these analytical tools to allow us to interrogate some
15 of the questions associated with any given scenario.

16 We reviewed the aerodynamic load definitions,
17 made sure we understood how the loads were being
18 derived and applied. We went through the process of
19 comparing the linear analysis methodology that came
20 with the Airbus model, with our own non-linear methods.

21 For us the non-linear analysis methods are important
22 because they help us understand the way the damage or
23 failures can progress through the sequence of events,
24 and they also allow us to account for phenomena such as
25 local buckling in a skin.

1 As you allow the pristine, or the original
2 state of the structure to be changed by assuming that
3 some part has failed, what happens is you change the
4 internal load distribution in the structure, and in the
5 process of changing the internal load distribution,
6 it's possible to activate other failure mechanisms or
7 response phenomena like a buckling phenomenon that you
8 may not have assumed to have happened if you were in
9 the design envelope.

10 We were using these analysis tools to help us
11 identify any location anywhere on either the fin or the
12 rudder, that we think would then merit much more
13 detailed examination and we would put together a much
14 fidelity analysis to try to interrogate some phenomenon
15 associated with the broken pieces that we've seen in
16 one of our laboratories.

17 I've already mentioned buckling. It's my
18 understanding that for a wing surface like a vertical
19 fin, you would design to be buckling-resistant at limit
20 load, at some place between limit and ultimate load,
21 you might find buckling occurring. This is not a bad
22 thing if you're accounting for it properly. Since this
23 aircraft saw loads greater than the design ultimate
24 load conditions, I have to assume that buckling could
25 have occurred. If buckling occurred, it would change

1 the internal load distribution in the structure, and
2 that could activate other failure mechanisms.

3 We were, at one time, concerned about the way
4 the fin would bend as it's being activated, say, from
5 plus ten degrees to minus ten degrees. When the fin
6 was bent over, would that create some interaction
7 forces at the hinge lines that might explain some of
8 the failures that we saw in the rudder itself. So we
9 began that interrogation. We introduced local failure
10 effects in specific locations that were consistent with
11 the failed pieces we've seen, and we understand how
12 those local failures might affect the rest of the
13 structure.

14 We use the global analysis results to provide
15 us with the local loads that should then be applied to
16 a much higher fidelity analysis model, so not only is
17 it an analysis tool itself, but it's used to provide
18 information necessary to study things at a much higher
19 fidelity of local detail.

20 We're also using this model to conduct modal
21 analyses in addressing this issue of flutter that I
22 mentioned earlier. One of the ways one does that is
23 you use the natural modes of frequency of the structure
24 as generalized coordinates that you would then use on a
25 flutter analysis, so we would then use a model that

1 will allow us to determine the natural vibration
2 frequencies and their associated modes to provide that
3 input into a flutter analysis.

4 Now, in addition, this global model is, in
5 our mind, very central in allowing us to help guide any
6 test or experimental work that's done. The issue here
7 would be if the fin failed as a result of being loaded
8 beyond its design envelope, what are the loading
9 conditions we would have to then apply to a structural
10 test specimen to verify that, in fact, the failures
11 that we see in the failed parts are in fact generated
12 by the kind of loads that we would apply that are
13 consistent with whatever the external load condition
14 is. So a lot of the test specimens will be modeled by
15 us and Airbus. They will be analyzed and we will use
16 the results of those analyses to determine what the
17 instrumentation patterns ought to be and whether or not
18 we can, in fact, replicate some of the failures that we
19 see on the broken parts.

20 May I have the next chart, please? This is
21 an example of the Airbus finite element model that
22 we're working with. I think Mr. Vinkler (ph) showed
23 you this during his testimony, so I won't dwell on it.

24 Next chart, please? This summarizes some of
25 the activities that we're currently engaged in in

1 trying to understand what happened for the lugs when
2 they failed. To do that we've interacted with Airbus.
3 We've taken advantage of a three dimensional lug model
4 that they put together. We have that at NASA Langley,
5 and we're using that as our starting point to try to
6 understand the response and failure characteristics of
7 a lug subjected to the loads that we believe were
8 applied during the failure of the fin. And we get
9 those loads from the global analysis.

10 In working with this process we feel that we
11 would want to be able to interrogate failure
12 initiation, as well as failure propagation as we start
13 to initiate the local failure event. This would then
14 propagate across whatever piece -- and it may have
15 propagated in a very, very rapid fashion until it
16 finally breaks apart. To do that we need to have the
17 ability to work in progressive failure analysis, and
18 that is a very computer-intensive process, so we're
19 trying to develop approximate models that would give us
20 the same physical behavior as the complete three
21 dimensional model, but with a much coarser model. In
22 doing that you, of course, have to understand the
23 assumptions and the approximations that you make in
24 changing anyone's model so that you don't add some
25 artificial behavior characteristics. And we've gone

1 through studies that will allow us to understand how to
2 homogenize various layers of the shell model itself, so
3 that we could then come up with an accurate
4 representation at a somewhat coarser level.

5 In addition, we're looking at some of the
6 more traditional layered shell models that would allow
7 us to study some of the delamination phenomena that may
8 have occurred. Again, it's the sort of thing that you
9 develop a model, it's based on assumptions and
10 approximations. You have to make sure that you're in
11 direct correlation with some of the other models that
12 are being developed. So anything we do in the sense of
13 changing the notion of a three dimensional model is
14 always done with the notion that we're going to use the
15 analysis results and make sure that they're not
16 inconsistent with what we see from other models or
17 tests.

18 Once we've got to the point where we believe
19 we've got the right local detailed three dimensional
20 models, then we want to start interrogating the various
21 failure events that we've seen. For example, when the
22 global model is bent over hard due to the external
23 pressure associated with any of the rudder and side
24 slip angles, the fin is still attached -- I mean if the
25 rudder is still attached to the fin, the rudder is also

1 going to bend with the fin, and that can put some high
2 compression or tension loads in the rudder itself that
3 we want to interrogate with local models.

4 As far as evaluating the certification
5 analysis used for the lug, we can do that by doing our
6 own independent analyses and comparing with the Airbus
7 results. We would also use this local analysis to help
8 us model and understand the test specimens that would
9 be used, as well as the global models.

10 Having gone through this process for the
11 right rear lug and gotten to the point where we
12 understand how whatever results we can derive from
13 these analyses, we would then interrogate the other
14 three lugs -- and three here means we want to look at
15 the forward lug, the center lug -- but the center lug
16 also has a repair added, so we can develop a similar
17 model that would allow us to interrogate what happens
18 as a result of repairing this center lug, so we
19 contrast the pristine center lug with a repaired center
20 lug. We can gain insight into what the repair might
21 have done in the way of affecting the behavior.

22 May I have the next chart, please? This is
23 an example of the local, three-dimensional model. This
24 particular one came from Airbus. There's a lot of
25 detail features not shown here, just so you can look at

1 the level of fidelity that was used to represent all of
2 the complex changes in shape and contour associated
3 with the way the lug is designed.

4 Next chart please. In the flutter analysis
5 work, we are trying to identify any potential flutter
6 modes that might be associated with either the fin or
7 the rudder or a combination thereof, including limit
8 cycle oscillation, which is a form of a dynamic
9 response characteristic. We want to assess and conduct
10 flutter analyses, both at Airbus and at NASA, and then
11 the aeroelastician is working with us and has a working
12 rapport with his counterpart at Airbus and they're
13 comparing things, just like the static structural
14 analysis folks have a working rapport with the Airbus
15 counterparts, and we're always comparing results to try
16 to help better develop understanding.

17 Depending on what we learn about the external
18 pressure distributions, if we find out that there's any
19 kind of a leading edge separation, this might excite
20 another kind of a flutter phenomenon that would be
21 associated with leading edge separation. So these are
22 all being interrogated.

23 Next chart please. The CFD pressure
24 distribution analyses that we're involved in. We're
25 using an unstructured mesh three dimensional knobby

1 (ph) or Stokes analysis that was developed by some of
2 the aerodynamicists at Langley, and we're using that to
3 develop a pressure distribution associated with several
4 of the points during that last eight seconds of flight.

5 We used our CFD results to compare them with the
6 Airbus pressure distribution to make sure that we have
7 a consistent understanding of what that external --
8 external forces might have been.

9 Once we develop the external pressure
10 distributions from a competition fluid dynamics
11 analysis, we then have to map the results from the CFD
12 analysis, which is usually different from the
13 coordinate system used in a structural analysis. So we
14 have to map the pressures from one coordinant system
15 used in fluid mechanics to the one that's used in
16 structural mechanics. Once we do that, then we just go
17 ahead execute the structural analyses.

18 Next chart, please. Ah, didn't show up.
19 Well, imagine a fin with about a billion grid points
20 around it, and that's what we use to study the -- or to
21 determine what the aerodynamic pressures might be.

22 Next chart, please. In our structural tests
23 planning, our objective is to conduct whatever tests we
24 think are appropriate that will allow us to confirm
25 that failure is possible for the accident loading

1 conditions. Can we replicate some of the failure
2 events that we see on the damaged structure. We
3 certainly will use analyses to try to predict that, but
4 the physics of the problem is embodied in the
5 experimental tests that we run. So if we try to
6 represent the physics of the accident, having a well
7 thought through test program will allow us to confirm
8 without doubt that we understand what happened.

9 We use the test results to validate the
10 failure modes that we observed in the accident
11 aircraft. We'll also use the test results to help us
12 verify both our global and our analytical models that
13 we're using to support the investigation.

14 Currently, the focus of the structures group
15 test activities is on coupons and element tests that
16 are removed from the accident vertical fin and rudder
17 to help interrogate the strength properties and the
18 mechanical properties. This is one of the things on
19 the fault tree where we wondered -- have the mechanical
20 properties or any of the strength properties been
21 degraded over time?

22 We're also focused on conducting a
23 subcomponent lug test. We have available to us -- we
24 being the structures group -- has available to us a
25 pristine right rear lug from another part that Airbus

1 had, and we'll use that part to interrogate the failure
2 mechanisms that we observed in the accident aircraft
3 right rear lug. So this is a very careful process of
4 trying to replicate those failure mechanisms.

5 As we go through this, if we find that we
6 need additional tests to help answer questions, then we
7 would recommend those to the NTSB to do that.

8 Next chart, please. This is the list of some
9 of the other structures and materials support that
10 Langley has provided. We did an in depth photographic
11 study. We recorded everything that we could see that
12 might have either failed or could have affected the
13 response or failure characteristics of the fin. And
14 we've mapped all of those photographs into a catalog of
15 failure sites and related them to various parts of the
16 structure.

17 Yesterday, you heard Dr. Winfer's (ph) report
18 of his in depth, non-destructive evaluation survey, so
19 we've done that. There's been fractographic analyses
20 done on both the failed metallic parts, the hinges, the
21 fasteners, as well as the failed composite parts. Dr.
22 Reeder told you about some of those results this
23 morning.

24 We've conducted, or are in the process of
25 conducting, mechanical property tests on the composite

1 parts to study the mechanical properties, of course,
2 but we've also conducted independent chemical analyses
3 of the composite parts that would then tell us whether
4 indeed the part cured the way it should have, it hasn't
5 degraded over the 13 or 14 years of service, and the
6 organic chemist that does this at Langley has been
7 interacting with Mr. Rachers who gave you his report
8 yesterday, and we agree that there has not been any
9 degradation of the material system.

10 And I think that's my last chart, so I'll
11 stop it at that.

12 FURTHER QUESTIONING OF DR. STARNES

13 BY MR. MURPHY:

14 Q Have the results of your finite element
15 analysis at both the global and the local level correlated
16 well with what you've received from Airbus to date?

17 A Yes. For the linear analyses that Airbus has
18 conducted, we've pretty much replicated their results
19 at both the global level and as well as the local,
20 right rear lug 3-D finite element analysis results. So
21 we find no concern with the model they put together.

22 Q I had a bunch of other questions here, but I
23 think your presentation brought out most of them. But
24 do you agree with the fundamentals behind the no-growth
25 concept and its suitability for its use in the aviation

1 industry?

2 A Yes. I think that's a very conservative
3 approach where we are working with materials systems
4 where we have to accept that there may be an internal
5 flaw, however it gets there, either during production
6 or service. If that flaw is below a certain size, it's
7 determined to be critical in the sense that it could
8 propagate, then we would assume that the design is safe
9 at ultimate load with that flaw, as long as we can
10 assure that it will not grow. So we put a no-growth
11 criterion on the flaws that we cannot detect or cannot
12 see, and accept that we can demonstrate by tests that
13 the concept of no-growth can be indeed verified by --
14 with a structure with a flaw in it.

15 Q Dr. Starnes, I've come to understand why NASA
16 Langley is considered a national resource over the last
17 year in the area of composites during the course of
18 this investigation, and I personally would like to
19 thank you and Langley's help and guidance in an area
20 where the wealth of information and data generated
21 within major manufacturers is currently not shared with
22 the general public and the rest of us when we need to
23 approach these types of problems. So, thank you.

24 A Thank you for having me.

25 MR. MURPHY: Madam Chairman, I have no

1 further questions.

2 CHAIRMAN CARMODY: Alright, are there other
3 questions from the technical panel this morning?
4 Seeing none, moving to the parties, then. I'll start
5 first with American, Mr. Ahearn, any questions for Dr.
6 Starnes?

7 MR. AHEARN: Just two quick topics, Madam
8 Chairman.

9 BY MR. AHEARN:

10 Q Dr. Starnes, I know you were in the audience
11 yesterday and you've heard that the lug would be the
12 failure point --

13 A Well, we consider it as a potential failure
14 point. We're trying to interrogate it and make sure
15 that that's, in fact, true.

16 Q Okay, with that, and your experiences, would
17 you describe the differences between how a metal fin
18 attachment lug assembly and how a composite assembly
19 attachment point would fail?

20 A I haven't really studied the metal part for
21 this Airbus aircraft, so I really can't make a direct
22 comparison for you.

23 Q Have you looked at any other assemblies that
24 would attach with a metal lug versus a composite lug?

25 A No.

1 Q Any other manufacturers?

2 A No.

3 Q One other question. Is the flutter analysis
4 -- do you have a timeline as to when you anticipate
5 that will be complete?

6 A Well, as soon as possible is usually the
7 answer we give, but there's a -- I prefer to come up
8 with an answer that we believe to be correct, rather
9 than say American Airlines wants the answer yesterday,
10 therefore give me an answer.

11 Q This is something that some people have had
12 an interest in, and I was just looking to see if you
13 had an idea, and if you don't that's fine. Again,
14 thank you for your time and thank you for your work on
15 this investigation.

16 A Thank you.

17 MR. AHEARN: That's all my questions, Madam
18 Chairman.

19 CHAIRMAN CARMODY: Thank you. Allied Pilots,
20 Captain Pitts, any questions for Dr. Starnes?

21 CAPTAIN PITTS: Thank you, ma'am, just a few.

22 BY CAPTAIN PITTS:

23 Q Sir, very complex subject and our
24 appreciation for your hard work there. You mentioned
25 there's much work to be done -- and a couple different

1 areas. Can you give us an idea of what percentage you
2 think might have been completed to date in the various
3 fault tree analyses that have taken place?

4 A No, I can't give you a percentage, but you
5 know a lot of the issues that we were concerned about
6 initially are systematically and methodically being
7 addressed and dispatched. At this point I would say we
8 don't have a problem with material degradation over
9 service time, so all the boxes in the fault tree that
10 would be associated with that would be closed based on
11 some hard, objective interpretations of what the data
12 show from the tests that are being done.

13 The structural analysis, we're just beginning
14 that, quite frankly, so that will take us a while to
15 say that failure event there did or did not contribute,
16 so we'll go through that process. The structural tests
17 that would interrogate some of the questions in the
18 fault tree, they're just beginning.

19 Things like the wake vortex encounters that
20 Dr. Proctor described for you -- that's as complete as
21 it can be until someone changes some meteorological
22 condition that would then affect his result. That's
23 also true for the CFD analyses. You know, we've
24 proceeded with the notion that we understand what are
25 the critical rudder angles and side slip conditions.

1 Whether we find out we had those off, then we would
2 have to go back and reinterrogate those.

3 So its as we get into the process we begin to
4 decide that the work that we have done to date is
5 indeed as much as needs to be done, or we might decide
6 we have to redo it. I can't say ten percent, 50
7 percent, 30 percent, whatever. It's just, we're
8 working at it.

9 Q Alright, sir, and I appreciate that because I
10 understand your commitment to find the answers -- the
11 correct answers. You've been at it almost a year now,
12 and I know you're familiar with Gant (ph) charge.
13 Would you even endeavor to make up an estimate of where
14 we might be on a timeline?

15 A No.

16 CAPTAIN PITTS: Alright, sir, thank you very
17 much. I have no further questions.

18 CHAIRMAN CARMODY: Airbus, Dr. Lauber?

19 DR. LAUBER: While I have no questions for
20 Dr. Starnes but if I could be permitted a general
21 observation with regard to NASA's contribution to the
22 investigation. I think they've done outstanding work
23 and we appreciate what they've done.

24 DR. STARNES: Thank you, sir, for your kind
25 words.

1 CHAIRMAN CARMODY: Thank you. Faa?

2 MR. DONNER: Thank you, ma'am.

3 BY MR. DONNER:

4 Q Dr. Starnes, just one question, and you gave
5 us some fascinating information here and I think you've
6 teased us waiting for the exciting outcome of your
7 work. At the end of the day, when you do have all of
8 your work put together, will you be giving us a most
9 likely scenario for the failure of the tail?

10 A Well, we'll give you what we think it will
11 be. I'll use as an example -- I was on the failure
12 investigation team for the X-33 liquid hydrogen tank
13 failure, and we went through this same fault tree
14 process and we had hundreds of boxes, and when it was
15 all over with, we ended up with nine features on that
16 fault tree that we felt could have contributed. So it
17 may be that we don't have a single most likely. We may
18 have three or four that could have, in a combined,
19 interactive effect -- method, affected the system. So
20 it may not be just one thing. It may be two or three.

21 Q Thank you --

22 A But that's what we hope to end up with, yes.

23 Q Thank you very much, appreciate it.

24 A You're welcome.

25 CHAIRMAN CARMODY: Going to the Board

1 members, any questions from Member Hammerschmidt?

2 MEMBER HAMMERSCHMIDT: Well, like Dr. Lauber,
3 no questions, but I would like to thank you, Dr.
4 Starnes for your informative presentation this morning
5 and for the work that you and the others at NASA
6 Langley have been involved in, assisting us, and of
7 course I also commend Dr. Reeder on his presentation
8 this morning. And Dr. Starnes I've noticed that you've
9 been in attendance throughout what -- all of this
10 public hearing?

11 DR. STARNES: Yes, that's correct.

12 MEMBER HAMMERSCHMIDT: Every minute of it, I
13 believe, and so I want to thank you for your interest
14 and your attentiveness to the work of our
15 investigators. Thank you very much.

16 CHAIRMAN CARMODY: Good point. Member
17 Golgia.

18 MEMBER GOGLIA: Just a ditto for that.

19 CHAIRMAN CARMODY: Member Black?

20 MEMBER BLACK: It's clearly the result of his
21 undergraduate education, where he received it.

22 CHAIRMAN CARMODY: Where could that have
23 been, I wonder. Is there anything further for this
24 witness from the technical panel? Or from any of the
25 parties?

1 MR. AHEARN: Madam Chairman?

2 CHAIRMAN CARMODY: Mr. Ahearn.

3 MR. AHEARN: I'm sorry, not a question for
4 Dr. Starnes, but to the issue of doing some research on
5 the metal fin attachment assemblies that other
6 manufacturers use. I'd just urge the Board to continue
7 to work with NASA to see if we can discover something
8 with that.

9 CHAIRMAN CARMODY: Thank you. Dr. Starnes,
10 let me add my thanks for your testimony. It's been
11 very informative and it's always difficult to be the
12 last of a three and a half day hearing, but we
13 appreciate your patience and that of all of the NASA
14 people who testified.

15 DR. STARNES: Thank you.

16 CHAIRMAN CARMODY: We'll now excuse this
17 witness.

18 (The witness was excused.)

19 CHAIRMAN CARMODY: I have some very, very
20 brief closing remarks as we wrap up the hearing. I
21 wonder if any of my colleagues would like to say
22 anything before we close out? Member Hammerschmidt --
23 you've said it all, I think. How about you, Member
24 Goglia? Alright.

25 MEMBER HAMMERSCHMIDT: I would -- of course

1 like to give a special thanks to not only the witnesses
2 for all their cooperation and responsiveness during
3 this public hearing, but also to the parties whose
4 input and wealth of expertise is essential for the
5 completion of this investigation. So, thanks to all
6 involved in this public hearing.

7 MEMBER BLACK: Well, I was going to thank the
8 staff too because we've had some brilliant people
9 talking to us on the left side here, and there were
10 some brilliant people on the right, and as always I
11 thank them for their efforts.

12 MR. CLARK: On that note, I especially want
13 to note Lorenda Ward, the Hearing Officer. I think
14 this has been one of the smoothest run hearings that
15 we've had in a long time, certainly on the aviation
16 side.

17 MEMBER BLACK: I'd like to ask her when the
18 final witness list is going to be out?

19 CHAIRMAN CARMODY: Ms. Ward is a very
20 flexible person. I'm sure she can reproduce one in a
21 matter of minutes, as she has been doing for several
22 weeks now.

23 Well, thank you all. First I want to
24 emphasize that this investigation will remain open at
25 any time to receive new and pertinent information that

1 may come up.

2 The Board may, at its discretion, reopen the
3 hearing in order that such information may be made part
4 of the public record.

5 In my opening statement I assured the family
6 members of those who lost loved ones on flight 587 that
7 the Safety Board will pursue every lead in search of
8 answers for the cause of this tragedy, and I hope this
9 hearing has given them some idea of the meticulousness
10 and the thoroughness of this process.

11 Our investigation is eleven months old now,
12 and so far we've issued two safety recommendations to
13 the FAA which were discussed in the hearing. This week
14 we released 3500 pages of documentation to the public
15 record. Much of the documentation is available on our
16 website which I will note again as www.nts.gov, and
17 all of the documentation is available to the public on
18 CD ROM.

19 As important as it is for us to find the
20 answers on behalf of the families of this tragedy, our
21 mission is substantially broader. We pursue causes of
22 such tragedies for the millions of people who fly
23 transport category aircraft every day. I can assure
24 those travellers that if we ever find an element of the
25 aviation system that needs safety improvement, we will

1 move quickly to issue other recommendations to deal
2 with them.

3 I know the inevitable question is when will
4 we complete the investigation, and I wish I had an
5 answer today. I do not. I never like to speculate. I
6 think the earliest would be this spring some time.

7 On behalf of the National Transportation
8 Safety Board, as my colleagues have reflected, I do
9 want to thank all the parties to this hearing. I know
10 it's been difficult. It's been a major commitment of
11 people, resources, expertise and patience, and you have
12 my thanks. You've all been very pleasant to work with.

13 I'd like to thank again, all the witnesses who have
14 been so forthcoming with their knowledge, and of course
15 the staff. They have put in really wonderful effort
16 for the past several months on this, and it's all, I
17 think, borne fruit this week. So my thanks to
18 everyone. I won't enumerate you all because there are
19 some who aren't here that also contributed, but you
20 have our thanks and our gratitude.

21 The record of the investigation, including
22 the transcript of the hearing and all Exhibits entered
23 into the record, will become part of the Safety Board's
24 public docket on this accident, and will be available
25 for inspection at the Board's headquarters. Anyone

1 wishing to purchase the transcript -- and that goes for
2 the parties as well -- may contact the court reporter
3 directly and make your arrangements.

4 I now declare the hearing to be in recess
5 indefinitely. Thank you all.

6 (Whereupon, at 9:54 a.m., the hearing in the
7 above captioned matter was recessed indefinitely.)