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On behalf of the Federal Aviation Administration:

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P R O C E E D I N G S

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.

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

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

Q Thank you, Dr. Reeder.

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

CHAIRMAN CARMODY: Thank you. Please go ahead.

BY DR. FOX:

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

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

PRESENTATION BY DR. REEDER

Composite fractures complex. That is, it's generally messy and interpreting fracture surfaces is not an exact science. The way this generally works is researchers go into the laboratory and create a fracture surface under a very controlled situation, look at the fracture surface and try and look for unique features on that fracture surface that they then identify with that form of failure.

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

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

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

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

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

To go through this, I will look at different combinations of these factors. For instance, the first fracture surface I will look at is fiber failure in the translaminar direction under tensile loading and a static failure. This type of failure is generally characterized by radial markings on the fracture surface of the fiber. When a fiber fails in tension, it is often initiated by a surface imperfection. The crack then grows across the fiber, across the fiber, leaving faint radial markings. And this directionality to the fracture is a very good indication of the fracture direction on that fiber, but it may not be a good indication of the overall fracture direction because these failures are often heavily influenced by where the imperfection happened to be around the circumference of the fiber.

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

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

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

Same type of failure, but we've changed the loading. We load the fibers in compression. This type of fracture is often characterized by chalk marks, that is, these lines on the fiber surface. These lines on the surface are created because when we push on a fiber in compression, the fiber doesn't actually fail in compression, it fails in buckling. When the fiber buckles, as you can see in these pictures, this picture, it bends. When the fiber bends, one surface of the fiber will go into tension, the other side of the fiber will go into compression. The change from tension to compression creates the line on the fracture surface.

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

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

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

On the same fracture surface, still failing fibers, but if you put the structure in bending, just as with the fiber, one side went into tension, one side went into compression. The same thing happens in the structure, and so you can see a compression failure on one side, a tension failure on the other, and you see this line between in this transition from tension to compression. It's characteristic of a bending failure.

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

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

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

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

Changing planes once again. This is delamination. This is interlaminar fracture, so we are breaking the composite between the layers of the plies. To make things a little more complicated, usually when we talk delamination, we no longer talk tension and shear, we talk mode I and mode II, that is a fracture mechanics terminology. Mode I is analogous to tension. You're pulling the crack faces open. Mode II is a shearing type action, where you're shearing the faces over each other and Mode III is also a shearing type action, but it is a scissoring action.

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

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

The hackles are formed because you are putting the matrix between two plies in shear. When you put the matrix in shear ahead of the crack tip, small matrix cracks will open up in a tension direction. These matrix cracks cannot grow easily into the ply because they're stopped by the fiber, so with increased load, a new matrix crack will open up, and another matrix crack. With continued loading, these matrix cracks will finally join up and they'll join up generally close to one fiber or another, and finally you can grow this crack all the way across the structure. If you open up the structure and look at the face, you're therefore left seeing these platelets of fibers which have been compared to shingles on a roof, existing between impressions of fibers. These plates of matrix are what we call the hackle, and they generally indicate a shearing force on the surface, opposite to the direction of the lean of the hackles.

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

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

We also can look at -- for evidence of fatigue on these delamination fracture surfaces, and that can come in many different forms. The first one, we call matrix rollers. These features are caused by rubbing of the surfaces. When you rub the surface, the hackles can break off and can be rubbed down into these cigar shaped features that are called matrix rollers.

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

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

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

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

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

BY DR. FOX:

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

So I guess for stepping through, first I'd like to discuss the fractures through the thickness, across the fiber layers on the right side of the vertical stabilizer. So, in your review of the fractographic examination of these longitudinal attachment lugs, could you describe the general features observed on the translaminar fracture surfaces on the right side?

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

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

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

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

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

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

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

The fracture on the rear side of this lug, that is the area marked by RF2(a) was slightly more complex. You have translaminar fracture happening at several different planes due to thickness, and these planes were connected by delaminations to make a complete fracture path.

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

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

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

On the center lug, you see this fracture -- page 19, Figure 41 -- this was a much cleaner fracture. It again failed, translaminar fracture, cutting fibers, and again this failure occurred at the row of rib one fastener bolts, and the general direction of growth was from the front towards the rear. This translaminar fracture also had an area of compression near the outboard side, which could indicate a bending on this lug. You will notice that this lug was the one that had been repaired during the manufacturing process, so you might be able to see all the additional fasteners above and below the rib one fastener, but the fracture occurred through the rib one fastener bolts.

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

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

A Page 21, Figure 45. There you go. Again, a wedge of material became detached in the lower section on the left front lug created by the translaminar fracture.

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

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

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

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

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

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

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

Q -- or necessarily the order of --

A Yes, right.

Q But it's the easiest way to describe the fracture path, --

A Which is very complicated.

Q -- that allows that to completely separate.

A Yes.

Q Okay.

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

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

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

Q Can we pull up the lower figure?

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

In general, the delaminations, particularly these larger delaminations, wherever we found them, almost always occurred at an interface between the zero degree tape and a plus or minus 45 degree weave layer. Those interfaces occurred at different points through the thickness of the structure, and the delamination almost always found one of those interfaces to run along.

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

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

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

What we did notice on the delamination fracture surface is that optically, in these areas, there tended to be -- they appeared to be tan or deep red in color in these pockets, and sometimes these -- that coloration was more prevalent than in other places, particularly higher on the lugs, particularly the left front lug -- this tannish color in these pockets became more evident.

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

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

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

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

A As I said, fractography is not an exact science. It does not provide definite answers. It provides clues. To back up the clues that we form by looking at the fracture surface, we generally would want to do mechanical analysis, structural analysis, to make sure that the types of failures that seem to be indicated by the fracture surface actually make sense for the structure, for the material.

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

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

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

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

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

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

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

BY DR. KUSHNER:

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

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

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

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

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

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

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

CHAIRMAN CARMODY: Alright, Allied Pilots, Captain Pitts?

BY CAPTAIN PITTS:

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

A Each failure event is different, and so that's a relative term. I'm not sure how to answer it. These were complex failures and you take the different parts as best you can. Certainly I've seen areas where you create multiple delaminations that -- when you put something in compression, and a bending would have put that side into compression.

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

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

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

CHAIRMAN CARMODY: Alright, Airbus. Dr. Lauber?

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

CHAIRMAN CARMODY: American. Mr. Ahearn.

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

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

MEMBER BLACK: Just a couple, thank you. Certainly one of the best presentations we've seen. I wish you were teaching somewhere, you have the flair for it, and conveying information.

BY MEMBER BLACK:

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

A You always want all the information you can get.

Q You always want everything, yes.

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

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

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

CHAIRMAN CARMODY: Dr. Reeder, the

microphone, please.

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

BY MEMBER BLACK:

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

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

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

A Again, that's in the design realms, and I wouldn't be comfortable speaking to it.

MEMBER BLACK: Fair enough. Thank you very much.

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

THE WITNESS: Thank you.

(The witness was excused.)

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

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

Whereupon,

DR. JAMES STARNES

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. Starnes, could you please state your full name, your present employer, and your business address?

A My name is James Herbert Starnes, Jr. I work for the NASA Langley Research Center in Hampton, Virginia 23681.

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

A I am currently the chief engineer for structures and materials, which is also known as the senior engineer for structure and materials competency. I have been in that position for a little over years. I'm sorry, did you have another question?

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

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

My educational background is I have a Bachelor of Science degree in engineering mechanics, and a Master of Science degree in engineering mechanics from Georgia Institute of Technology, also known as Georgia Tech. I also have a Ph.D. in aeronautics, structural mechanics option from the California Institute of Technology, also known as Cal Tech.

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

Q Thank you, Dr. Starnes.

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

CHAIRMAN CARMODY: Please continue.

BY MR. MURPHY:

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

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

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

This led to, in the very early 70's, a period of time where we would begin to think about how to introduce composite structures into transport category aircraft. The way we began that was to begin studying the application of these material systems for things like ferrings, control surfaces, what we typically thought of as secondary structures. We would work with industry to develop the design for whichever these components were interested in, do ground tests, flight tests, gain practical experience in service with airline operators.

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

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

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

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

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

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

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

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

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

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

I mentioned having two strings of research activities, one basic research, one focused on technology research -- it's more applied. It was in one of our early basic research programs that we became involved with the notion of the effect of low speed impact damage on compression strength. That's one of these phenomena where we wondered what would happen if we imposed a constraint that we had not seen before, what it would do to the structural integrity of a part. So the mental exercise that went on is what would happen if one of these aileron surfaces we were concerned about in our very early days, would be struck by foreign object damage or some sort of runway debris that was spun up by tires or engine exhaust blast. And we learned early on, in fact, that low speed impact damage could degrade the compression strength of a phenyl-all (ph) sandwich structure, quite significantly.

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

Q No, it's fine.

A -- you got me started.

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

A My experience and my belief is that there are many phenomena that you simply cannot address at a lower scale. If you're working at the coupon scale, you will see some failure mechanisms that are particular to that kind of loading system at that geometry, and when you get up to the more complicated structures, such as a wing box, where you have interaction between cover panels and ribs and spars and so on, you can't see that phenomena, that interaction phenomena at coupon level. You have to go to the larger scale structure to see that.

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

And the reason you want to do this is because it's a whole lot less expensive to learn about a failure mechanism at a smaller scale than to go ahead and build your entire final component part and discover, oops, got a little problem down in this little detail. So the try you address the failure mechanisms, the response phenomena at the smallest scale you possibly can, to integrate a whole lot of confidence, to get up to the next, more expensive scale.

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

Q Thank you.

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

PRESENTATION BY DR. STARNES

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

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

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

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

We're pursuing flutter analyses because when we started thinking about building or populating the fault tree, we realized that there could have been an aeroelastic instability that one of our colleagues at Langley turns out to be a flutter expert, so of course he looks for flutter problems. But in the process of interrogating what he saw, it seemed logical that we would want to consider that.

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

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

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

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

DR. STARNES: Is that what this is?

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

DR. STARNES: Will it work off that screen?

MR. CLARK: Whichever one it works to.

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

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

Now once you get into one of these higher level boxes on a fault tree, recognize that under these there are several tiers of additional types of questions that would lead to trying to understand what might have happened that would be associated with the fin being less than expected, or the fin loads being greater than expected.

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

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

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

Now there are interfaces between what we do in the structures group, the flight data recorder group, the systems people, the human factors folks, the performance group, so what this represents is just the piece that we felt was important to study the structure's activity.

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

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

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

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

DR. STARNES: There's a definite link between what happens in stability and control, but we would need input from another group working on the investigation to tell us whether or not there would be some influence on what happened to the structure. This would then lead us to an anticipation of understanding how the loads might have been greater than expected, if in fact that's what we come to.

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

May I have the next chart please? This is a summary of the activities that we're doing in our global fin and rudder structural analysis. Now the first thing we did was to try to get an understanding internal to NASA of what Airbus did to certify the part. How was the structure designed in the sense that if you compare any of the local stresses, let's say, with what you might, in the United States, might refer to as a design allowable stress, how much margin of safety, or in the Airbus language, what is the reserve factor that would be associated with any of these critical points in the structure under given loading conditions?

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

So after we had gained an understanding of the model, the way Airbus designed the aircraft, the reserve factors that were part of it, the correlation between the certification tests and what we were able to interpret from the analytical methods, we began to wonder what would happen if we would take that model that we now believe we understand, and use that model to begin to interrogate what would happen if some feature had a failure initiation event that eventually propagated in such a fashion that we would have a sequence of events, say lug -- the right rear lugs failed, perhaps, that led to the failure of the center lug, that led to the failure of the forward lug. So we would go through a process of studying these sequences that would then let us understand which failure scenarios we think we can support as most likely have happened.

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

We reviewed the aerodynamic load definitions, made sure we understood how the loads were being derived and applied. We went through the process of comparing the linear analysis methodology that came with the Airbus model, with our own non-linear methods. For us the non-linear analysis methods are important because they help us understand the way the damage or failures can progress through the sequence of events, and they also allow us to account for phenomena such as local buckling in a skin.

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

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

I've already mentioned buckling. It's my understanding that for a wing surface like a vertical fin, you would design to be buckling-resistant at limit load, at some place between limit and ultimate load, you might find buckling occurring. This is not a bad thing if you're accounting for it properly. Since this aircraft saw loads greater than the design ultimate load conditions, I have to assume that buckling could have occurred. If buckling occurred, it would change the internal load distribution in the structure, and that could activate other failure mechanisms.

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

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

We're also using this model to conduct modal analyses in addressing this issue of flutter that I mentioned earlier. One of the ways one does that is you use the natural modes of frequency of the structure as generalized coordinates that you would then use on a flutter analysis, so we would then use a model that will allow us to determine the natural vibration frequencies and their associated modes to provide that input into a flutter analysis.

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

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

Next chart, please? This summarizes some of the activities that we're currently engaged in in trying to understand what happened for the lugs when they failed. To do that we've interacted with Airbus. We've taken advantage of a three dimensional lug model that they put together. We have that at NASA Langley, and we're using that as our starting point to try to understand the response and failure characteristics of a lug subjected to the loads that we believe were applied during the failure of the fin. And we get those loads from the global analysis.

In working with this process we feel that we would want to be able to interrogate failure initiation, as well as failure propagation as we start to initiate the local failure event. This would then propagate across whatever piece -- and it may have propagated in a very, very rapid fashion until it finally breaks apart. To do that we need to have the ability to work in progressive failure analysis, and that is a very computer-intensive process, so we're trying to develop approximate models that would give us the same physical behavior as the complete three dimensional model, but with a much coarser model. In doing that you, of course, have to understand the assumptions and the approximations that you make in changing anyone's model so that you don't add some artificial behavior characteristics. And we've gone through studies that will allow us to understand how to homogenize various layers of the shell model itself, so that we could then come up with an accurate representation at a somewhat coarser level.

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

Once we've got to the point where we believe we've got the right local detailed three dimensional models, then we want to start interrogating the various failure events that we've seen. For example, when the global model is bent over hard due to the external pressure associated with any of the rudder and side slip angles, the fin is still attached -- I mean if the rudder is still attached to the fin, the rudder is also going to bend with the fin, and that can put some high compression or tension loads in the rudder itself that we want to interrogate with local models.

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

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

May I have the next chart, please? This is an example of the local, three-dimensional model. This particular one came from Airbus. There's a lot of detail features not shown here, just so you can look at the level of fidelity that was used to represent all of the complex changes in shape and contour associated with the way the lug is designed.

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

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

Next chart please. The CFD pressure distribution analyses that we're involved in. We're using an unstructured mesh three dimensional knobby (ph) or Stokes analysis that was developed by some of the aerodynamicists at Langley, and we're using that to develop a pressure distribution associated with several of the points during that last eight seconds of flight. We used our CFD results to compare them with the Airbus pressure distribution to make sure that we have a consistent understanding of what that external -- external forces might have been.

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

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

Next chart, please. In our structural tests planning, our objective is to conduct whatever tests we think are appropriate that will allow us to confirm that failure is possible for the accident loading conditions. Can we replicate some of the failure events that we see on the damaged structure. We certainly will use analyses to try to predict that, but the physics of the problem is embodied in the experimental tests that we run. So if we try to represent the physics of the accident, having a well thought through test program will allow us to confirm without doubt that we understand what happened.

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

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

We're also focused on conducting a subcomponent lug test. We have available to us -- we being the structures group -- has available to us a pristine right rear lug from another part that Airbus had, and we'll use that part to interrogate the failure mechanisms that we observed in the accident aircraft right rear lug. So this is a very careful process of trying to replicate those failure mechanisms.

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

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

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

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

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

FURTHER QUESTIONING OF DR. STARNES

BY MR. MURPHY:

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

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

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

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

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

A Thank you for having me.

MR. MURPHY: Madam Chairman, I have no

further questions.

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

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

BY MR. AHEARN:

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

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

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

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

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

A No.

Q Any other manufacturers?

A No.

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

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

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

A Thank you.

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

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

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

BY CAPTAIN PITTS:

Q Sir, very complex subject and our appreciation for your hard work there. You mentioned there's much work to be done -- and a couple different areas. Can you give us an idea of what percentage you think might have been completed to date in the various fault tree analyses that have taken place?

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

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

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

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

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

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

A No.

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

CHAIRMAN CARMODY: Airbus, Dr. Lauber?

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

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

CHAIRMAN CARMODY: Thank you. Faa?

MR. DONNER: Thank you, ma'am.

BY MR. DONNER:

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

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

Q Thank you --

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

Q Thank you very much, appreciate it.

A You're welcome.

CHAIRMAN CARMODY: Going to the Board

members, any questions from Member Hammerschmidt?

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

DR. STARNES: Yes, that's correct.

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

CHAIRMAN CARMODY: Good point. Member Golgia.

MEMBER GOGLIA: Just a ditto for that.

CHAIRMAN CARMODY: Member Black?

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

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

MR. AHEARN: Madam Chairman?

CHAIRMAN CARMODY: Mr. Ahearn.

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

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

DR. STARNES: Thank you.

CHAIRMAN CARMODY: We'll now excuse this witness.

(The witness was excused.)

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

MEMBER HAMMERSCHMIDT: I would -- of course like to give a special thanks to not only the witnesses for all their cooperation and responsiveness during this public hearing, but also to the parties whose input and wealth of expertise is essential for the completion of this investigation. So, thanks to all involved in this public hearing.

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

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

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

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

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

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

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

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

As important as it is for us to find the answers on behalf of the families of this tragedy, our mission is substantially broader. We pursue causes of such tragedies for the millions of people who fly transport category aircraft every day. I can assure those travellers that if we ever find an element of the aviation system that needs safety improvement, we will move quickly to issue other recommendations to deal with them.

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

On behalf of the National Transportation Safety Board, as my colleagues have reflected, I do want to thank all the parties to this hearing. I know it's been difficult. It's been a major commitment of people, resources, expertise and patience, and you have my thanks. You've all been very pleasant to work with. I'd like to thank again, all the witnesses who have been so forthcoming with their knowledge, and of course the staff. They have put in really wonderful effort for the past several months on this, and it's all, I think, borne fruit this week. So my thanks to everyone. I won't enumerate you all because there are some who aren't here that also contributed, but you have our thanks and our gratitude.

The record of the investigation, including the transcript of the hearing and all Exhibits entered into the record, will become part of the Safety Board's public docket on this accident, and will be available for inspection at the Board's headquarters. Anyone wishing to purchase the transcript -- and that goes for the parties as well -- may contact the court reporter directly and make your arrangements.

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

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