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Role of Metallurgy in Aircraft Accident Investigation and Litigation

Alan S. Tetelman

Harry S. Redmon Jr.

THE ROLE OF METALLURGY IN AIRCRAFT ACCIDENT INVESTIGATION AND LITIGATION

ALAN S. TETELMAN, Ph.D.*
HARRY S. REDMON, JR.**

When the Board of Editors invited Dr. Alan S. Tetelman and Harry S. Redmon, Jr., Esq. to participate in the 1977 Air Law Symposium, they were asked to use a question and answer format to cover the topic of the role of metallurgy in aircraft accident investigation and litigation. Based on a given set of facts, Mr. Redmon questioned Dr. Tetelman as though he were the defendant's expert metallurgist on direct examination in an aircraft accident case.

—The Board of Editors

For the purposes of our demonstration, please assume that a light, single-engine aircraft crashed on landing. The pilot was a high-time instructor and the passenger was a student. Ground witnesses reported that when the aircraft was at about 800 feet on final, it made an uncontrolled bank to the left and crashed.

Survivors of the passenger sued the aircraft manufacturer. The plaintiff maintains that the strands of the flap cable activating the left flap in the down position failed progressively in fatigue to the

* B.S., M.E., D.E., Metallurgy, Yale University; Past Professor of Engineering, UCLA; Past Chairman of the Materials Department at the UCLA School of Engineering; Past recipient of the Robert L. Hardy Gold Medal of the American Institute for the Advancement of Engineering; Past Distinguished Lecturer at the American Society of Metals Westec Congress; and Past President of Failure Analysis Associates. The Board of Editors regretfully announces that Dr. Tetelman perished in the Pacific Southwest Airlines crash in San Diego on September 25, 1978.

** B.S., J.D., Louisiana State University; partner, Phelps, Dunbar, Marks, Clauerie & Sims, New Orleans, La.; Member American Bar Association, Louisiana Bar Association, International Association of Insurance Defense Counsel, and Maritime Law Association of the United States; Fellow, American College of Trial Lawyers.

point where the cable's strength ultimately became so low that it failed while the aircraft was on approach. Plaintiff claims that this caused the left flap to retract, as a result of which the pilot lost control. The defendant-manufacturer maintains that the accident resulted from pilot error or incapacitation and that the flap cable, Exhibit 1, failed in overload on ground impact.

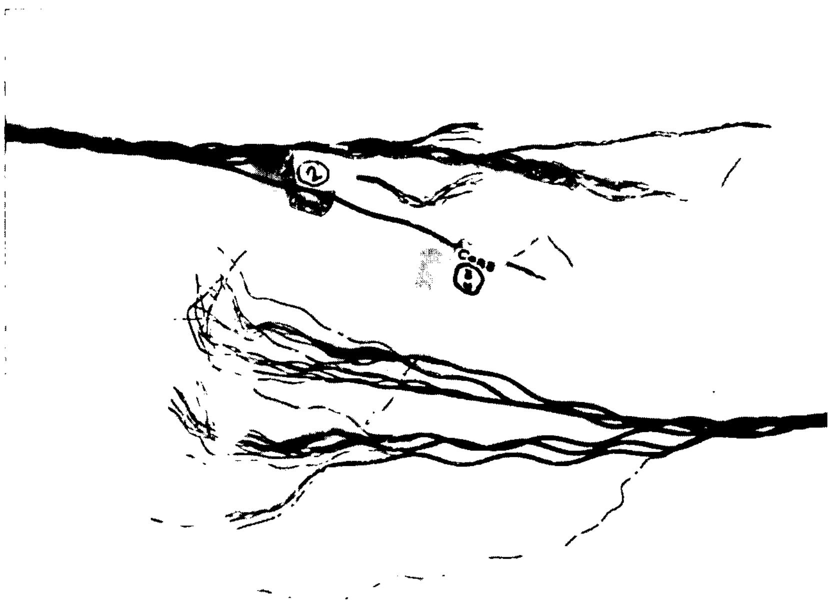

EXHIBIT 1

HSR: Doctor, would you give us your name and address?

AST: Dr. Alan S. Tetelman, my address is 11777 Mississippi Avenue, Los Angeles, California.

HSR: Please state your occupation and employer.

AST: Professor of Engineering, University of California at Los Angeles, and Head of the Technical Staff at Failure Analysis Associates.

HSR: What is the business of Failure Analysis Associates?

AST: Failure Analysis Associates is an engineering consulting firm devoted to the analysis and prevention of mechanical and structural failures. Approximately half of our work relates to the analysis of failures and the other half of our work relates to preventing failures. We have an engineering staff of approximately forty full-time personnel located in Palo Alto, Los Angeles, and Houston.

HSR: Would you summarize your educational background and any professional societies of which you are a member?

AST: Certainly. I received a Bachelors, Masters, and Doctorate of Engineering degrees from Yale University and I am a past member of the National Materials Advisory Board, an advisor of the National Science Foundation and National Commission on Consumer Product Safety. I have received several awards such as the Engineering Merit Award of the Engineering Foundation and was Distinguished lecturer for the American Society of Metals.

HSR: Are you the author of any books or publications in the field of metallurgy?

AST: Yes. I have authored two books and ninety technical publications dealing with the areas of fatigue and brittle fracture, stress corrosion cracking, and risk and reliability.

HSR: Are you a registered professional engineer?

AST: Yes.

HSR: Doctor, just what is involved in the field of metallurgy?

AST: Metallurgy is a field that is related to the study of the properties of materials and how those properties such as strength and hardness can be changed by changing the composition of the metal, changing its heat treatment and its microstructure.

HSR: Doctor, a number of experts will testify in this case including metallurgists, mechanical engineers, aerodynamicists, and aeronautical engineers and meteorologists. Would you explain for us how these fields interrelate in an aircraft crash investigation?

AST: Certainly. If we're talking about the possibility of in-flight break up, the meteorologist would testify as to what type of winds were present. The aerodynamicist would talk about how winds would produce various loads on portions of the wing. The aeronautical structural engineer would talk about how those loads would produce stresses in various structural members such as sparcaps and skin and the metallurgist and the structural engineer together would determine whether or not those stresses exceeded the design allowables for the wing. The metallurgist would also determine whether there were any defects in the material and whether the material's strength meets its specifications.

HSR: Have you previously qualified as an expert witness in metallurgy?

AST: Yes, I have.

HSR: Does your work include investigations into failures of metals in both aircraft and non-aircraft cases?

AST: Yes, it does. From a metallurgical point of view it doesn't matter whether the metal is in an aircraft or whether it's in a pipeline or whether it is in a heart valve. A metallurgist approaches the problems the same way and in trying to solve them uses a certain set of logical principles and experimental tools.

HSR: Doctor, as you know from previous testimony, the plaintiff in this case maintains that plaintiff's Exhibit 1, which is the flap cable activating the left flap in the down position, failed progressively in fatigue with the result that its strength was so low that the cable eventually failed as the aircraft was approaching for landing. Now Doctor, I am going to show you plaintiff's Exhibit 1 and I ask you whether or not at my request you undertook to determine the cause of the failure of that exhibit.

AST: Yes, I did.

HSR: What approach did you use in this analysis?

AST: The approach that I used in this analysis as to the cause of failure is shown in Exhibit 2. Basically, an analysis into the cause of failure of a critical component involves four parts. In conjunction with the physical examination, exemplar tests are often conducted to compare the alleged mode of failure with known modes of failure. First, there is a physical exam to determine the mode of failure. Second, there is a mechanical stress-strength analysis to determine whether the stresses on the part were too high or the strengths were too low, and hence, what

Failure Analysis Associates

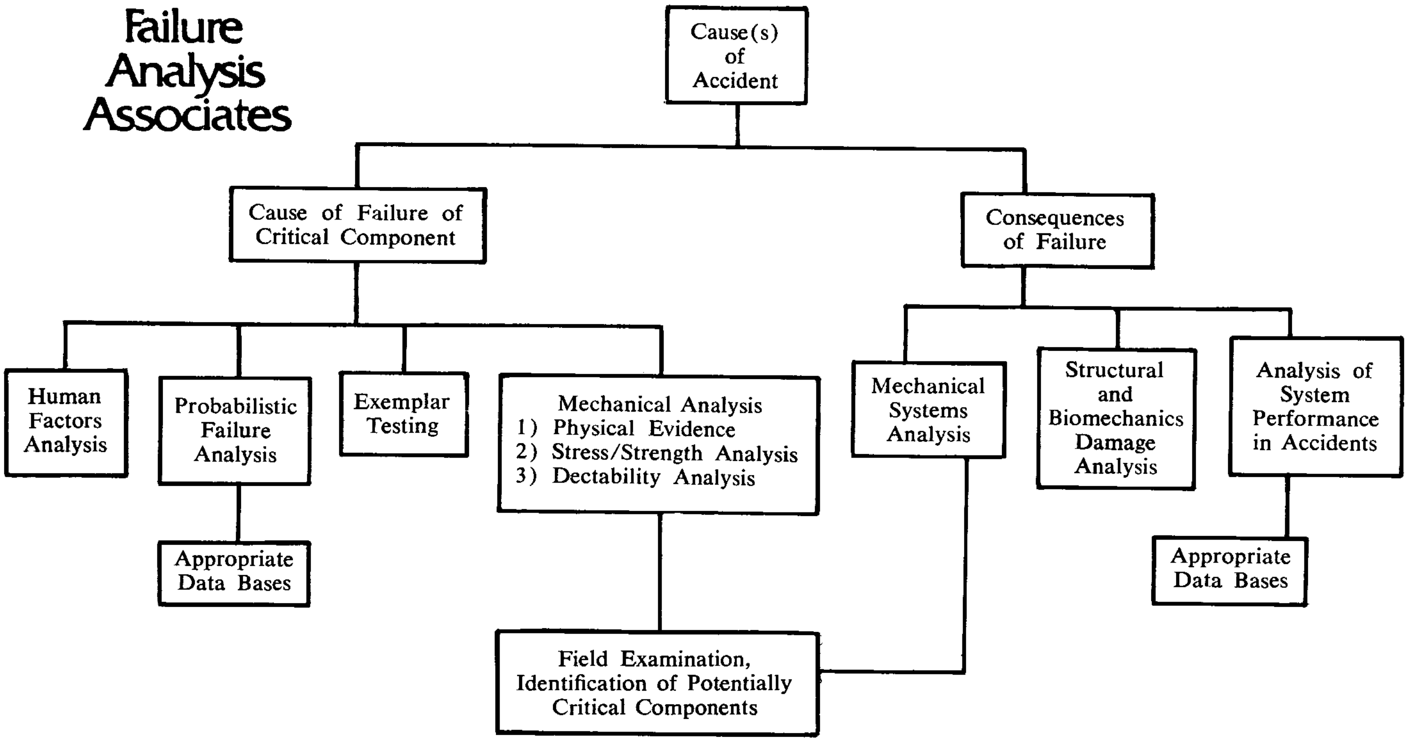

EXHIBIT 2
Failure Analysis and Accident Reconstruction Methodology

factor was responsible for the failure. Third is an analysis of the way in which any incipient failure might have been detected prior to the accident. A probabilistic analysis is done to examine the past history of the component and determine if there was a likelihood that it could fail in this case, based on previous history. Finally, having determined something about the cause of the failure, a human factor analysis is conducted, in which I have no direct role, to determine which human being in the sequence of events may have contributed to the cause of the failure. Now all of these things begin to take place after a field examination of the parts which occurs on the accident site, and a review of pertinent documents.

Fatigue takes place over a period of time as compared to overload fracture which occurs instantaneously when the stresses on the component exceed its strength. Fatigue is a progressive form of damage, rather like cancer in a person, and an overload fracture is like a heart attack.

HSR: Now Doctor, before we move on to your physical examination of plaintiff's Exhibit 1, let me ask whether you reviewed any documents or other materials in preparation for that analysis.

AST: Yes, I did.

HSR: Did you have available manufacturer's and aircraft component's specifications, blueprints, test data, or product safety studies?

AST: Yes, I did.

HSR: What about FAA General Aviation Airworthiness Alerts[1] and Service Difficulty Reports?[2]

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[1] General Aviation Airworthiness Alerts are available from the FAA by writing:

FAA General Aviation Airworthiness Branch
AFS-830
800 Independence Avenue, S.W.
Washington, D.C. 20591
Telephone (202) 426-8203

[2] Service Difficulty Reports are available from the FAA by writing:

FAA Maintenance Analysis
AFS-513A
P.O. Box 25082
Oklahoma City, Oklahoma 73125
Telephone: (405) 686-4171

AST: I checked those out. There were no General Aviation Airworthiness Alert or Service Difficulty Reports on this particular subject.

HSR: Did you check for Airworthiness Directives,[3] service bulletins,[4] or service letters?[5]

AST: Yes, I did.

HSR: How about aircraft maintenance and overhaul records and logs and flight manuals?

AST: Yes, I did review those.

HSR: Did you have the NTSB report with exhibits and any photographs that might have been available?

AST: Yes, I did at the time I began my examination.

HSR: Did you review the plaintiff's metallurgical reports?

AST: Yes, I did.

HSR: As I mentioned to you earlier, this case turns on whether plaintiff's Exhibit 1 failed in fatigue or overload. Would you explain for us just what a fatigue failure is as opposed to an overload failure?

AST: Certainly. A fatigue failure involves the initiation and progressive growth of a crack over a period of time. Generally, fatigue occurs in components that are subject to reversed or alternating loading, that is a load that is put on and then taken off or put on in tension and then reversed into compression.

HSR: Turning again to plaintiff's Exhibit 1, Doctor, did you analyze the fracture surface to determine the mode of failure?

AST: Yes, I did.

HSR: Would you please now proceed to describe the steps in your study of the fracture surface in your efforts to determine the mode of failure?

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[3] Airworthiness directives are issued by the FAA pursuant to 49 U.S.C. §§ 1421, 1423 (1976) and 14 C.F.R. § 39 (1978). They are published weekly in the Federal Register.

[4] Service bulletins are published and available through the manufacturer of an aircraft or a component part of the aircraft.

[5] Service letters are published, and available through the manufacturer of an aircraft or a component part of the aircraft.

1. Physical Evidence	Level of Observation
a. Actual Failure	Macro/Micro/SEM
b. Parallel Failure in Same Accident	
c. Textbook Failure	
d. Exemplar Failure in Laboratory Field Test	

2. Specifications and Properties Check
   a. Chemistry
   b. Hardness
   c. Microstructure, etc.
   d. Dimensions

EXHIBIT 3

AST: Certainly. Exhibit 3 illustrates the type of physical examination that is conducted to see what the metal has to say for itself about the way it failed. There are two parts to the physical exam. First, there's the examination of the physical evidence itself; this involves an examination of the actual failure surfaces and a comparison of the failure surface with other types of failure such as: 1) with a failure that has occurred in the same accident in a similar component where the failure mode is known; 2) with a textbook type of failure such as fatigue, brittle fracture of ductile fracture; and 3) in some cases, if there is no textbook failure available, it's necessary to produce your own textbook failure by going into the laboratory and producing a fatigue failure or an overload failure and having that for comparison with the one that failed in the accident. The subject failure and the exemplar failure can be compared at different levels of observation. You can do it microscopically with an optical microscope (60X - 1000X) or increasingly today with the scanning electron microscope which allows you to do it at high magnifications (100X - 5000X). The first part of the physical exam, then, involves determining what type of failure mode has taken place.

The second part involves determining whether the material in question meets the specified alloy chemistry, hardness, the microstructure, and the dimensions that were called for on the blueprint. In some cases, particularly where a failure has occurred near a weld, it's important to determine whether any repairs have been made, usually by determining the different chemistries of weld overlays.

HSR: Would you now review for us your physical examination of plaintiff's Exhibit 1?

AST: Certainly. The allegation has been made in this case that the failure has occurred progressively because of the unravelling of the cable. Now, there was also a second control cable that was located adjacent to the one that is the subject of this lawsuit. The second failure had taken place by overload. That failure occurred in the E cable. Exhibit 4 shows that in overload fracture unravelling of the strands has also taken place. This tells us that the presence of unravelling does not prove the presence of progressive fracture, since we have unravelling in a cable that has failed by overload.

EXHIBIT 4

Exhibit 5 shows a scanning electron micrograph of the fracture of the subject cable itself, one of the strands of the cable that is alleged to have failed by fatigue. And

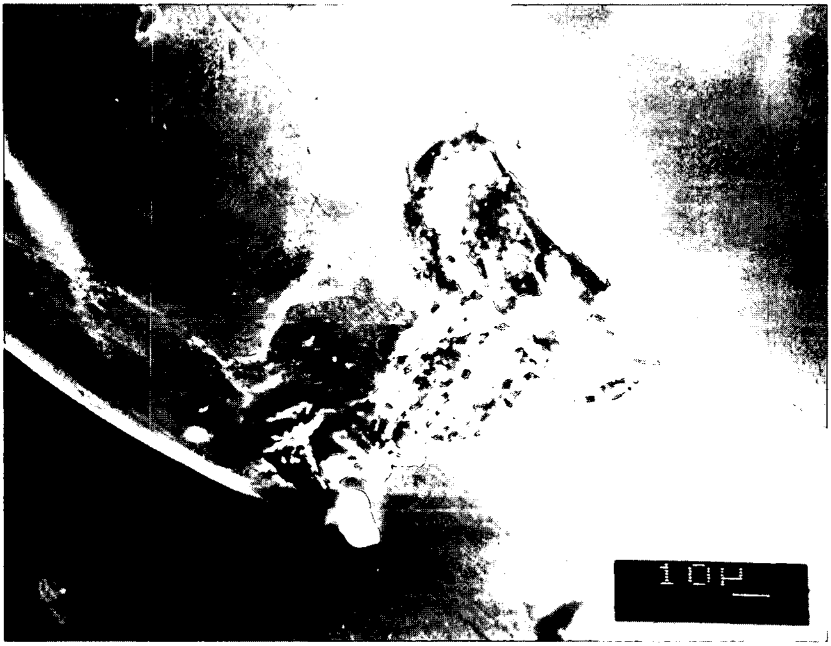


EXHIBIT 5

the important features here are the fact that the cable has necked down, you can see it drawing down to a chisel point, and also the fact that there are dimples on the fracture surface and the fracture surface is slanted and does not contain any flat fracture.

Exhibit 6 shows a fracture surface of a cable strand from the overload fracture which also shows the presence of necking down and dimples and this strand looks like one of the strands in alleged fatigue failure. Consequently, this tells us that the fracture appearance of the subject cable is similar to that of an overload fracture. Now in doing this type of work it's desirable not only to show what has occurred but what has not occurred. Exhibit 7 is the textbook failure of fatigue in a strand, showing that when we get fatigue of wire, there is generally a very flat structure followed by some longitudinal splitting or tearing fracture. This was not observed in the subject cable.

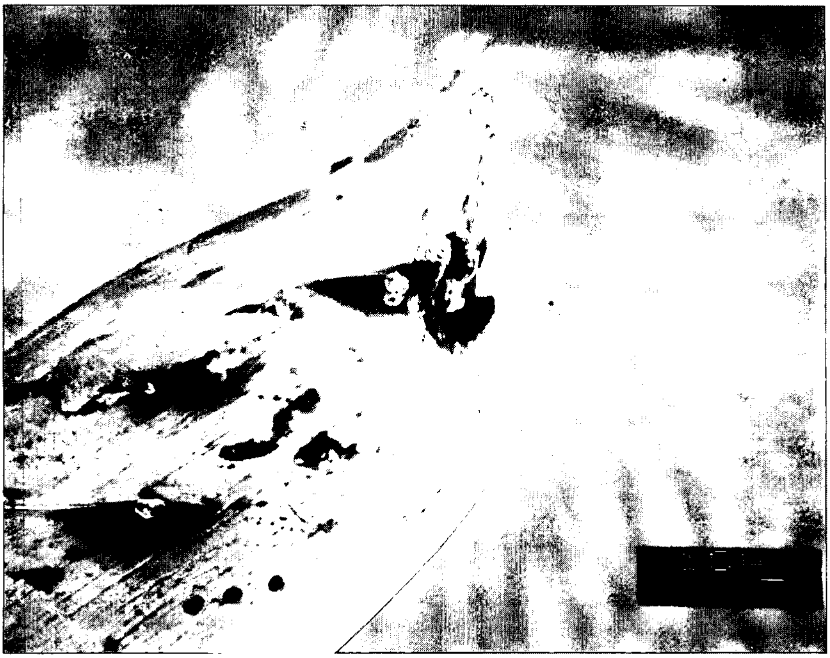


EXHIBIT 6

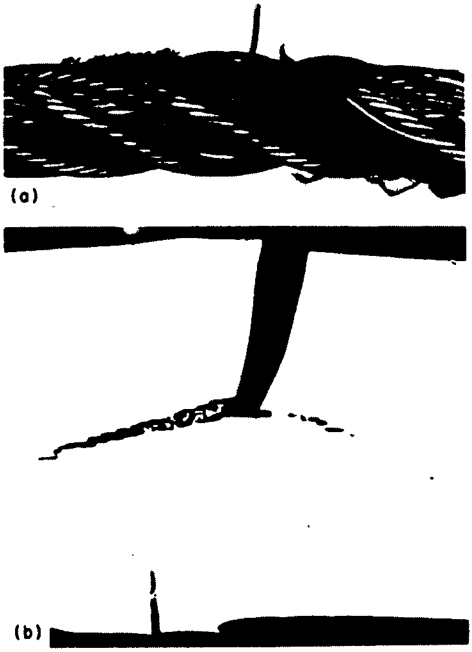
Exhibit 8 is a slide showing an electron micrograph of a fatigue failure in stainless steel indicating that when fatigue occurs one generally sees the presence of striations which are the little parallel lines on the photograph. These also were not found on the subject cable.

Therefore, based upon the macroscopic and the microscopic examination in the scanning electron microscope exam we conclude that the subject cable failed by overload rather than by fatigue since it has all the appearances of overload and none of the appearance of fatigue.

HSR: Doctor, did you conduct a microprobe examination?

AST: No, we did not. The microprobe examination is conducted to determine the presence of any foreign elements on a fracture surface—paint smears or foreign species. There were none—that was not an issue in this case and hence the microprobe exam was not conducted.

HSR: Now Doctor, having concluded from your examination of



(a) Section of the wire rope adjacent to the fracture, at about 1½×. (b) Micrograph, at about 75×, of an unetched longitudinal section of a wire from the rope, showing fatigue cracks originating from both sides.

Fig. 5. Steel wire rope, used on a cleaning-line crane, that failed from fatigue resulting from vibration caused by shock loading **(Example 3)**

EXHIBIT 7

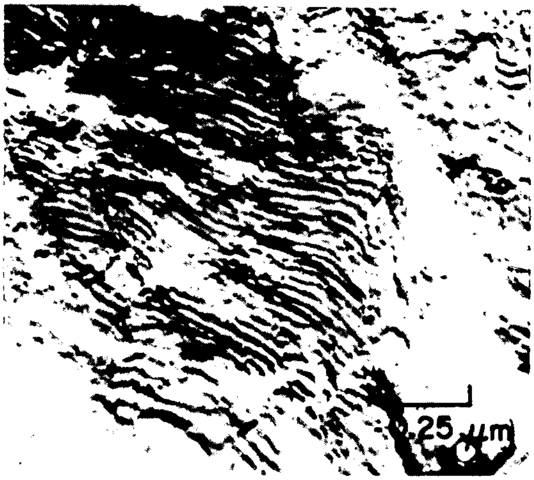
Reprinted with the permission of the American Society of Metals from 10 METALS HANDBOOK 462, fig. 5 (8th ed. 1975).

the physical evidence that plaintiff's Exhibit 1 failed in overload, did you run a specifications and property check?

AST: Yes, I did.

HSR: Just what exactly is a specifications and property check and why was it run in this case?

AST: As I indicated earlier, a specifications and property check involves a determination of whether the material was of the correct chemistry called for on the drawings. In some



TEM fractograph (p-c replica) 40,000×

3885 Surface of a fatigue crack in type 301 stainless steel, produced at a stress-intensity range (ΔK) at the crack tip of 37.9 $\text{MPa}\cdot\text{m}^{1/2}$ (34.5 $\text{ksi}\cdot\text{in.}^{1/2}$) at 95 C (203 F). Spacing of clearly defined fatigue striations is about 0.04 μm. See also 3886.

EXHIBIT 8

Reprinted with the permission of the American Society of Metals from 9 METALS HANDBOOK 223, fig. 3885 (8th ed. 1974).

cases, the chemical analysis might determine if a part was part of an original manufacturer's production run based upon the material he used at the time, was an accounted for replacement part, or was a bogus part. The most appropriate test in this case was a dimensional check to determine whether the cable strands were the right diameter and a hardness test to determine whether each strand had the appropriate hardness, since the overall cable strength is determined by the cable size and the cable hardness. Both of those checks were run.

HSR: Did plaintiff's Exhibit 1 meet the required specifications?

AST: Yes. it did.

HSR: Having found that plaintiff's Exhibit 1 met the specifications, does that help you determine whether or not it failed under normal loads?

AST: Yes, it does.

HSR: In what way?

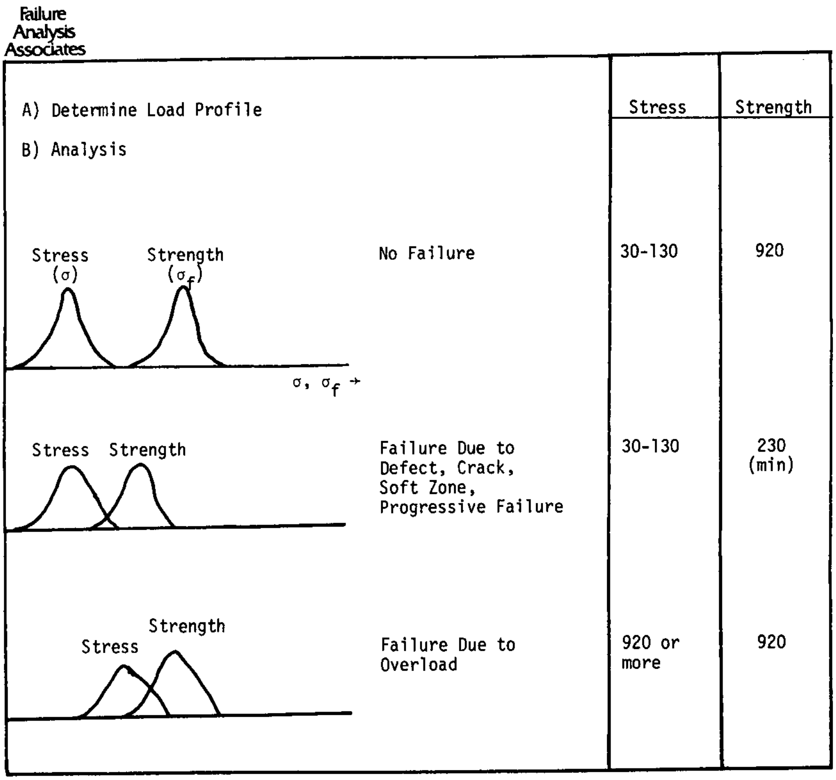


EXHIBIT 9
STRESS/STRENGTH RELATIONSHIP

AST: The approach that we used is best illustrated by Exhibit 9 which describes the conditions for failure and the conditions for no failure. A properly designed part is one where the stresses acting on the component are below the strength of the component. As shown on the top example of Exhibit 9, we have no failure when the stress is less than the strength and in this particular case the loads acting on the cable were thirty to 130 pounds maximum during flight.

The cable itself is designed to handle a load of 920 pounds; we know that because we know the cross-sectional area of each strand and we know the number of strands and we know the tensile strength of each strand. If you determine tensile strength and multiply the strength by the area you get the load carrying capacity, which is 920 pounds. This cable, then, is one where there is a very large factor of safety, where the maximum stress the cable is supposed to bear is far below its strength.

HSR: Now Doctor, I'd like for you to assume, as the plaintiff maintains, that seventy-five percent of the strands of plaintiff's Exhibit 1 had failed progressively before the crash. Assuming that to be true, could that have any effect on the operational integrity of plaintiff's Exhibit 1?

AST: No, I don't believe it could because even if we have three-quarters of that cable gone the residual strength would still be 230 pounds. Since the maximum load on the cable is 130 pounds, that failure would not have taken place.

HSR: Did the result of the stress/strength analysis affect in any way your earlier stated opinion that plaintiff's Exhibit 1 failed in overload?

AST: Not at all. The failure occurred in overload and I believe that the failure occurred during ground impact when the wing moved away from the fuselage. The cables were stretched and at least 920 pounds of load was applied to the cable, as shown in the third example, and the applied stresses reached the strength of the cable.

HSR: Did you consider any other factors in your analysis?

AST: Yes, I did.

HSR: What factors were those?

AST: I considered the fact that this failure occurred at 3,020 hours of operation, and at 3,000 hours two inspectors had checked off on the log book that they had run towels across the cables and found no broken strands. We know that in any form of progressive failure that the failure takes place over a period of time. If the plaintiff's theory were correct there would have been some strands broken at the 3,000 hour mark. According to plaintiff's theory, the cable would have had full strength at 3,000 hours but by 3,020 hours the strength would have dropped down to 130 pounds. That is so improbable that I would consider this an unlikely event.

HSR: Now Doctor, considering your analysis in its entirety would you give us your opinion relative to the cause of the failure of plaintiff's Exhibit 1?

AST: Well, in summary, I believe that plaintiff's Exhibit 1 failed during ground impact when the wing separated from the fuselage and the cable was overloaded and the unraveling of the cable was simply a consequence of the release of any stored energy in the strands that had been put in during the manufacturing process.

HSR: Thank you, Doctor; your witness, counsel.