THE INFLUENCE OF STRESS RAISERS ON THE PERFORMANCE OF MATERIALS

by

N. C. FICK

(*Physical Sciences Administrator*)
Research and Development Board Washington 25, D.C.

ABSTRACT

The publications on fracture of metals emphasize the importance of avoiding so far as possible all causes of local stress concentration, particularly in closely designed, lightweight, highly stressed parts subject to repetitions of large fluctuations of load. In cases where the design considerations make some stress concentration unavoidable, certain precautions can be taken. Among these are:

(1) use materials known to have the minimum of sensitivity to notches, tough materials that will resist brittle fracture ;

(2) design for a lower average stress ;

(3) avoid sharp corners and abrupt changes of cross section by providing fillets with as large radius as possible ;

(4) finish the surface smoothly ; and

(5) protect the surface from damage during operation and maintenance. Several specific cases of aircraft and ship failure are described.

Four years ago an airliner left Chicago with 37 persons abroad. An hour later several persons along the countryside approximately (158 kilometers) southeast of Minneapolis were watching a thunderstorm which was approaching from the northwest. As the storm moved closer, the wind increased in intensity and considerable lightning and thunder were observed. At this time the airliner was seen flying below the overcast. The airliner appeared to enter the roll cloud or the leading edge of the thunderstorm, at which time it was lost from view. Seconds later parts of the airplane were seen falling. All of the 37 occupants were killed, and the aircraft was destroyed. A thorough investigation was made by the Civil Aeronautics Board and National Bureau of Standards. The probable cause of the accident was determined to be the loss of the outer panel of the left wing, which separated from the aircraft as a result of a fatigue crack in the left front outer panel attachment fitting which had been induced by a faulty design of that fitting. The fatigue crack was aggravated by severe turbulence encountered in the thunderstorm.

The outer wing front and rear spar flanges attach to the center wing front and rear lowers par flanges by means of a dihedral wedge, as illustrated in Figure 1. Originally, the spar flanges were bolted directly together, but tests of the prototype airplane demonstrated the need for a grater lateral stability. Therefore, the outer wing was rotated seven degrees upward by means of incorporating the dihedral wedge in the attachment of the outer wing to the center section.

It will be noted in Figure 1 that the attachment ends of the lower spar flanges and dihedral wedge have four steps or vertical increases in thickness. In each step the vertical increase in thickness is approximately 0.5 centimeter, except for the fourth step inboard on the center-section spar flange, where the vertical increase in the thickness is approximately 1.8 centimeters. The radius of the fillet of these steps is about 0.3 centimeter. Evidence indicated that the outer wing had first separated from the center section in the fillet of the fourth step of the lower front center-section spar flange.

The spar flanges, consisting of 75ST aluminium alloy, were tested by the National Bureau of Standards. They were found to be of the proper chemical composition, and the tensile strength, yield strength, and elongation met the specifications for the material. However, micrographic examination of the mating portions of the failed spar flanges revealed that several fatigue cracks had developed. Examination of the flange fracture revealed that the separation had started from a fatigue crack approximately 2.2 centimeters long and .24 centimeter deep, the remaining cross section of the material at this point failing from tension.

The right wing of another plane of the same type which went through the same storm failed as a result of fatigue cracks which developed in exactly the same location. Fortunately, the buckled wing was discovered by a mechanic while the plane was standing on the ground.

In the spar flanges that were examined there was an abrupt change of cross section, a fillet of small radius with transverse grinding or machining marks, sharp edges around the bolt holes, and axial scratches within them. All these are features long recognized to be conducive to fatigue failure.

Soon after the crash of the one plane and the discovery of a fractured wing fitting in the other, all aircraft of this type were grounded for inspection. Of the 19 airplanes, including the two mentioned above, five had fatigue cracks in the lower fourth step-down fitting of the front spars. Three of these aircraft had fatigue cracks on both wings, and two had fatigue cracks on one wing.

The immediate corrective steps taken were: (1) the front center-section spar flange was modified so as to indude five steps or vertical increases in thickness to avoid any radical change in cross section, (2) the radius in the fifth-step fillet was increased from 0.3 centimeter to 1.8 centimeters, (3) two bolts were added, (4) all parts were polished, and (5) the wing root fittings were given frequent and thorough inspections for fatigue cracks.

After completion of 3,000 hours of flight, extensive structural changes were made to the wings. These included replacing the 75ST aluminium spars with larger extrusions made out of 24ST aluminum and replacing the step splice with a scarf splice. (The lower strength 24ST is less sensitive to notches and surface irregularities than the higher strength 75ST).

Several years ago an oil tanker that was over 150 meters in length split close to amidships while moored at her repair dock in Boston. The entire deck and strake on each side was parted and a huge "V" opened up as the forward and aft sections separated. The bottom buckled and fractured in several places, but did not completely separate until the ship was moved. The crack went nearly straight across the vessel extending from the chock on the starboard side to slightly forward of the chock on the port side.

The water temperature was 5°C and the air temperature 1°C. The front of the ship projected into the stream for a distance of 54 meters beyond the dock. A wind of 40 kilometers per hour with gusts up to 72 kilometers per hour, blowing against the starboard side of the front of the ship and forcing the stern against the dock, was of sufficient force to snap one of the mooring cables a short time before the ship itself fractured. In addition, the vessel was subjected to an unknown amount of stress by fully loaded water and oil tanks in both the forward and aft sections. This was the third tanker of this type to fail by complete fracture amidships during a two year period. All three fractures were of a brittle nature and took place when the temperatures were below 10°C.

The portion of the vessel including what appeared to be the origin of failure was subjected to a thorough metallurgical examination at the Watertown Arsenal. Visual examination showed clearly that the fracture lines start from a crater on the top surface of the deck and proceed in both directions from this point. The crater was probably caused by striking an arc without depositing sufficient weld metal to fill the hole. There was no evidence of fatigue.

The chemical analyses of the metals were:

	C	Mn	Si	S	P	Al
Deck Plate Semikilled as rolled	·23	·50	·07	·031	·021	·011
Strake Plate Rimmed as rolled	·225	·36	·01	·048	·009	·009
Weld Metal	·075	·33	·18	·034	·027	·012

The mechanical properties were:

	Average Yield Strength ·01% Offset	Average Tensile Strength	Average Elongation 2″ (5 cm)
Deck As received	29,385 psi	64,803 psi	36·9
Normalized 843°C. 1 hr. Air Cooled	32,530	63,650	38·5
Strake As received	25,258	56,940	38·6
Normalized 843°C. 1 hr. Air Cooled	34,230	62,870	41·5

The yield strength of both plates as received from the fractured ship was less than half the tensile strength and, therefore, failed to comply with the American Bureau of Ships specifications. In addition, the tensile strength of the sheer strake was less then the 58,000-psi minimum specified. Both plates were generally rather low in strength, particularly yield strength. This low strength appears to have been a contributing factor to the failure of the vessel. The ductility of the steel was excellent and the fractured test specimens showed no evidence of embrittlement. Charpy " V " notch impact specimens of the deck plate had an impact strength at 27°C of 13 foot pounds as received and 28 foot pounds after normalizing at 843°C. At —40°C the energy required to fracture was nearly the same for as received and normalized specimens, 3 and 4 foot pounds respectively. The as-received deck plate tested about 6 foot pounds at 5°C. The transition temperatures of the steels were:

	As Received (Hot Rolled)	Normalized 1 hr. at 843°C.
Deck	43°C	23°C
Strake	56°C	33°C

The transition temperature of these steels as hot rolled is rather high ; therefore, the resistance of the steel to brittle fracture was poor at low temperature. The improved toughness of the normalized plate appears to be due to the grain refinement. Both the deck and strake plates had an A.S.T.M. grain size of 2-4 in the as-received condition. After normalizing at 843°C the deck-grain size had reduced to 5—7 and the strake grain size to 7—8.

The welds around the chock and in the area of the failure were examined carefully. The microstructure of the steel was considerably influenced by the rapid cooling that occurs within this zone. Although the hardness and microstructure would not influence the toughness to a marked degree, the increase in grain size will, in all probability, further raised the temperature at which brittle failure will occur in the ship plate. This factor is of considerable importance since microscopic examination revealed that the metal directly under the crater at the origin of failure was heat affected.

The problem of ship failure would seem to be more easily solved by using steels that are less susceptible to brittle failure at low temperatures than by attempting to remove all notches and similar structural stress raisers, although changes in design and care in fabrication and use to reduce these stress raisers to the very minimum will reduce the number of failures.

" The problem of acquiring an understanding of the exact cause of failure is very difficult because of the many complex factors that exert an influence. Extensive studies have been made and are continuing on such factors as stress distribution, strain rate, temperature, design, fatigue, welding, internal stresses, decarburization, corrosion and corrosion fatigue, coatings, hydrogen embrittlement, inculsions, and notches, both built-in and accidental.

The nucleus of a fracture is almost invariably located at some surface imperfection in the form of a notch, scratch, damage mark, flaw, or sharp change in contour or section thickness. Heavy parts of large sections which are subjected to light loads often have these stress raisers and do not fail, in spite of them. Because of this, many designers are inclined to forget the disastrous consequences of these stress raisers in less massive and more heavily loaded structures.

These surface imperfections are a very serious matter in parts that are designed to reduce weight to the very minimum.

The " factor of safety " has also been reduced. Nearly all aircraft parts fall into this category. Airplane propellers have failed as a result of progressive fatigue starting at an identification number which had been stamped into the surface of the blade. Engine cyclinders have failed in fatigue as a result of quench cracks which formed during the heat-treating operation. Improper machining of a bolt from a ring cowling of an airplane resulted in failure. An engine-mount bolt failed because there was no fillet at the head and tool marks were left on the piece. A poor fillet caused axle failure in service during the landing of an airplane. Fatigue failures which occured during the testing of an experimental airoplane engine started at unchamfered oil holes. The fatigue failure of an aircraft engine crankshaft started from a keyway. A crack was discovered in a landing-gear axle weld after 496 landings. This part had been magnafluxed earlier in its life, without the crack appearing.

All engineering structures must be properly fabricated initially and carefully handled during operation and maintenance to prevent damage. Automobile leaf springs have failed prematurely because the men unloading a shipment of springs have carelessly thrown them off a truck, denting the edges. Pipe lines operating under pressure have failed because of surface imperfections. Bridges have succumbed to fatigue failure and fallen into the river. Orthopedic braces supporting the paralyzed legs of a crippled child have, after only a few weeks of use, failed through the marks inadvertantly made on the surface by the sharp jaws of a vise while being assembled by the brace maker.

Although it is important that fundamental research on materials and structures be continued to extend the frontiers of knowledge, it is equally important that we, as engineers, designers and users of engineering materials, interpret and apply the knowledge that has already become a part of the public record.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to the members of the staffs of the National Academy of Sciences, the Civil Aeronautics Board, the Battelle Memorial Institute, the Army Ordnance Corps, and the National Bureau of Standards who have furnished data and helpful suggestions for this paper. The staff of the National Metallurgical Laboratory, Council of Scientific and Industrial Research is to be congratulated for fostering this symposium on Industrial Failure of Engineering Metals and Alloys.