AD 667 144

FACTORS OF SAFETY AND FAIL SAFE STRENGTH CRITERIA

William J. McNair

Federal Aviation Agency
Washington, D.C.

November 1966

FACTORS OF SAFETY AND FAIL SAFE STRENGTH CRITERIA

by

William J. McNair

FAA MAINTENANCE SYMPOSIUM

November 4, 1966

SYNOPSIS

This paper briefly traces the origin and use of the term "fatigue" in civil aviation. Sections of the current Federal Aviation Regulations pertaining to factors of safety and fail safe strength criteria for fixed wing transport aircraft are briefly reviewed. Emphasis is also focused on the importance of adequate maintenance inspection intervals and procedures for aircraft.

ORIGIN OF "FATIGUE" IN THE REGULATIONS

Research and study on the phenomenon of fatigue in metals date back several decades and over the years various theories with mathematical interpretation have been presented on this problem. In the field of civil aviation, references to "fatigue" are found in the earliest publications. Early regulatory material containing reference to the problem include the following:

1. "The Handbook for Airplane Designers," which was issued in 1927 by the Department of Commerce, stated that care must be taken to avoid the use of standard eyebolts on control systems and surfaces where vibration might cause fatigue failure.

2. In 1934, detailed airworthiness standards were issued by the Department of Commerce (in Aeronautics Bulletin No. 7-A) which stated, in part, that care shall be taken toward preventing fatigue failures by proper material distribution and shape in the detail design of members and fittings.

3. In 1945, airworthiness requirements appeared as Part 04. This requirement was reissued by the Civil Aeronautics Board as: (1) Part 03 for small aircraft (now Part 23), and (2) Part 4b (now Part 25) for transport aircraft. These provided in part that the design of the structure shall avoid points of stress concentration where variable stresses above fatigue limits are likely to occur.

4. In 1954, the predecessor of the FAA, The Civil Aeronautics Administration, sponsored a study to develop more specific fatigue criteria for transport aircraft.

Reproduced by the
CLEARINGHOUSE
for Federal Scientific & Technical
Information Springfield Va. 22151

9

5. As a result of this coordinated study by the industry and government, a new section 4b.270 (now 25.571) titled, "Fatigue Evaluation of the Flight Structure," was added in 1956 to the airworthiness standards. Since the adoption of this section, there have been revisions to it which, in part, provided additional fatigue criteria treating with asymmetrical loads and landing gears.

MULTIPLYING FACTORS OF SAFETY

Terms of reference related to factors of safety as discussed below, are defined as follows:

1. Strength requirements are specified in terms of limit loads and ultimate loads. Unless otherwise provided, prescribed loads are limit loads.
2. Limit load means the maximum load to be expected in service. All loads referred to below are limit loads unless specifically indicated as ultimate loads.
3. Ultimate load means the limit load multiplied by the prescribed factors of safety.

Although aircraft are not supposed to undergo greater loads than the specified limit loads, a certain amount of reserve strength against structural failure of a unit is necessary in the design of any machine or structure. Possibly the most important reason for prescribing factors of safety for airplanes is to provide for limitations that practically every airplane is subjected to with reference to the maximum velocity and maximum acceleration under which it can be flown. Since these are usually under the control of the pilot, it is possible to exceed slightly in emergency conditions the limit loads while preserving a reserve factor of safety against failure. Thus, exceeding the limit load should not prove serious from an airplane safety standpoint, although it might cause permanent structural deformations that would require repair or replacements of units or parts of the structure.

Certain sections of FAR 25 (reference 1, back page) refer to factors of safety as follows:

1. The section titled, "Factor of Safety" -- states that a safety factor of 1.5 must be used, unless otherwise provided. Ultimate load is equal to the limit load x 1.5.
2. Another section states that safety factor of 1.5 must be multiplied by other special factors of safety. That is, these multiplying factors are required for castings, bearings or fittings, whose strength is uncertain, or likely to deteriorate in service before normal replacement or where it may be subject to variability because of uncertainties in manufacturing methods.

FAIL SAFE STRENGTH

A section of FAR 25 titled "Fail Safe Strength" concerns redundancies and states in part that after failure of a single principal structural element, the remaining structure must be able to withstand static loads corresponding to certain loading conditions. (Single principal structural element is covered in later paragraph.)

This section further provides, that after failure of a single principal structural element, the remaining structure must be able to withstand cruise speed loads corresponding to fail safe maneuvering load factors of 2.0 at V_C. From data, in National Advisory Committee for Aeronautics (NACA) TN3086 (reference 2, back page) it is brought out that the probability of experiencing a 2g maneuvering load in normal operations is remote. This data covering 150,000 miles at normal operations showed five values in the range between .5g and .6g. For combined operational and flight check maneuvers, increment of 1.0g is indicated once in every 200,000 miles. Data covering 15.2 x 10^5 miles for jet powered transports, since adoption of the 2.0g fail safe maneuver load, confirms these determinations (reference 3, back page).

The design maneuver load factor is 2.5. Figure 1 refers to maneuver load factors.

FIGURE 1
MANEUVER LOAD FACTOR, DESIGN AND FAIL SAFE

$$\Delta N_{FS} = 1.0$$

$$1 + \Delta N_{FS} = 2.0$$

FAIL SAFE MANEUVER LOAD FACTOR

$$\Delta N_{DES} = 1.5$$

$$1 + \Delta N_{DES} = 2.5$$

DESIGN MANEUVER LOAD FACTOR

$$\frac{\Delta N_{FS}}{\Delta N_{DES}} = \frac{1.0}{1.5} = .67 \times 100\% = 67\%$$

At cruise speed, V_C, the aircraft design is usually significantly influenced by design gust. Specific gust velocities at V_C are 50 fps between sea level and 20,000 feet and reduced linearly to 25 fps at 50,000 feet. However, since the incremental maneuver load factor for fail safe design of 1.0g is 67 percent of the design limit maneuver load factor, the fail safe gust velocity was chosen as 67 percent of the limit gust velocity (50 fps) or 33 fps.

At V_B, design speed for maximum gust intensity, the rough air gust velocities are 66 fps between sea level and 20,000 feet and reduced linearly to 38 fps at 50,000 feet. The fail-safe gust for V_B was chosen as 75 percent of design gust (66 fps) or 49 fps.

At V_D, the design dive speed, the gust velocities are 25 fps between sea level and 20,000 feet and reduced linearly to 12.5 fps at 50,000 feet. The fail safe gust for V_D was chosen as 60 percent of design gust (25 fps) or 15 fps. Figure 2 refers to gust velocities.

FIGURE 2
GUST VELOCITIES, DESIGN AND FAIL SAFE

$$\left.\begin{aligned} V_{B_{DES}} &= 66\text{FPS} \\ V_{B_{FS}} &= 49\text{FPS} \end{aligned}\right\} \qquad V_{B_{FS}} = .75V_{B_{DES}}$$

$$\left.\begin{aligned} V_{C_{DES}} &= 50\text{FPS} \\ V_{C_{FS}} &= 33\text{FPS} \end{aligned}\right\} \qquad V_{C_{FS}} = .67V_{C_{DES}}$$

$$\left.\begin{aligned} V_{D_{DES}} &= 25\text{FPS} \\ V_{D_{FS}} &= 15\text{FPS} \end{aligned}\right\} \qquad V_{D_{FS}} = .60V_{D_{DES}}$$

At cruise speed, V_C, the aircraft design is usually significantly influenced by design gust. Specific gust velocities at V_C are 50 fps between sea level and 20,000 feet and reduced linearly to 25 fps at 50,000 feet. However, since the incremental maneuver load factor for fail safe design of 1.0g is 67 percent of the design limit maneuver load factor, the fail safe gust velocity was chosen as 67 percent of the limit gust velocity (50 fps) or 33 fps.

At V_B, design speed for maximum gust intensity, the rough air gust velocities are 66 fps between sea level and 20,000 feet and reduced linearly to 38 fps at 50,000 feet. The fail-safe gust for V_B was chosen as 75 percent of design gust (66 fps) or 49 fps.

At V_D, the design dive speed, the gust velocities are 25 fps between sea level and 20,000 feet and reduced linearly to 12.5 fps at 50,000 feet. The fail safe gust for V_D was chosen as 60 percent of design gust (25 fps) or 15 fps. Figure 2 refers to gust velocities.

FIGURE 2

GUST VELOCITIES, DESIGN AND FAIL SAFE

$$\left.\begin{array}{l} V_{B_{DES}} = 66\text{FPS} \\ V_{B_{FS}} = 49\text{FPS} \end{array}\right\} \qquad V_{B_{FS}} = .75V_{B_{DES}}$$

$$\left.\begin{array}{l} V_{C_{DES}} = 50\text{FPS} \\ V_{C_{FS}} = 33\text{FPS} \end{array}\right\} \qquad V_{C_{FS}} = .67V_{C_{DES}}$$

$$\left.\begin{array}{l} V_{D_{DES}} = 25\text{FPS} \\ V_{D_{FS}} = 15\text{FPS} \end{array}\right\} \qquad V_{D_{FS}} = .60V_{D_{DES}}$$

Magnitude and frequency of gust accelerations and gust velocities data experienced during operations of five types of turbine airplanes are reported in NACA TN D-1392 (reference 3, see back page) which states, "In general, gust-acceleration and gust-velocity histories for the turbine airplanes do not appear to be significantly different from the histories recorded in piston-engine airplanes."

It is quite possible that during the lifetime of an airplane, turbulent conditions near storm areas or over mountains or water areas might produce air gust velocities slightly greater than that specified in the load requirements, thus the factor of safety should insure against failure if such situations arise.

A level of fail safe structural integrity rather than an absolute value is represented by the distance mentioned, above, of 200,000 miles (reference 2, back page). Since fail safe loads are determined for envelope design conditions that set forth critical c.g., critical speed, critical altitude, and critical weight distribution, a multiple of this value represents the distance in miles which an airplane could safely fly with an initial fatigue failure. This current requirement is considered conservative because the probability of combining these critical items is remote.

Further, this section on fail safe design criteria stipulates a multiplying factor of 15 percent (1.15) unless dynamic effects of failure under static loads are considered during test and analysis. The 1.15 factor was provided as an additional supporting feature and was justified by test data at hand from two principal manufacturers. A 15 percent increase in the fail safe load would provide adequately for dynamic stress increase upon sudden failure of a part (reference 4, back page).

A recent amendment to Part 25 titled, "Sonic Fatigue Evaluation," is pertinent to this discussion. Amendment 25-10, effective October 10, 1966, (reference 6, back page) requires that turbojet-powered transport aircraft be evaluated during type certification to show that either: (1) sonic cracks are not probable in any part of the flight structure in the event of a sonic excitation and (2) catastrophic failure caused by sonic fatigue cracks is not probable. The rule prior to this amendment did not adequately cover sonic fatigue problems, providing only for evaluation by analysis without tests and for substantiation of a single principal structural element only. Further, that rule applied only for low frequency pressure loads whereas sonic excitation involves high frequency load.

GENERAL DISCUSSION ON FATIGUE EVALUATION

CAM 4b, Appendix H, titled "Fatigue Evaluation of a Flight Structure," (reference 6) is in use by the industry. Appendix H will eventually be released as an advisory circular. Notwithstanding, the information contained in this Appendix is presented merely for guidance purposes and is not mandatory in nature. Section IIB of Appendix H, titled "Fail Safe Strength Evaluation," provides examples of the principal structural elements and states that such elements "are those which contribute significantly to carrying flight and pressurization loads and whose failure could result in a catastrophic failure of the aircraft."

A realistic definition of a principal structure element is necessary. It is obvious that sufficient reference to structure be included in this definition so that should structural loss occur it would be evident upon normal maintenance inspections. This would preclude accumulation of large amounts of flying time in a structurally weakened aircraft.

The need for a uniform approach to fatigue evaluation is self-evident. However, this problem concerns a complex and controversial area. Design features and methods of fabrication, new approaches to fatigue evaluation and new configurations complicate an attempt to standardize the approach. Since the need is "self-evident" what are you going to do about it?

INSPECTIONS

Until such time as the uniform approach mentioned above is discovered, we should be guided by the following known facts:

Section II, I of Appendix H, titled "Inspection," points out that detection of fatigue cracks before they become dangerous is the ultimate control in insuring fail safe characteristics of the flight structure.

Figure 3 shows a typical life of a structure. Early in the life the "built-in" faults lead to the familiar "teething troubles," then come the "random" faults, which appear during the major part of the working life, and finally the faults of "age." The figure also shows, at regular intervals, a number of vertical lines, the "vertical fault detectors" which represent the routine inspections. These vertical fault detectors extend from the "detection level" to the failure level.

They are, therefore, effective in detecting and stopping all faults, which have reached, at the time of the inspection, a level of development above that of detection, but they will pass others, which at the time are still below that level.

The level of development of a fault at discovery depends on three factors:

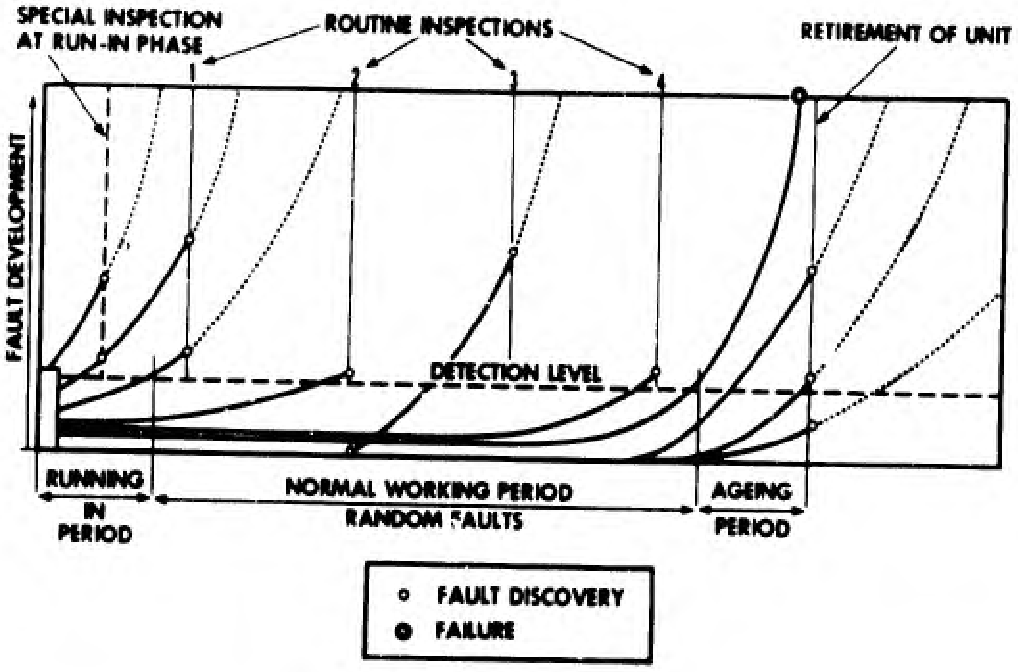
a. The detection level of the fault detector (inspection)

b. The time space between two consecutive inspections

c. The shape of the fault development curve in this time space.

Clearly, if the detection level is low and the time space between inspections is short, then little opportunity is given for the fault to develop to a dangerous level at discovery. If, on the other hand, the curve of fault development rises abruptly, there may be a high level of fault development at discovery, or a failure before any discovery may be possible. Short periods between inspections, combined with low detection levels are, therefore, desirable. Also steep rises in the development of faults must be avoided.

FIGURE 3
STRUCTURE INSPECTIONS



An aircraft should be able to continue in a condition for safe operation when nonconcurrent members of a multipath fail safe structure have wholly or partially failed. Notwithstanding, protection against structural fatigue failures, by continuous periodic inspections of the airplane, cannot be stressed too much. However, these methods have their limitations. The cold fact appears to be that inspections work when we know where to look in the aircraft structure. It is generally known, however, that detection of a fatigue crack without prior knowledge -- for exemple, one which occurs in a rivet hole -- parallels finding the proverbial needle in a haystack.

CONCLUSIONS

Fatigue evaluation of the aircraft structure and the importance of maintenance inspection have been briefly discussed. It is hoped this short discussion will further encourage the development of safe, efficient, aircraft maintenance practices and programs.

REFERENCES

1. Federal Aviation Regulations, Part 25, Airworthiness Standards Transport Category Aircraft.

2. T. C. Coleman and Mr. Copp, "Maneuver Accelerations Experienced by Five Types of Commercial Transport Airplanes During Routine Operations," NACA TN 3086, April 1954.

3. "Operational Experiences of Turbine-Powered Transport Airplanes," NACA TN D-1392, October 1962.

4. James E. Dougherty, "FAA Fatigue Strength Criteria and Practices," presented at Symposium on Fatigue Design Procedures, Munich, Germany, June 1965.

5. Amendment 25-10, 31 F.R. 11933, September 10, 1966, titled "Sonic Fatigue Evaluation."

6. Federal Aviation Agency Civil Aeronautics Manual 4b, Appendix H, Fatigue Evaluation of Flight Structure, September 1962.