U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: DAMAGE-TOLERANCE AND FATIGUE EVALUATION OF STRUCTURE
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Change:

1. PURPOSE. This advisory circular (AC) sets forth an acceptable means of compliance with the provisions of Part 25 of the Federal Aviation Regulations (FAR) dealing with the damage-tolerance and fatigue evaluation requirements of transport category aircraft structure. It also provides rational guidelines for the evaluation of scatter factors for the determination of life for parts categorized as Safe-Life.

2 CANCELLATION. Advisory Circular 25.571-1A, dated March 5, 1986, is canceled.

3. DEFINITIONS OF TERMS USED IN THIS AC.

a. Damage tolerance means that the structure has been evaluated to ensure that should serious fatigue, corrosion, or accidental damage occur within the operational life of the airplane, the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected.

b. Fail-safe means that the structure has been evaluated to assure that catastrophic failure is not probable after fatigue failure or obvious partial failure of a single, principal structural element.

c. Safe-life means that the structure has been evaluated to be able to withstand the repeated loads of variable magnitude expected during its service life without detectable cracks.

d. Principal structural elements are those which contribute significantly to carrying flight, ground, and pressurization loads, and whose failure could result in catastrophic failure of the airplane.

e. Critical structural elements are those elements whose failure would result in catastrophic failure of the airplane.

f. Primary structure is that structure which carries flight, ground, or pressure loads.

g. Secondary structure is that structure which carries only air or inertial loads generated on or within the secondary structure.

h. Single load path is where the applied loads are eventually distributed through a single member within an assembly, the failure of which would result in the loss of the structural integrity of the component involved.

i. Multiple load path is identified with redundant structures in which (with the failure of individual elements) the applied loads would be safely distributed to other load-carrying members.

j. Reliability refers to detail designs or methodologies which service history has demonstrated to be reliable.

k. Probability refers to a probability of occurrence of an event consistent with past successful experience..

l. Scatter factor. A life reduction factor used in the interpretation of fatigue analysis and test results.

4. BACKGROUND.

a. Since the early 1970's, there have been significant state-of-the-art and industry-practice developments in the area of structural fatigue and fail-safe strength evaluation of transport category airplanes. Recognizing that these developments could warrant some revision of the existing fatigue requirements in §§ 25.571 and 25.573 of Part 25 of the FAR, the FAA, on November 18, 1976, gave notice of its Transport Category Airplane Fatigue Regulatory Review Program and invited interested persons to submit proposals to amend those requirements (41 FR 50956). The proposals and related discussions formed the basis for the revision of the structural fatigue evaluation standards of §§ 25.571 and 25.573 and the development of guidance material. To that end, § 25.571 was revised, § 25.573 was deleted (the scope of § 25.571 was expanded to cover the substance of the deleted section), and guidance material (AC 25.571-1) was provided which contained compliance provisions related to the proposed change.

b. Since issuance of AC 25.571-1 on 9/28/78, additional guidance material, including discrete source damage, was developed and incorporated in revision 1A on 3/5/86. The AC is further revised to add guidance on the elements to be considered in developing scatter factors for certification.

5. INTRODUCTION.

a. The contents of this advisory circular are considered by the FAA in determining compliance with the damage-tolerance and fatigue requirements of § 25.571.

(1) Although a uniform approach to the evaluation required by § 25.571 is desirable, it is recognized that in such a complex field new design features and methods of fabrication, new approaches to the evaluation, and new configurations could necessitate variations and deviations from the procedures described in this advisory circular. Close adherence to the procedures in this advisory circular is encouraged.

(2) Damage tolerance design is required, unless it entails such complications that an effective damage-tolerant structure cannot be achieved within the limitations of geometry, inspectability, or good design practice. Under these circumstances, a design that complies with the fatigue evaluation (safe-life) requirements is used. A typical example of structure that might not be conducive to damage-tolerance design is the landing gear and its attachments.

(3) Experience with the application of methods of fatigue evaluation indicates that a test background should exist in order to achieve the design objective. Even under the damage tolerance method discussed in paragraph 6 of this AC, it is the general practice within industry to conduct damage tolerance tests for design information and guidance purposes. Damage location, growth, and detection data should also be considered in establishing a recommended inspection program.

b. Typical loading spectrum expected in service. The loading spectrum should be based on measured statistical data of the type derived from government and industry load history studies and, where insufficient data are available, on a conservative estimate of the anticipated use of the airplane. The principal loads that should be considered in establishing a loading spectrum are flight loads (gust and maneuver), ground loads (taxiing, landing impact, turning, engine runup, braking, thrust reversing, and towing), and pressurization loads.. The development of the loading spectrum includes the definition of the expected flight plan which involves climb, cruise, descent, flight times, operational speeds and altitudes, and the approximate time to be spent in each of the operating regimes. Operations for crew training and other pertinent factors, such as the dynamic stress characteristics of any flexible structure excited by turbulence or buffeting, should also be considered. For pressurized cabins, the loading spectrum should include the repeated application of the normal operating differential pressure, and the superimposed effects of flight loads and external aerodynamic pressures.

c. Components to be evaluated. In assessing the possibility of serious fatigue failures, the design should be examined to determine probable points of failure in service. In

this examination, consideration should be given, as necessary, to the results of stress analyses, static tests, fatigue tests, strain gage surveys, tests of similar structural configurations, and service experience. Service experience has shown that special attention should be focused on the design details of important discontinuities, main attach fittings, tension joints, splices, and cutouts such as windows, doors, and other openings. Locations prone to accidental damage (such as that due to impact with ground servicing equipment near airplane doors) or to corrosion should also be considered.

d. Analyses and tests. Unless it is determined from the foregoing examination that the normal operating stresses in specific regions of the structure are of such a low order that serious damage growth is extremely improbable, repeated load analyses or tests should be conducted on structures representative of components or subcomponents of the wing, control surfaces, empennage, fuselage, landing gear, and their related primary attachments. Test specimens should include structure representative of attachment fittings, major joints, changes in section, cutouts, and discontinuities. Any method used in the analyses should be supported, as necessary, by test or service experience. Typical (average) values of material properties and other parameters may be used in residual strength, crack growth, and damage detection analyses for damage tolerance evaluations per paragraph 6 and discrete source damage per paragraph 8.

6. DAMAGE-TOLERANCE EVALUATION.

a. General. The damage tolerance evaluation of structure is intended to ensure that should serious fatigue, corrosion, or accidental damage occur within the operational life of the airplane, the remaining structure can withstand reasonable loads without failure or excessive structural deformation until the damage is detected. Included are the considerations historically associated with fail-safe design. The evaluation should encompass establishing the components which are to be designed as damage-tolerant, defining the loading conditions and extent of damage, conducting structural tests or analyses, or both, to substantiate that the design objective has been achieved, and establishing data for inspection programs to ensure detection of damage. Although this evaluation applies to either single or multiple load path structure, the use of multiple load path structure should be given high priority in achieving damage-tolerant design. Design features which should be considered in attaining a damage-tolerant structure include the following:

(1) Multiple load path construction and the use of crack stoppers to control the rate of crack growth, and to provide adequate residual static strength;

(2) Materials and stress levels that, after initiation of cracks, provide a controlled slow rate of crack propagation combined with high residual strength;

(3) Arrangement of design details to ensure a sufficiently high probability that a failure in any critical structural element will be detected before the strength has been reduced below the level necessary to withstand the loading conditions specified in § 25.571(b), so as to allow replacement or repair of the failed elements; and

(4) Provisions to limit the probability of concurrent multiple damage, particularly after long service, which could conceivably contribute to a common facture path. Examples of such multiple damage are:

(i) A number of small cracks which might coalesce to form a single long crack;

(ii) Failures, or partial failures, in adjacent areas due to the redistribution of loading following a failure of a single element; and

(iii) Simultaneous failure, or partial failure, of multiple load path discrete elements, working at similar stress levels.

b. Normally, the damage tolerance assessment consists of a deterministic evaluation of the above design features. This paragraph provides guidelines for this approach. In certain specific instances, however, damage-tolerant design might be more realistically assessed by a probabilistic evaluation employing methods such as risk analysis. They are routinely employed in fail-safe evaluations of airplane systems and have occasionally been used where structure and systems are interrelated. These methods can be of particular value for structure consisting of discrete isolated elements where damage tolerance depends on the ability of the structure to sustain redistributed loads after failures of discrete elements resulting from fatigue, corrosion, or accidental damage. Where considered appropriate on multiple load path structure, probabilistic analysis may be used if it can be shown that loss of the airplane is extremely improbable, and the statistical data employed in the analysis is based on tests or operational experience, or both, of similar structure.

c. Identification of principal structural elements. Principal structural elements are those which contribute significantly to carrying flight, ground, and pressurization loads, and whose failure could result in catastrophic failure of the airplane. Typical examples of such elements are as follows:

(1) Wing and empennage.

(i) Control surfaces, slats, flaps, and their mechanical systems and attachments (hinges, tracks, and fittings);

(ii) Integrally stiffened plates;

(iii) Primary fittings;

(iv) Principal splices;

(v) Skin or reinforcement around cutouts or discontinuities;

(vi) Skin-stringer combinations;

(vii) Spar caps; and

(viii) Spar webs.

(2) Fuselage.

(i) Circumferential frames and adjacent skin;

(ii) Door frames;

(iii) Pilot window posts;

(iv) Pressure bulkheads;

(v) Skin and any single frame or stiffener element around a cutout;

(vi) Skin or skin splices, or both, under circumferential loads;

(vii) Skin or skin splices, or both, under fore and aft loads;

(viii) Skin around a cutout;

(ix) Skin and stiffener combinations under fore and aft loads;

(x) Door skins, frames, and latches; and

(xi) Window frames.

(3) Landing gear and their attachments.

(4) Engine mounts.

d. Extent of damage. Each particular design should be assessed to establish appropriate damage criteria in relation to inspectability and damage extension characteristics. In any damage determination, including those involving multiple cracks, it is possible to establish the extent of damage in terms of detectability with the inspection techniques to be used, the associated initially detectable crack size, the residual strength capabilities of the structure, and the likely damage-extension rate, considering the expected stress redistribution under the repeated loads expected in service and with the expected inspection frequency. Thus, an obvious partial failure could be considered to be the extent of the damage for residual strength assessment, provided a positive determination is made that the fatigue cracks will be detectable by the available inspection techniques at a sufficiently early stage of the crack development. In a pressurized fuselage, an obvious partial failure might be detectable through the inability of the cabin to maintain operating pressure or controlled decompression after occurrence of the damage. The following are typical examples of partial failures which should be considered in the evaluation:

(1) Detectable skin cracks emanating from the edge of structural openings or cutouts;

(2) A detectable circumferential or longitudinal skin crack in the basic fuselage structure;

(3) Complete severance of interior frame elements or stiffeners in addition to a detectable crack in the adjacent skin;

(4) A detectable failure of one element where dual construction is utilized in components such as spar caps, window posts, window or door frames, and skin structure;

(5) The presence of a detectable fatigue failure in at least the tension portion of the spar web or similar element; and

(6) The detectable failure of a primary attachment, including a control surface hinge and fitting.

e. Inaccessible areas. Every reasonable effort should be made to ensure inspectability of all structural parts, and to qualify them under the damage tolerance provisions (reference § 25.611).

f. Testing of principal structural elements. The nature and extent of residual strength tests on complete structures or on portions of the primary structure will depend upon applicable previous design, construction, tests, and service experience, in connection with

similar structures. Simulated cracks should be as representative as possible of actual fatigue damage. Where it is not practical to produce actual fatigue cracks, damage can be simulated by cuts made with a fine saw, sharp blade, guillotine, or other suitable means. If sawcuts in primary structure are used to simulate sharp fatigue cracks, sufficient evidence should be available from element tests to indicate equivalent residual strength. In those cases where bolt failure, or its equivalent, is to be simulated as part of a possible damage configuration in joints or fittings, bolts can be removed to provide that part of the simulation.

g. Identification of locations to be evaluated. The locations of damage to structure for damage tolerance evaluation should be identified as follows:

(1) Determination of general damage locations. The location and modes of damage can be determined by analysis or by fatigue tests on complete structures or subcomponents. However, tests might be necessary when the basis for analytical prediction is not reliable, such as for complex components. If less than the complete structure is tested, care should be taken to ensure that the internal loads and boundary conditions are valid.

(i) If a determination is made by analysis, factors such as the following should be taken into account:

(A) Strain data on undamaged structure to establish points of high stress concentration, as well as the magnitude of the concentration;

(B) Locations where permanent deformation occurred in static tests;

(C) Locations of potential fatigue damage identified by fatigue analysis; and

(D) Design details which service experience of similarly designed components indicates are prone to fatigue or other damage.

(ii) In addition, the areas of probable damage from sources such as severe corrosive environment damage should be determined from a review of the design and past service experience.

(2) Selection of critical damage areas. The process of actually locating where damage should be simulated in principal structural elements identified in paragraph 6c of this AC should take into account factors such as the following:

(i) Review analysis to locate areas of maximum stress and low margin of safety;

(ii) Select locations in an element where the stresses in adjacent elements would be the maximum with the damage present;

(iii) Select partial fracture locations in an element where high stress concentrations are present in the residual structure; and

(iv) Select locations where detection would be difficult.

h. Damage tolerance analysis and tests.

(1) It should be determined by analysis, supported by test evidence, that:

(i) The structure, with the extent of damage established for residual strength evaluation, can withstand the specified design limit loads (considered as ultimate loads); and

(ii) The damage growth rate under the repeated loads expected in service (between the time the damage becomes initially detectable and the time the extent of damage reaches the value for residual strength evaluation) provides a practical basis for development of the inspection program and procedures described in paragraph 6i of this AC.

(2) The repeated loads should be as defined in the loading, temperature, and humidity spectra. The loading conditions should take into account the effects of structural flexibility and rate of loading where they are significant.

(3) The damage tolerance characteristics can be shown analytically by reliable or conservative methods such as the following:

(i) By demonstrating quantitative relationships with structure already verified as damage tolerant;

(ii) By demonstrating that the damage would be detected before it reaches the value for residual strength evaluation; or

(iii) By demonstrating that the repeated loads and limit load stresses do not exceed those of previously verified designs of similar configuration, materials, and inspectability.

(4) The maximum extent of immediately obvious damage from discrete sources should be determined and the remaining structure shown to have static strength for the maximum load (considered as ultimate load) expected during the completion of the flight. Normally, this would be an analytical assessment. In the case of uncontained engine failures, the fragments and paths to be considered should be consistent with those used in showing compliance with § 25.903(d)(1) of the FAR, and with typical damage experienced in service.

i. Inspection.

(1) Detection of damage before it becomes critical is the ultimate control in ensuring the damage tolerance characteristics of the structure. Therefore, the applicant should provide sufficient guidance information to assist operators in establishing the frequency, extent, and methods of inspection of the critical structure. This kind of information must, under § 25.571(a)(3) of the FAR, be included in the Instructions for Continued Airworthiness required by § 25.1529 of the FAR.

(2) Due to the inherent, complex interactions of the many parameters affecting damage tolerance, such as operating practices, environmental effects, load sequence on crack growth, and variations in inspection methods, related operational experience should be taken into account in establishing inspection procedures.

(3) A comparative analysis can be used to guide the changes from successful past practice when necessary. Therefore, maintenance and inspection requirements should recognize the dependence on experience and should be specified in a document that provides for revision as a result of operational experience, such as the one containing the operator's FAA-approved structural inspection program developed through the Maintenance Review Board (MRB) procedures for FAR Part 121 operators.

7. FATIGUE EVALUATION.

a. General. The evaluation of structure under the following fatigue (safe-life) strength evaluation methods is intended to ensure that catastrophic fatigue failure, as a result of the repeated loads of variable magnitude expected in service, will be avoided throughout the structure's operational life. Under these methods, the fatigue life of the structure should be determined. The evaluation should include the following:

(1) Estimating or measuring the expected loading spectra for the structure;

(2) Conducting a structural analysis including consideration of the stress concentration effects;

(3) Performing fatigue testing of structure which cannot be related to a test background to establish response to the typical loading spectrum expected in service;

(4) Determining reliable replacement times by interpreting the loading history, variable load analyses, fatigue test data, service experience, and fatigue analyses;

(5) Evaluating the possibility of fatigue initiation from sources such as corrosion, stress corrosion, disbonding, accidental damage and manufacturing defects based on a review of the design, quality control and past service experience; and

(6) Providing necessary maintenance programs and replacement times to the operators. The maintenance program should be included in Instructions for Continued Airworthiness in accordance with § 25.1529.

b. Scatter Factor for Safe-life Determination. In the interpretation of fatigue analyses and test data, the effect of variability should, under § 25.571(c), be accounted for by an appropriate scatter factor. In this process it is appropriate that the applicant justify the scatter factor chosen for any safe-life part. The following guidance is provided (see Figure 1):

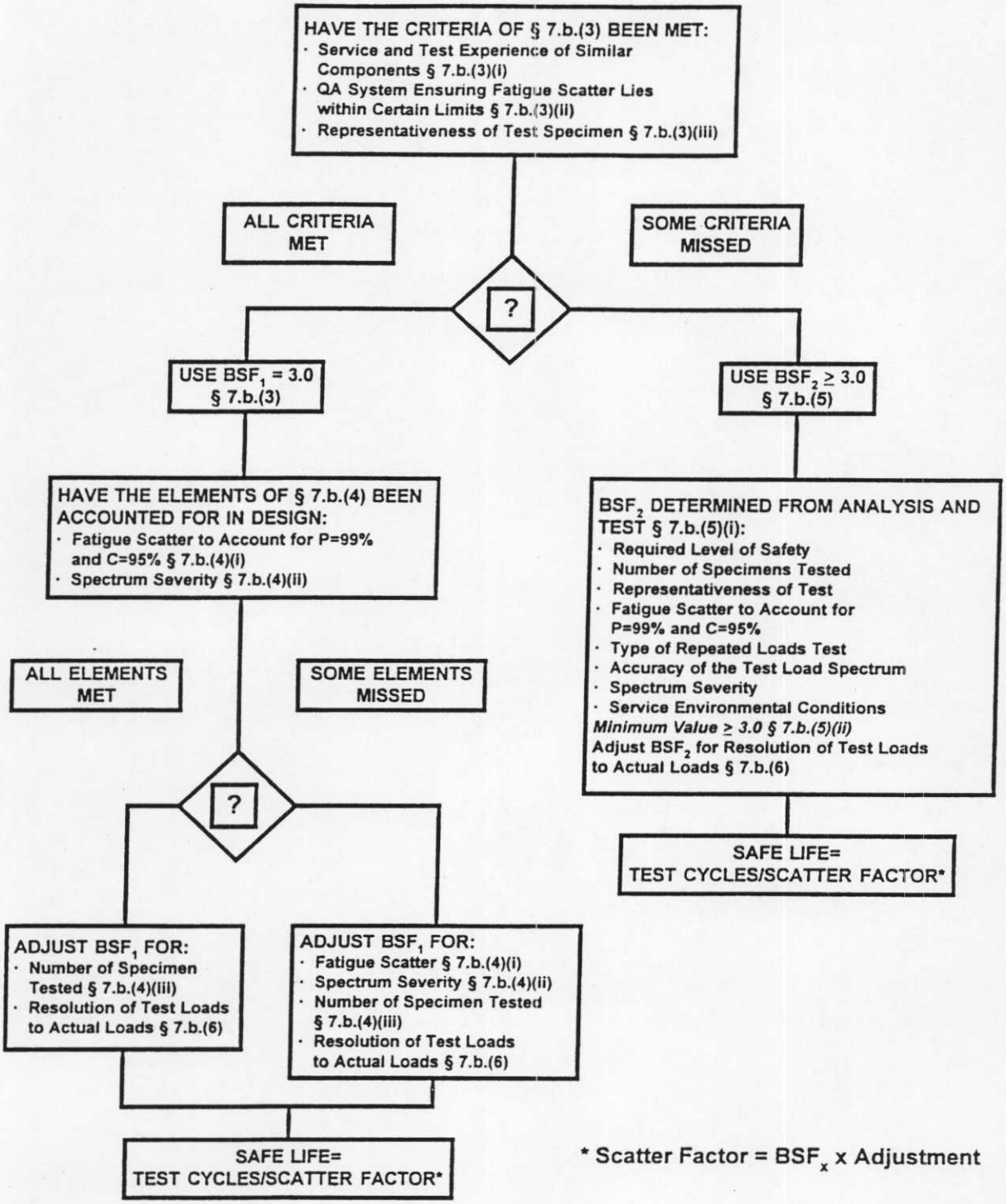

Figure 1. Safe-Life Determination

(1) The base scatter factors applicable to test results are: $BSF_1 = 3.0$, and BSF_2 = (see paragraph 7b(5) of this AC). If the applicant can meet the requirements of paragraph 7b(3) of this AC, he may use BSF_1 or, at his option, BSF_2.

(2) The base scatter factor, BSF_1, is associated with test results of one representative test specimen.

(3) Justification for use of BSF_1. BSF_1 may only be used if the following criteria are met:

(i) Understanding of load paths and failure modes. Service and test experience of similar in-service components that were designed using similar design criteria and methods should demonstrate that the load paths and potential failure modes of the components are well understood.

(ii) Control of design, material, and manufacturing process quality. The applicant should demonstrate that his quality system (e.g., design, process control, and material standards) ensures the scatter in fatigue properties is controlled, and that the design of the fatigue critical areas of the part account for the material scatter.

(iii) Representativeness of the test specimen.

(A) The test article should be full scale (component or sub-component) and represent that portion of the production aircraft requiring test. All differences between the test article and production article should be accounted for either by analysis supported by test evidence or by testing itself.

(B) Construction details, such as bracket attachments, clips, etc., should be accounted for, even though the items themselves may be non-load bearing.

(C) Points of load application and reaction should accurately reflect those of the aircraft, ensure correct behavior of the test article, and guard against uncharacteristic failures.

(D) Systems used to protect the structure against environmental degradation can have a negative effect on fatigue life and therefore should be included as part of the test article.

(4) Adjustments to base scatter factor BSF_1. Having satisfied the criteria of paragraph 7b(3), justifying the use of BSF_1, the base value of 3.0 should be adjusted to

account for the following considerations, as necessary, where not wholly taken into account by design analysis. As a result of the adjustments, the final scatter factor may be less than, equal to, or greater than 3.0.

(i) Material fatigue scatter. Material properties should be investigated up to a 99% probability of survival and a 95% level of confidence.

(ii) Spectrum severity. Test load spectrum should be derived based on a spectrum sensitive analysis accounting for variations in both utilization (i.e. aircraft weight, cg etc.) and occurrences/size of loads. The test loads spectrum applied to the structure should be demonstrated to be conservative when compared to the usage expected in service.

(iii) Number of representative test specimens. Well established statistical methods should be used that associate the number of items tested with the distribution chosen, to obtain an adjustment to the base scatter factor.

(5) If the applicant cannot satisfy the intent of all of paragraph 7b(3) of this AC, BSF_2 should be used.

(i) The applicant should propose scatter factor BSF_2 based on careful consideration of the following issues: the required level of safety, the number of representative test specimens, how representative the test is, expected fatigue scatter, type of repeated load test, the accuracy of the test loads spectrum, spectrum severity, and the expected service environmental conditions.

(ii) In no case should the value of BSF_2 be less than 3.0.

(6) Resolution of test loadings to actual loadings. The applicant may use a number of different approaches to reduce both the number of load cycles and number of test set-ups required. These include, but are not limited to, spectrum blocking (e.g., a change in the spectrum load sequence to reduce the total number of test setups); high load clipping (e.g., the reduction of the highest spectrum loads to a level such that the beneficial effects of compression yield are reduced or eliminated); and low load truncation (e.g., the removal of non-damaging load cycles to simplify the spectrum). Due to the modifications to the flight-by-flight loading sequence caused by these changes, the applicant should propose either analytical or empirical approaches to quantify an adjustment to the number of test cycles which represents the difference between the test spectrum and assumed flight-by-flight spectrum. In addition, an adjustment to the number of test cycles may be justified by raising or lowering the test load levels, as long as appropriate data supports the applicant's position. Other effects to be considered are different failure locations, different response to fretting

conditions, temperature effects, etc. The analytical approach should use well established methods or be supported by test evidence.

c. Replacement times. Replacement times should be established for parts with established safe-lives and should, under § 25.571(a)(3), be included in the information prepared under § 25.1529. These replacement times can be extended if additional data indicates an extension is warranted. Important factors that should be considered for such extensions include, but are not limited to, the following:

(1) Comparison of original evaluation with service experience.

(2) Recorded load and stress data. Recorded load and stress data entails instrumenting airplanes in service to obtain a representative sampling of actual loads and stresses experienced. The data to be measured include airspeed, altitude, and load factor versus time data; or airspeed, altitude, and strain ranges versus time data; or similar data. The data, obtained by instrumenting airplanes in service, provide a basis for correlating the estimated loading spectrum with the actual service experience.

(3) Additional analyses and tests. If test data and analyses based on repeated load tests of additional specimens are obtained, a re-evaluation of the established safe-life can be made.

(4) Tests of parts removed from service. Repeated load tests of replaced parts can be utilized to reevaluate the established safe-life. The tests should closely simulate service loading conditions. Repeated load testing of parts removed from service is especially useful where recorded load data obtained in service are available, since the actual loading experienced by the part prior to replacement is known.

(5) Repair or rework of the structure. In some cases, repair or rework of the structure can gain further life.

d. Type design developments and changes. For design developments or design changes involving structural configurations similar to those of a design already shown to comply with the applicable provisions of § 25.571(c), it might be possible to evaluate the variations in critical portions of the structure on a comparative basis. Typical examples would be redesign of the wing structure for increased loads, and the introduction in pressurized cabins of cutouts having different locations or different shapes, or both. This evaluation should involve analysis of the predicted stresses of the redesigned primary structure and correlation of the analysis with the analytical and test results used in showing compliance of the original design with § 25.571(c).

e. Environmental effects such as temperature and humidity should be considered in the damage tolerance and fatigue analysis and should be demonstrated through suitable testing.

8. DISCRETE SOURCE DAMAGE.

a. General. The purpose of this section is to establish FAA guidelines for consistent selection of load conditions for residual strength substantiation in showing compliance with § 25.571(e), Damage tolerance (discrete source) evaluation. The intent of these guidelines is to define load conditions that will not be exceeded with a satisfactory level of confidence on the flight during which the specified incident of § 25.571(e) occurs. In defining these load conditions, consideration has been given to the expected damage to the airplane, the anticipated response of the pilot at the time of the incident, and the actions of the pilot to avoid severe load environments for the remainder of the flight consistent with his knowledge that the airplane may be in a damaged state. With these considerations in mind, the following ultimate loading conditions should be used to establish residual strength of the damaged structure.

b. The maximum extent of immediately obvious damage from discrete sources (§ 25.571(e)) should be determined and the remaining structure shown, with an acceptable level of confidence, to have static strength for the maximum load (considered as ultimate load) expected during completion of the flight.

c. The ultimate loading conditions should not be less than those developed from the following conditions:

(1) At the time of the incident:

(i) The maximum normal operating differential pressure, multiplied by a 1.1 factor, plus the expected external aerodynamic pressures during 1g level flight, combined with 1g flight loads.

(ii) The airplane, assumed to be in 1g level flight, should be shown to be able to survive any maneuver or any other flight path deviation caused by the specified incident of § 25.571(e), taking into account any likely damage to the flight controls and pilot normal corrective action.

(2) Following the incident:

(i) Seventy percent (70%) limit flight maneuver loads and, separately, 40 percent of the limit gust velocity (vertical and lateral) at the specified speeds,

each combined with the maximum appropriate cabin differential pressure (including the expected external aerodynamic pressure).

(ii) The airplane must be shown by analysis to be free from flutter up to V_D/M_D with any change in structural stiffness resulting from the incident.

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