(b) Damage-tolerant characteristics

A damage-tolerant structure has two notable attributes:

(1) The structure can tolerate a significant amount of damage, due to fatigue, environmental or accidental deterioration without compromising the continued airworthiness of the aeroplane (residual strength and rigidity).

(2) The structure can sustain that damage long enough to be found and repaired during scheduled or unscheduled maintenance (inspectability).

(c) Design considerations

To achieve a damage-tolerant structure, criteria should be established to guide the design process so that this design objective is achieved. The design process should include a damage tolerance evaluation (test and analysis) to demonstrate that the damage-tolerant design objectives are achieved, and to identify inspections or other procedures necessary to prevent catastrophic failure. Reliance on special inspections should be minimised by designing structure with easily detectable (e.g. visual) cracking modes. Since the occurrence of WFD can complicate a damage-tolerant evaluation to the point that reliable inspections programmes cannot be developed even with extremely intensive inspection methods, it must be demonstrated, with sufficient full-scale fatigue test evidence, that adequate maintenance procedures are contained in the ALS of the ICA, such that WFD will not occur within the LOV. A discussion on several issues that an applicant might face in demonstrating freedom from WFD is contained in Appendix 2 to this AMC.

(d) Design features

Design features which should be considered in attaining a damage-tolerant structure include the following:

(1) multiple load path construction and/or the use of damage containment features to arrest fast fracture or reduce the crack growth rate, and to provide adequate residual strength;

(2) materials and stress levels that provide a slow rate of crack propagation combined with high residual strength; and

(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 CS 25.571(b).

(e) Probabilistic evaluations

No guidance is provided in this AMC on probabilistic evaluation. Normally, damage tolerance assessments consist of a deterministic evaluation of design features described in paragraphs 7(d)(1), (2) and (3). Paragraphs (f) to (i) below provide guidelines for this approach.

(f) PSEs, detail design points, and locations to be evaluated

In accordance with CS 25.571(a), a damage tolerance and fatigue evaluation should be conducted for each part of the structure which could contribute to a catastrophic failure. PSEs such as wing, empennage, control surfaces and their systems, the fuselage, engine mountings, landing gears, and their related primary attachments, and all DDPs susceptible to fatigue that could contribute to a catastrophic failure should be evaluated.

In accordance with CS 25.571(a)(1)(ii), this evaluation must include the identification of PSEs and DDPs, the failure of which could contribute to catastrophic failure of the aeroplane. As defined in this AMC, a principal structural element is an element of structure that contributes significantly to the carrying of flight, ground, or pressurisation loads and whose integrity is essential in maintaining the overall structural integrity of the aeroplane. When identifying PSEs, consideration should be given to the effect caused by partial or complete loss or failure of structure with respect to continued safe flight and landing, considering all flight phases including stability, control and aeroelasticity.

A DDP is an area at higher risk of fatigue cracking than other areas, and may warrant specific actions such as special inspections or other procedures to ensure continued airworthiness.

(1) Locations requiring evaluation can be determined by analysis or by fatigue tests on complete structures or subcomponents. However, tests may 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.

The selection criteria for DDPs should also include the following considerations:

(a) any evidence of cracking encountered in service on a comparable structure;

(b) any evidence of cracking found during fatigue testing on a comparable structure;

(c) available strain gauge data;

(d) locations where permanent deformation occurred on static test articles;

(e) areas analytically shown to have a relatively low crack initiation life;

(f) susceptibility to corrosion or other environmental deterioration (e.g. disbonding);

(g) potential for manufacturing anomalies (e.g. new or novel manufacturing processes where the potential for damage may not be well understood);

(h) vulnerability to in-service induced accidental damage;

(i) areas whose failure would create high stresses in the remaining structure;

(j) elements in high tension or shear;

(k) low static margin;

(l) high stress concentrations;

(m) high load transfer;

(n) materials with high crack growth rates;

(o) some DDPs may exist outside of PSEs and may also have been classified as fatigue critical structure, e.g. undercarriage door attachments (see Appendix 5 for discussion on PSEs, FCS and DDP);

(p) areas where detection of damage would be difficult;

(q) locations subject to vibrations or other mechanisms that may lead to premature wear fastener holes; and

(r) locations vulnerable to moisture ingress or retention.

(2) Examples of principal structural elements (PSEs)

Typical examples of structure which are usually considered to be PSEs are:

(i) Wing and empennage

(a) control surfaces, slats, flaps, and their mechanical systems and attachments (hinges, tracks, and fittings);

(b) primary fittings;

(c) principal splices;

(d) skin or reinforcement around cut-outs or discontinuities;

(e) skin-stringer combinations or integrally stiffened plates;

(f) spar caps;

(g) spar webs; and

(h) ribs and bulkheads.

(ii) Fuselage

(a) circumferential frames and adjacent skin;

(b) pilot window posts;

(c) pressure bulkheads;

(d) skin and any single frame or stiffener element around a cut-out;

(e) skin or skin splices, or both, under circumferential loads;

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

(g) skin and stiffener combinations under fore and aft loads;

(h) door skins, frames, stops and latches;

(i) window frames; and

(j) floor beams[1].

(iii) Landing gear and their attachments

(iv) Engine mounts and struts

(v) Thrust reverser components, whose failure could result in inadvertent deployment

(3) 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

[1] Floor beams are not always critical but should be checked for criticality, particularly those located next to cut-outs or within non-circular pressurised sections.

considered to be the extent of the damage or 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. The following are typical examples of partial failures which should be considered in the evaluation:

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

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

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

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

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

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

(g) Inaccessible areas

Every reasonable effort should be made to ensure inspectability (reference CS 25.611) of all structural parts. In those cases where inaccessible and uninspectable blind areas exist, the damage tolerance evaluation should allow for extension of damage into detectable areas or demonstrate sufficient residual strength up to the LOV without inspection.

(h) Residual strength testing of principal structural elements

Analytical prediction of the residual strength of structures can be very complex due to non-linear behaviour, load redistribution and the potential for a multiplicity of failure modes. The nature and extent of residual strength tests will depend on previous experience 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. Whatever artificial means are used to simulate sharp fatigue cracks, sufficient evidence should be available from tests to indicate equivalent residual strength. If equivalency cannot be shown, every attempt should be made to apply enough cyclic loading to generate fatigue cracks from the artificial damage prior to applying residual strength loads. Special consideration should be given to the procedure for pre-cracking so that subsequent test results are representative. This can be an issue when slow stable tearing in ductile sheet or plate material is part of the failure mechanism. Inappropriate pre-cracking loads can lead to non-conservative results. 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.

(i) 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 residual strength loads (considered as ultimate loads); and

(ii) the crack growth life 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 programme and procedures described in Section 8 of this AMC.

(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; or

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

8. INSPECTION REQUIREMENTS

(a) Damage detection

Detection and repair of damage before it becomes critical is the most important factor in ensuring that the damage tolerance characteristics of the structure are maintained. For this reason, CS 25.571 requires that the applicant establish inspections or other procedures, as necessary, to prevent catastrophic failure from accidental, environmental, or fatigue damage, and include those inspections and procedures in the ALS of the Instructions for Continued Airworthiness required by CS 25.1529 (see also Appendix H to Part-25).

Due to the complex interactions of the many parameters that affect the damage tolerance evaluation, such as operating practices, environmental effects, load sequence effects on crack growth, and variations in inspection methods, operational experience should be taken into account in establishing inspection thresholds, repeat intervals, and inspection procedures.

(b) Environmental and accidental damage inspection programmes

The inspections developed under CS 25.571(b) are primarily for the detection of cracks developing from fatigue, accidental damage, and corrosion. As required by CS 25.571(a)(5), a separate programme needs to be implemented for the early detection of environmental and accidental damage. This is intended to minimise the risk of:

(1) interaction between corrosion and fatigue cracking;

(2) accidental damage developing into fatigue cracks; or

(3) corrosion developing due to accidental damage.

In many cases this can be accomplished through the Maintenance Review Board (MRB) activity or equivalent process agreed by EASA, for a new large aeroplane model using MSG-3 procedures. These procedures also require that a CPCP be developed.

For ED and AD programmes developed under the auspices of the MRB, the minimum ALS content associated with AD and ED may generally be limited to:

— a reference to the documents that contain the MRB report (MRBR) derived maintenance tasks for AD and ED; and

— the need to incorporate and maintain an effective CPCP in the operators' programme; and

— a statement requiring operators to control corrosion to Level 1 or better.

It is also important to explain to operators the link between the AD and ED inspection programmes and CS 25.571 and CS 25.1529 compliance.

Inspections that are designed to detect fatigue cracking resulting from AD or ED, where the originating damage cannot otherwise be demonstrated to be detected prior to the development of the fatigue cracks, must also be directly included in the ALS. For new structure where there is limited supporting data from service experience, the MRB will depend heavily on input from the analyses and test programmes conducted by the applicant during certification, and for this reason significant cooperation is required between those involved directly in certification and those participating in the MRBR development. Care should also be taken to ensure that the damage assumptions made remain conservative after entry into service. A check of the continued validity of the certification assumptions can be achieved through fleet leader programmes and robust reporting requirements. If there is any doubt about the likely performance of a completely new structure with respect to AD and ED, certain specific inspections in vulnerable areas may be better placed in the ALS.

The baseline CPCP may be established through the MRB Industry Steering Committee (ISC) using existing procedures for MRBR development or developed by the applicant and submitted directly to EASA. (Note: Provided the operator has an NAA-approved maintenance programme that controls corrosion to Level 1 or better, it does not need to follow exactly the baseline CPCP offered by the type certificate holder (TCH). However, all revisions to the TCH's programme for ED and AD must be considered by the operator for incorporation in the operators MP under the Part-M requirements.)

Reporting requirements for these programmes should extend to overhaul procedures where the condition of the part should be assessed and reported if outside of approved limits, whether or not it is to remain on the component being overhauled.

Changes and supplemental type certificates (STC) must also be provided with inspection programmes that address ED and AD.

(c) Inspection threshold for fatigue cracking

The inspection threshold is the point in time at which the first planned structural inspection is performed following entry into service. The threshold may be as low as the repeat interval, or may allow for a longer period of operation, provided certain conditions are met.

The concept of delaying an inspection threshold beyond the repeat interval is based on the premise that it will take a certain amount of time before fatigue cracks would develop to a size that would be detectable during a structural inspection. Consequently, it may be acceptable to wait some period of time before starting to inspect for fatigue cracks.

CS 25.571(a)(4) requires inspection thresholds for certain structure to be derived assuming that the structure contains an initial flaw of the maximum probable size that could exist as a result of manufacturing processes or manufacturing or service-induced damage. For metallic structure this would typically be achieved using crack growth analysis supported by tests. This approach applies to:

(1) single load path structure, and

(2) multiple load path 'fail-safe' structure and crack arrest 'fail-safe' structure, where it cannot be demonstrated that the resulting load path failure or partial failure (including arrested cracks) will be detected and repaired during normal maintenance, inspection, or operation of an aeroplane prior to failure of the remaining structure.

In this context, normal maintenance includes general visual structural inspections for accidental and environmental damage derived from processes such as the MRB application of MSG-3. Inspections should begin early enough to ensure that there is a high confidence of detecting cracks before they could lead to a catastrophic structural failure.

For the locations addressed by CS 25.571(a)(4) that are also susceptible to accidental (manufacturing or service induced) damage, the assumed initial flaw size for crack growth determination of the threshold should not be less than that which can be supported by service experience or test evidence. For example, if the type of damage expected is well defined, e.g. it is limited to dents, then there may be data that supports a longer threshold than would be derived by the assumption of a crack that is similar in size to the dent. However, in this case, the worst case manufacturing flaw should still be considered as a crack and the most conservative resulting threshold adopted. If supporting data is not available (e.g. for a completely new design where no specific investigation of the accidental damage threats or their influence on fatigue has been made), then the fatigue cracking inspection threshold should be set equal to the repeat interval derived for a crack detectable by general visual inspection means, since the initial damage and its growth is not well defined and could occur at any time.

The remaining areas of the structure evaluated under CS 25.571(b), i.e. multiple load path 'fail-safe' structure and crack arrest 'fail-safe' structure, where it can be demonstrated that the resulting load path failure, partial failure, or crack arrest will be detected and repaired during normal maintenance, inspection, or operation of an aeroplane prior to failure of the remaining structure must also have thresholds established for fatigue cracking. For these locations, methods that do not account for worst-case damage may be used in lieu of crack growth analysis if desired. For example, fatigue SN analysis and tests with an appropriate scatter factor or slow crack growth analysis based on appropriate initial manufacturing damage, i.e. typical manufacturing flaws as opposed to the maximum probable flaw (e.g. a 0.127 mm corner crack representing a typical manufacturing flaw in a fastener hole versus a 1.27 mm crack representing the maximum probable flaw).

The means of establishing the LOV and maintenance actions (including inspections) specifically associated to WFD is addressed in detail in Section 11 of this AMC.

All inspections necessary to detect fatigue cracking that have thresholds less than the approved operating limitation (LOV or interim limitations) of the maintenance programme must be included in the ALS.

Appendix 3 provides further details on threshold determination.

(d) Inspection

The basis for setting inspection intervals is the period of time during which damage is detectable and the residual strength remains above the required levels. The reliability of the repeat inspection programme (i.e. frequency of inspections and probability of detection) should assure damage detection before the residual strength of the aircraft is compromised. Inspection intervals must be established by applying appropriate reduction factors to this period to ensure that the crack or other damage or failed load path will typically be found well before the residual strength of the structure drops below the required level. Long periods of exposure to residual strength levels only just above the load limit should be avoided. This applies in particular to crack-arrest structure. It should be borne in mind that CS 25.305 is the principle requirement for strength of the airframe, and that CS 25.571 is primarily intended to provide an inspection programme that will ensure the timely detection and repair of damage in order to restore the aircraft to the required (CS 25.305) strength capability and preserve this capability throughout the majority of the aircraft's operational life.

Detectable crack sizes and shapes assumed to determine inspection intervals should be consistent with the inspection method capabilities and the cracking characteristics of the structure being evaluated. If concurrent cracking in adjacent areas or surrounding structure is expected within the operational life of the aeroplane, then this should be accounted for in the cracking scenario assumed.

9. FATIGUE (SAFE-LIFE) EVALUATION

9.1. Reserved

9.2. Fatigue (safe-life) evaluation

9.2.1. 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:

(a) estimating or measuring the expected loading spectra of the structure;

(b) conducting a structural analysis, including consideration of the stress concentration effects;

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

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

(e) 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

(f) providing necessary maintenance instructions including replacement times in the ICA in accordance with CS 25.1529.

9.2.2. Scatter factor for safe-life determination

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

(a) The base scatter factors (BSF) applicable to test results are: BSF1 = 3.0, and BSF2 = (see paragraph 9.2.2(e) of this AMC). If the applicant can meet the requirements of 9.2.2(c) of this AMC, he/she may use BSF1 or, at his/her option, BSF2.

(b) The base scatter factor, BSF1, is associated with test results of one representative test specimen.

(c) Justification for use of BSF1. BSF1 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/her 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 subcomponent) and represent that portion of the production aircraft requiring test. All differences between the test article and the 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-loadbearing.

(C) Points of load application and reaction should accurately reflect those of the aircraft, ensure correct behaviour 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.

(d) Adjustments to base scatter factor BSF1. Having satisfied the criteria of paragraph 9.2.2(c), justifying the use of BSF1, 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 utilisation (i.e. aircraft weight, cg, etc.) and occurrences/size of loads. The test load spectrum applied to the structure should be demonstrated to be conservative when compared to the expected usage 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.

(e) If the applicant cannot satisfy the intent of all of paragraph 9.2.2(c) of this AMC, BSF2 should be used.

(i) The applicant should propose scatter factor BSF2 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 BSF2 be less than 3.0.

(f) 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 the number of test set-ups required.

These include the following:

— spectrum blocking (i.e., a change in the spectrum load sequence to reduce the total number of test set-ups);

— high-load clipping (i.e., reduction of the highest spectrum loads to a level at which the beneficial effects of compression yield are reduced or eliminated); and

— low-load truncation (i.e., the removal of non-damaging load cycles to simplify the spectrum).

Due to the modifications to the flight-by-flight loading sequence, the applicant should propose either analytical or empirical approaches to quantify an adjustment to the number of test cycles which represents the