Fatigue and Damage Tolerance Airworthiness Research of Structural Repairs and Alterations of Transport Airplanes

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Abstract. Subpart E of Chinese Civil Avialion Regulation - Continued Airworthiness and Safety Improvement for Transport Category Airplanes (CCAR-26), requires for the evaluation of airplanes structures after repairs and modifications.This study analyzes the requirements of CCAR 26.41, CCAR 26.43, CCAR 26.45, CCAR 26.47, and CCAR 26.49. The differences between CCAR-26 subpart E and 14 CFR Part 26 Subpart E are studied. The related technical requirements and means of compliance of Subpart E are summarized. The findings can provide reference for the certification of transport airplanes.

Keywords: Fatigue, Damage tolerance, Airworthiness, Repair, Alteration

1 Introduction

Fatigue cracks is a problem that has been concerned in aviation field for many years. The fatigue cracks will damage the structural integrity of airplanes, reduce the flight performance, and even lead to catastrophic accidents.

As shown in Figure 1, since the ALOHA Airlines accident in 1988, the U.S. Congress issued the Aging Aircraft Safety Act (AASA), requiring the FAA to establish regulations to prevent catastrophic failures caused by fatigue cracks and ensure airplanes airworthiness. Based on this requirement, the FAA issued the Aging Aircraft Safety Regulations (AASR) in 2005, requiring that inspections of fatigue critical structures and inspections of repair and modification of fatigue critical structures, shall be based on damage tolerance evaluations.

J. Zhang et al. (eds.), *Proceedings of the 2026 2nd International Conference on Engineering Management and Safety Engineering (EMSE 2026)*, Advances in Engineering Research 300,
https://doi.org/10.2991/978-94-6239-703-3_5

Fig. 1. ALOHA Airlines accident in 1988.

Prompted by the safety regulations, the FAA issued the certification regulation — 14 CFR Part 26[1] 'Continued Airworthiness and Safety Improvements for Transport Category Airplanes'—on December 12, 2007. in which Subpart E focuses on damage tolerance requirements for repair and alteration.The regulation became effective on January 11, 2008. Jia Baohui et al. provided an interpretation of the formulation, promulgation, and implementation of 14 CFR Part 26[2].

However, the structural damage tolerance and fatigue evaluation requiredin CCAR-25 25.571 only applied to aircraft baseline structures, without addressing inspections after repairs and alterations. Civil Aviation Administration of China issued CCAR-26-R0 on December 11, 2007. To resolve potential structural fatigue issues arising from repairs and modifications, Subpart E of CCAR-26-R0 'Damage Tolerance Data for Repairs and Alterations' requires type certificate holders or applicants to develop damage tolerance data that affect repair and alteration of fatigue critical structures. Additionally, certain airplanes are also requied to develop repair evaluation guidelines and submit them to the operators.

2 Analysis of Airworthiness Regulations

The following sections of CCAR-26 apply to damage tolerance and fatigue evaluation of structural repairs and modifications of transport airplanes:

CCAR 26.41 gives the definition of some terms, such as damage tolerance evaluation, damage tolerance inspection, fatigue critical structure, etc.

CCAR 26.43 requires for airplanes repair, and the holders of or applicants for type certificates (TC)/ validation of type certificates (VTC) should show compliance with this section.

CCAR 26.43(a) specifies the scope of airplane models. The airplane's certification date and capacity must be considered to determine whether compliance with § 26.43 is required.

CCAR 26.43(b) requires the identification of fatigue critical baseline structures (FCBS) for all airplane model variations and derivatives approved under TC or VTC.

The list of FCBS must be submitted to CAAC for approval, and once approved, shall be made available to operators required to comply with CCAR 26.47, CCAR-121[3] and CCAR-129[4].

CCAR 26.43(c) and (d) require that for existing repair data published by the holder of TC that is current as of December 7, 2011, for future published repair data, and for future repair data not published, the holders of or applicants for TC/ VTC must perform damage tolerance evaluations and develop damage tolerance inspections for repairs of such critical baseline structures, and submit the damage tolerance data to CAAC for approval. Upon approval, the data must be made available to operators required to comply with CCAR-121[3] and CCAR-129[4].

CCAR 26.43(e) requires that airplane models whose TC/ VTC is issued before December 7, 2011, the holder of TC must develop repair evaluation guidelines for operators' use. These guidelines shall be submitted to CAAC for approval. Upon approval, the guidelines shall be made available to operators required to comply with CCAR-121[3] and CCAR-129[4].

CCAR 26.43(f) sets out the deadline for showing compliance with paragraph (b) to (e) of this section.

CCAR 26.45 sets out requirements for repairs to alterations. The holders of or applicants for TC/ VTC should show compliance with this section.

CCAR 26.45(a) specifies that 26.45 apply to airplanes subject to CCAR 26.43.

CCAR 26.45(b) requires that for existing and future alteration data developed by the holders of TC/ VTC, the holders must (1) review the alteration data and identify all alterations that affect FCBS, (2) identify all fatigue critical alteration structure (FCAS) for each alteration that affects FCBS, (3) develop a list of FCAS and submit it to CAAC, (4) upon approval, the list of FCAS shall be made available to operators required to comply with CCAR-121[3] and CCAR-129[4].

CCAR 26.45(c) requires that for existing and future alteration data developed by the holders of TC/ VTC that affects FCBS, the holders must: (1) perform damage tolerance evaluations and develop corresponding damage tolerance inspections, (2) submit these damage tolerance evaluations (including damage tolerance inspections) to CAAC; (3) upon approval, the damage tolerance data shall be made available to relevant operators.

CCAR 26.45(d) requires that for repairs to alterations data developed by the holders of TC/ VTC must: (1) review the repair data and identify all repairs that affect FCAS (2) perform damage tolerance evaluations and develop damage tolerance inspections for all repairs that affect FCAS (3) submit these damage tolerance data (including damage tolerance inspections) to CAAC; (4) upon approval, the damage tolerance data shall be made available to relevant operators..

CCAR 26.45(e) sets out the deadline for showing compliance with paragraph (b) to (d) of this section.

CCAR 26.47 applies when the alteration is implemented by the holder of and applicants for a supplemental type certificate (STC) or the verification of supplemental type certificate (VSTC), or Modification Design Approval (MDA). The requirements of this section are highly similar to those in CCAR 26.45, with only slight differences in the compliance deadline date.

CCAR 26.49(a) requires that each person identified in CCAR 26.43, CCAR 26.45, CCAR 26.47, must submit a compliance plan, except for applicants for TC/ VTC/ STC/ MDA whose applications are submitted after December 7, 2011. In other words, when the certification date or application date is after CCAR-26-R0 issue date, the holders or the applicants must submit a compliance plan. The submit date of the compliance plan is specified in 26.49(b).

3 Analysis of Regulations' Difference

14 CFR Part 26 Subpart E[5] has been amended for three times, that is Amendment 26-1, 26-4 and 26-7. Amendment 26-1 issued Subpart E for the first time, and Amendment 26-4 modified applicable airplane types, and Amendment 26-7 changed FAA Oversight Office to responsible Aircraft Certification Service office.These three amendments do not affect the certification tasks required to show compliance with sections. The current effective 14 CFR Part 26 Subpart E and CCAR 26 Subpart E are highly similar (even one-to-one) in the regulation text. Furthermore, EASA has not established any regulation equivalent to Subpart E of CCAR 26 or of 14 CFR Part 26 regarding continued airworthiness and safety improvements for transport category airplanes.

4 Conformity Verification

4.1 Recommended Means of Compliance

During the certification review process, applicants typically implement various means to obtain evidence for showing compliance with airworthiness regulations. These means are collectively referred to as means of compliance (MC). To harmonize understanding and facilitate information exchange between CAAC and the applicants, the means of compliance are categorized into the following ten categories: MC0 Compliance Statement, MC1 Descriptive Document MC2 Analysis/Calculation, MC3 Safety Assessment, MC4 Laboratory Test, MC5 Ground Test on Related Product, MC6 Flight Test, MC7 Engineering Conformity Inspection, MC8 Simulator Test, and MC9 Equipment Certification[6].

Typically, the recommended means of compliance of CCAR-26 Subpart E are shown in Table 1.

Table 1. Recommended Means of Compliance.

Sections	Major	Means of compliance									
		0	1	2	3	4	5	6	7	8	9
CCAR 26.43	damage tolerance and fatigue evaluation		1	2							

CCAR 26.45	damage tolerance and fatigue evaluation	1	2
CCAR 26.47	damage tolerance and fatigue evaluation	1	2
CCAR 26.49	damage tolerance and fatigue evaluation	1	

4.2 Certification Approach for Validation

CCAR 26.41 defines the relevant terms of Subpart E to accurately specify airworthiness requirements in the following sections. Therefore, no compliance task is required in 26.41. The subsequent content outlines the compliance tasks associated with CCAR 26.43, CCAR 26.45, CCAR 26.47, and CCAR 26.49.

To show compliance with CCAR 26.43, the MC1 for fatigue critical baseline structure (FCBS) shall be provided in accordance with the description of fatigue critical structures in Appendix 5 of AC 25.571-1D, considering the specific structural characteristics of the airplanes. The FCBS must cover all baseline structure details which are prone to fatigue cracks.. Additionally, damage tolerance evaluations must be conducted for every repair that affects the FCBS, and the MC2 for damage tolerance inspection shall be provided. The damage tolerance evaluation method must be experimentally validated. The scope of damage tolerance evaluations shall be comprehensive. If repairs to non-FCBS will affect the FCBS or creates a new FCBS, the damage tolerance evaluation for such repairs shall also be conducted.

For airplane models whose type certificate/ validation of type certificate is issued before the effective date of CCAR 26, since the aircplanes are already in service on routes, repair evaluation guidelines must be developed for operators' use (MC2). The repair evaluation guidelines shall include:

(1) the process for conducting investigations on affected airplanes;

(2) the process for operators to obtain the targeted damage tolerance inspections;

(3) and the implementation plan for repairs.

To show compliance with CCAR 26.45, alterations that affect FCBS must be identified, and the MC1 for a list of FCAS shall be provided. The list of FCAS must be submitted for each alteration that affects FCBS. The FCAS should cover all baseline structure details of the alteration that are prone to fatigue cracks.

Damage tolerance evaluations will be performed for each alteration that affects FCBS, and the damage tolerance inspections will be developed (MC2). The evaluation items shall include FCBS structures impacted by alterations, newly added FCAS structures, and any repairs to the FCAS.

CCAR 26.45 is applicable to the holders of and applicants for TC/ VTC, while CCAR 26.47 is applicable to the holders of and applicants for STC/ VSTC/ MDA. The certification approach for validation and the means of compliance may refer to CCAR 26.45. Similarly, the holders of and applicants for STC/ VSTC/ MDA are required to

perform damage tolerance evaluations for alterations and repairs to alterations by MC1 and MC2.

CCAR 26.49 requires that applicants for TC/ VTC/ STC/ VSTC/ MDA whose applications are submitted before December 7, 2011, must submit project implementation plans, means of compliance plans, and proposed review plans of compliance project data, whose major milestones that meet their deadlines in accordance with CCAR 26.43, CCAR 26.45, and CCAR 26.47. Meanwhile, the applicants must submit them to CAAC within the specified timeframe. Typically, a MC1 is developed to state the submission plan for structure repair damage tolerance data.

4.3 Examples

4.3.1. Conformity Verification Pre-TC. During the TC process for a certain transport category airplane, the applicants determined that the applicable certification basis within CCAR-26 Subpart E comprised CCAR 26.43(b)(d)(f). To show compliance, the applicants has prepared and submitted the reports, as presented in Table 2 below, for certification.

Table 2. XXX Airplane Compliance Document List.

Sections	Means of compliance	Compliance Document
CCAR 26.43(b)	1	FCBS of the XXX Airplane
CCAR 26.43(d)	2	Damage Tolerance Analysis Report for Allowable Damage to Fuselage Skin of the XXX Airplane, etc.
CCAR 26.43(f)	1	Submission Plan for Damage Tolerance Data of Structural Repairs for the XXX Airplane

(1) The report entitled 'FCBS of the XXX Airplane' presented the list of FCBS for the airplane. In accordance with the requirements of CCAR 26.43(b), and with reference to the PSE items of the XXX airplane, a total of more than one hundred structure components were secleted as FCBS for the XXX airplane full airframe, including the forward service door frame longeron, engine pylon diagonal brace and pin, horizontal stabilizer hinge joint fitting, aft pressure bulkhead[7], etc.

During the process of showing compliance, two technical problmes should be paid attention to: how to establish the selection criteria for FCBS and how to determine whether FCBS should encompass composite structures and landing gear structures. The applicants finally established the selection criteria for FCBS as follows：metallic structures within PSE items, as well as composite structures within PSE items that have not been validated through fatigue and damage tolerance strength tests. Landing gear structures were excluded from the provided FCBS.

(2) Damage tolerance evaluations shall be conducted for repairs to identified FCBS. Taking the fuselage skin as an example case, the report entitled 'Damage Tolerance Analysis Report for Allowable Damage to Fuselage Skin of the XXX Airplane' presented the damage tolerance evaluation for repairs to the fuselage skin. Fuselage skin, classified as a FCBS, may experience fatigue cracks in its repaired structure that could

lead to catastrophic failure. Consequently, damage tolerance evaluation is required for all structural repair schemes of the skin. According to the Airplane Structural Repair Manual, damage catagories for fuselage skin include cracks, dents, and perforations. Xie Minghua et al, investigated the dent defect rates of A320 series and Boeing 737-800 airplane operated by a certain airline, which were found to be 42.53% and 42.85%, respectively[8]. Upon damage removal, finite element modeling shall be performed for the residual structure to extract stress and estabilish load spectra. Model parameters and material properties shall be determined based on structural configuration. Crack growth analysis shall be conducted utilizing NASGRO software, with the selected NASGRO crack growth model in acccordance with the specific structure. Inspection thresholds and intervals shall be established based on analytical results.

(3) The report entitled 'Submission Plan for Damage Tolerance Data of Structural Repairs for the XXX Airplane'presented damage tolerance evaluation data for allowable damage and repairs to FCBS, together with its submission plan, in accordance with the requirements of CCAR 26.43(f). This report stipulates the submission timelines for damage tolerance analysis reports, specifically indicating whether such data shall be submitted pre-TC or pre-delivery and post-TC.

4.3.2. Conformity Verification of Passenger-to-freighter Alteration. Passenger-to-freighter alterations were performed on the certain transport category airplane post-TC. The holders of TC must show compliance with CCAR 26.45. The holders has prepared and submitted the reports, as presented in Table 3 below, for certification.

Table 3. Passenger-to-Freighter Alteration of the XXX Airplane Compliance Document List.

Sections	Means of compliance	Compliance Document
CCAR 26.45(b)	1	FCAS for Passenger-to-Freighter Alteration of the XXX Airplane
CCAR 26.45(b)(c)	2	Structural Airworthiness Limitation Items for Passenger-to-Freighter Ateration of the XXX Airplane
CCAR 26.45(b)(c)(e)(3)	2	Damage Tolerance Analysis Report for Main Cargo Door Frame Structure of the XXX Airplane Passenger-to-Freighter Alteration, etc.

(1) The report entitled 'FCAS for Passenger-to-Freighter Alteration of the XXX Airplane' presented the list of FCAS for Passenger-to-Freighter alteration. The holders of TC conducted a systematic review of FCBS associated with the passenger-to-freighter alterations (including adaptative changes and secondary changes), and established FCAS.

To show compliance, a technical issue requiring attention is the establishment of selection criteria for FCAS, specifically regarding whether the sealing of service and emergency doors introduces new structural components and details, and whether these components constitute fatigue-critical structures. In accordance with the relevant requirements of CCAR-26 Subpart E, the holders of TC established the FCAS selection criteria as follows: any detail, structural element, or assembly that plays a significant

role in sustaining flight loads, ground loads, pressurization loads, or control loads, whose failure would compromise the structural integrity essential to aircraft safety, with particular emphasis on fatigue critical details affecting primary load paths. Based on the alteration schemes for service doors and emergency doors, the alterations to existing door structures were minimal, and no fatigue critical details were introduced.

(2) Damage tolerance evaluations shall be conducted to identified FCAS. Taking the main cargo door frame as an example case, the report entitled 'Damage Tolerance Analysis Report for Main Cargo Door Frame Structure of the XXX Airplane Passenger-to-Freighter Alteration' presented the damage tolerance evaluation to the main cargo door frame. Inspection thresholds and intervals shall be established based on evaluation results.

The report entitled 'Structural Airworthiness Limitation Items for Passenger-to-Freighter Ateration of the XXX Airplane'presented a comprehensive compilation of inspection thresholds and intervals to all FCAS.

(3) To show compliance with CCAR 26.45(e)(3), all compliance documents shown in Table 3 were submitted prior to the approval of the passenger-to-freighter alteration.

5 Technical Essential

It is important to emphasize that when showing compliance with CCAR-26 Subpart E, the following key points should be prioritized:

(1) The lists of the FCBS/FCAS must be ensured comprehensive. The FCBS shall include structures that are susceptible to fatigue cracks in primary structural element (PSE), or all initial structure details that are susceptible to fatigue crack following airplanes repair/alteration. The FCAS shall include all airplanes modified structures that are susceptible to fatigue crack leading to catastrophic failure. For instance, when showing compliance, the selection criteria for FCBS and FCAS must be established, with particular emphasis on new structural components and details introduced by alterations.

(2) Structural inspection thresholds, repeat inspection intervals, and inspection methods shall be established effectively for damage tolerance evaluations of repairs, alterations, and repairs of alterations. Inspection measures may be iteratively updated through engineering conformity inspection. For instance, following engineering conformity inspections, certain structures may be found visually inaccessible. necessitating modification of the inspection method to ultrasonic inspection or high-frequency eddy current inspection. Liu Lingfeng's research demonstrated that elastic wave inspection enable effective monitoring of cracks with dimensions of 5 mm and above in titanium alloy structures[9]. Additionally, attention must be paid to the maturity of damage tolerance evaluation methods and whether the methods have been experimentally validated. For new materials and processes introduced in repair plans, necessary tests should be conducted to validate the evaluation methods. When material properties are missing for damage tolerance analysis, data from similar materials may be employed, provided that the analysis results remain conservative. Subsequently, material-level testing should be planned to obtain the relevant material property data, such as the material properties of

2099 aluminum-lithium alloy[10], and damage tolerance analysis results should be updated accordingly.

(3) A repair evaluation guideline shall be provided when the TC/ VTC is issued before December 7, 2011,and the evaluation and repairs shall be conducted effectively in accordance with this guideline.

(4) The submission time of all the data is in accordance with CCAR 26.49.

6 Conclusion

This study analyzes the airworthiness requirements of CCAR 26.41, CCAR 26.43, CCAR 26.45, CCAR 26.47, and CCAR 26.49 one by one. The differences between CCAR-26 Subpart E and 14 CFR Part 26 Subpart E are studied. The means of compliance and certification approach for validation corresponding to the regulations are reviewed. The technical requirements to be considered are summarized when showing compliance with CCAR-26 Subpart E. All the above studies can provide reference for damage tolerence and fatigue evaluations of structural repairs and alterations of transport airplanes.

Acknowledgments

This work was supported by the Airworthiness Engineering Department, Shanghai Aircraft Design and Research Institute, COMAC.

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