공학석사학위논문

Research on Establishing Fatigue Evaluation Procedures of Composite Structures Using Load Enhancement Factor Approach

하중증대계수 방법을 통한 복합재 구조의 피로 평가 절차 연구

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이창배의 공학석사 학위논문을 인준함

2020 년 2 월

위 원 장 ___이 관 중___ (인)

부위원장 ___신 상 준___ (인)

위　　원 ___윤 군 진___ (인)

Abstract

Research on Establishing Fatigue Evaluation Procedures of Composite Structures Using Load Enhancement Factor Approach

Changbae Lee

Department of Mechanical and Aerospace Engineering

The Graduate School

Seoul National University

As composite materials became widely used in aerospace industries and the behaviors under repeated loads were understood, amended airworthiness standards, damage tolerance and fatigue evaluation procedure has been established. However, depending on the usage of materials, loading conditions, and environmental conditions need to be addressed differently. To fully understand the behavior of composite materials used in the composite rotor blades, this thesis focuses on the coupon-level tests and the issues that need to be considered. For the application, the rotor blade design and its baseline material is selected for testing. Furthermore, the baseline static and fatigue tests are performed while considering effects of the environment, material/process variability, and geometry, which needs to be treated within the coupon-level experiments. Based on the results, scatter analysis is performed to consider the effects of environment, geometry, and loading modes for the static and fatigue tests. The load enhancement factors as a function of test duration are obtained statistically. Furthermore, the effects of the shape parameters upon the load enhancement factors are discussed.

By estimating the strength and life shape parameters from the static and fatigue test results, load enhancement factors can be obtained. Thus, the uncertainties from the scatter of composite properties can be analyzed. However, depending on the Weibull parameter estimation and scatter analysis methods, the load enhancement factors may differ. Therefore, in this thesis, improved Weibull parameter estimation and scatter analysis methods have been proposed. The static-strength shape and fatigue-life shape parameters are evaluated for eight Weibull parameter estimation and three scatter analysis methods. Moreover, based on the strategies of the Weibull parameter estimation and scatter analysis methods, the load enhancement factors are evaluated as a function of test duration. The load enhancement factors obtained by the largest and the smallest shape parameters are compared each other by applying various Weibull parameter estimation methods for the scatter analysis. Finally, the consequences of model selection on distribution fitting and the scatter analysis along with the effect of life factors and strength parameters on the load enhancement factors are evaluated to apply the more realistic model for the scatter of material properties.

Keywords : Fatigue evaluation, Rotorcraft structure, Airworthiness certification, Scatter analysis, Load enhancement factor, Weibull parameter estimation

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Chapter 1

Introduction

1.1 Background and Previous Studies

Fatigue evaluation of rotorcraft has first been established as “safe life” methodology in 1950’s. Thanks to such methodology, the fatigue issues in rotorcraft structures were successfully addressed with sufficient level of safety. However, such methodology did not account for degradation of the material properties due to damage, impact, and others. Additionally, behavior of the composites has not been fully understood. Since the safe life methodology did not account for those effects, the lifetime of the components was predicted in a conservative way and became quite short for operations. Subsequently, in 1980’s, to consider usage of the composites in rotorcraft structures and effects of damage, impact and etc. on fatigue substantiation, “flaw tolerant safe life” for the metal structures and “damage tolerant evaluation” for the composite structures were established. The procedures of “damage tolerant evaluation” and “damage tolerance and fatigue evaluation of composite rotorcraft structures” are summarized in Table 1.1, in accordance with both FAR 29.573[1] and AC 29.573[2]. In the literatures, Bansemir, et al.[3] conducted fatigue substantiation and damage tolerance evaluation on the composite rotorcraft structures. In addition, Mariani, et al.[4] substantiated both metallic and composite structures in rotorcraft to establish retirement times and inspection intervals. Many aerospace companies and research laboratories attempted to meet satisfactory results in accordance with such revised methodologies. Furthermore, Rouchon [5] applied issues of the scatter and impact damage in the composite materials into the aircraft usage. Moreover, extensive researches have been performed to address characterization, usage, design, and analysis of the polymer matrix composites. Those were summarized in CMH-17-1G [6] and CMH-3G [7].

To establish retirement times of the composite structures as described in FAR 29.573, "damage tolerant safe-life" was selected. Using the "damage tolerant safe life," issues with fatigue and damage could be addressed which established capability of the structure with damage present to survive expected repeated loads of variable magnitude without detectable damage growth and to maintain ultimate load capability throughout service life of a rotorcraft. Damage tolerant safe life can be divided into two methods, which are the scatter analysis method and curve-fit method based on the damage growth.

Since the curve fitting on the damage growth is confined on the particular material system and loading conditions, scatter analysis method is selected to comply with the procedures on fatigue and damage tolerance evaluation. Scatter analysis method is not confined to the means of compliance in FAR 29.573 or with rotorcraft rotor system. However, the rotorcraft rotor blade is selected to establish the procedures for fatigue and damage tolerance evaluation.

Table 1.1 Procedures for fatigue and damage tolerance evaluation

	Procedures
1	Identification of the principal structural element
2	Threat assessment
3	Fatigue / damage tolerance evaluation
4	Establishment of the replacement time, inspection interval or equivalent means

Various concerns have existed on choosing a model for establishing life and load enhancement factors. The procedures for determining the fatigue life of composite structures can be divided into the following three categories: scatter analysis of the fatigue results, parameter estimation of the assumed distribution, and statistical significance tests. For scatter analysis of the fatigue results, the commonly used models are Sendeckyj equivalent static-strength model, individual Weibull method, or joint Weibull method. Tomblin and Seneviratne suggested the fatigue scatter analysis and compared the results by pooling extensive static and fatigue results [8]. However, only one model was suggested for estimating the shape parameters. Furthermore, numerous methods for estimating the parameters of Weibull distribution were studied. For example, Al-Fawzan summarized the graphical and analytical methods, such as maximum likelihood estimation (MLE), the least squares method and method of moments, for fitting Weibull distribution and compared the results among them [9]. The resulting Weibull parameters and load enhancement factors generally lead to different values depending on the scatter analysis method and Weibull distribution parameter estimation used. However, there has been no comprehensive evaluation reported on the consequences of either method in terms of the life and load enhancement factors when fitting the Weibull distribution and performing the scatter analysis.

1.2 Thesis Overview

In this thesis, the research is focused on establishing the fatigue evaluation procedures of composite structures by the load enhancement factor approach. Therefore, in Chapter 2, the concept of fatigue certification for the rotorcraft rotor system is proposed and the considerations for scatter analysis method is summarized. Then, in Chapter 3, the rotorcraft rotor blade design is selected and the baseline material is selected from the rotor blade design. The specimens are designed according to the recommended design of FAA. Furthermore, the baseline static and fatigue tests are conducted and scatter analysis is conducted for the pooled results the test results conducted in this thesis. The means to consider the effect of geometry, environment and loading conditions at the coupon level are discussed when the composite structure is evaluated for fatigue and damage tolerance. In Chapter 5, for the further research, improved graphical and analytical procedures for estimating Weibull distribution parameters have been proposed. Various Weibull parameter estimation methods are suggested for scatter analysis methods including the three commonly used fatigue scatter analyses. Finally, the life and load enhancement factors are established, and the results by each procedure are compared and evaluated.

Chapter 2

Methodology for Fatigue Evaluation of Composite Structures

2.1 Building Block Approach on the Rotor System

Composites have been widely used since 1950's as primary structural applications in rotorcraft. Composites are lightweight and have high specific stiffness, corrosion resistance, and fatigue resistance. However, despite those advantages over metallic structures, it is difficult to predict failure of the composite materials especially when they are loaded in various conditions. Moreover, environmental effects such as temperature and humidity, process control and geometry effects may influence composite material properties to have high scatter while enforcing it difficult to predict by analysis. Therefore, metallic and composite structures need to be addressed separately. Fatigue evaluation procedures of the metallic structures can be substantiated mainly on analysis via the flaw onset and growth rate. However, to verify the composite materials, extensive testing should be done on every critical location identified from material to component level. This is done by the building block approach as shown in Fig. 2.1. Using the building block approach, experiments are conducted in coupon, element, subcomponent and full-scale level, step-by-step from the lower to higher degree of complexity. Lower level tests are to uncover the failure modes through coupon testing and along with tests of higher-level complexity, analytical methods are developed and verified.

For the rotor system, building block approach can be divided into three stages, which are the design allowables testing, design development testing, and full-scale substantiation testing. At the design allowables testing, the analytical input for strength, stiffness and environmental/processing effect knockdown factors are derived by the lamina and laminate testing. Furthermore, at the design development testing, strength allowables for the specific design are tested and analysis methods are developed and validated. The issues with damage tolerance are addressed in this section. Finally, full-scale components or systems are tested to validate the analysis developed in the lower level of complexity.

For design allowables testing, analytical input for strength or stiffness of structures can be predicted from lamina or laminate level. From the lamina level tests, the strengths and stiffness on the ply-level are evaluated. However, the failure modes on the laminates do not correlate well with the ply-level information from lamina-level tests. Therefore, laminate-level tests are still required. In the laminate-level experiments, maximum strain failure criteria on the ply-by-ply basis at a given location is used. Variables such as stacking sequence and geometry are interchanged and statistically derived. Information derived from the laminate-level experiments is less sensitive to the scatter or uncertainty of strength or stiffness. Consequently, this thesis will focus on the laminate-level coupon tests and the methods to consider the variables will be discussed.

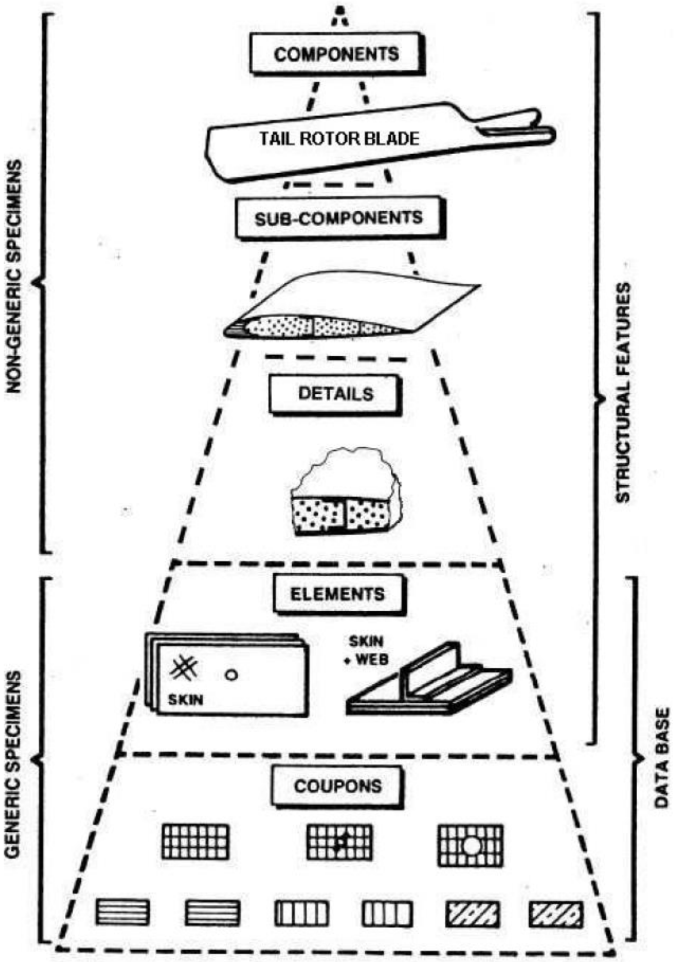


Fig. 2.1 Schematic diagram of the building block approach [7]

2.2 Scatter Analysis Methodology

For the laminate-level coupon tests, scatter analysis may be conducted to consider the uncertainty of the strength of the various material systems. The scatter or the variability of the material properties may be interpreted in the lower levels of the building block approach. This can be taken into account by the flowchart of the load enhancement factor approach as shown in Fig. 2.2. The scatter of the strength of the representative data sets is analyzed to obtain strength shape parameter α_R via static tests. In addition, SN data of the fatigue results is analyzed to take the life scatter into account and the life shape parameters α_L can be obtained. The strength and life shape parameters obtained from the static and fatigue results are then processed into the load enhancement factors (LEF) using life factor approach or load enhancement factor approach. Finally, the component-level fatigue test spectrum can be obtained using the LEFs using Eqs. (2.1) – (2.3). The LEFs may be applied to the fatigue spectrum to *1-g* mean fatigue load using Eq. (2.1), to amplitude using Eq. (2.2) or to minimum/maximum load using Eq. (2.3).

$$P_{mean} = [P_{1-g} \cdot LEF + (\frac{\Delta P}{\Delta g}) \cdot \Delta g] \tag{2.1}$$

$$P_{amplitude} = [P_{1-g} + (\frac{\Delta P}{\Delta g}) \cdot \Delta g \cdot LEF] \tag{2.2}$$

$$P_{min/max} = [P_{1-g} + (\frac{\Delta P}{\Delta g}) \cdot \Delta g \ ] \cdot LEF \tag{2.3}$$

where

N : test duration

P_{1-g} : mean fatigue load of a load block

Δg : amplitude with respect to 1-g fatigue load

$\frac{\Delta P}{\Delta g}$: load per Δg

To generate reliable LEFs, minimum of 6 result sets for the static and fatigue will be recommended as shown in Fig. 2.3 [7, 8]. For the static results, the variables such as geometry, loading modes, environment, and lay-ups should be taken into account. If significant batch variability exists in the laminal level, the number of batch, B three distinctive material batches are required for the specimen fabrication. However, when it is proven that the batch variability does not exist in the laminal level with the significance level equal to 0.01 in Anderson Darling test, only one batch is required. In addition to the variables considered for the static results, the effect of R-ratio should be considered for the fatigue results. In addition, at least three stress levels are required for the fatigue tests. Six result sets for the fatigue results, which is shown in Fig. 2.3 as F are required for the individual fatigue analysis. However, if pooled analysis technique is conducted, only two results at each stress level are needed. In such way, the considerations that should be pursued on the coupon level may be established.

The test results should be examined for the scatter of the selected material system under particular loading conditions and environmental conditions. FAA conducted the scatter analysis with various material systems, loading conditions, environmental conditions and lay-ups. This resulted in the static strength shape parameter, 26.31 and the fatigue life shape parameter, 1.25, which are considered to be the conservative factor for generating LEFs or life factors. For insufficient result sets, the conservative factors reported by FAA are used. To develop the LEFs or life factors, the life shape parameter should be verified for the representative fatigue result set of a fatigue-critical design detail and a representative stress ratio to examine that the requirements for using the load enhancement factor approach are satisfied. The resulting life shape parameter should be greater than 1.25.

In this thesis, the baseline static tests for the two environmental conditions and fatigue tests are conducted. Additionally, the test results of Cytec AS4/E7K8 (AS4-PW) are pooled to meet the minimum requirements for generating the reliable LEFs. Moreover, to examine the statistical significance between the baseline test results and the pooled test results, Anderson-Darling test is conducted with the significance level equal to 0.01.

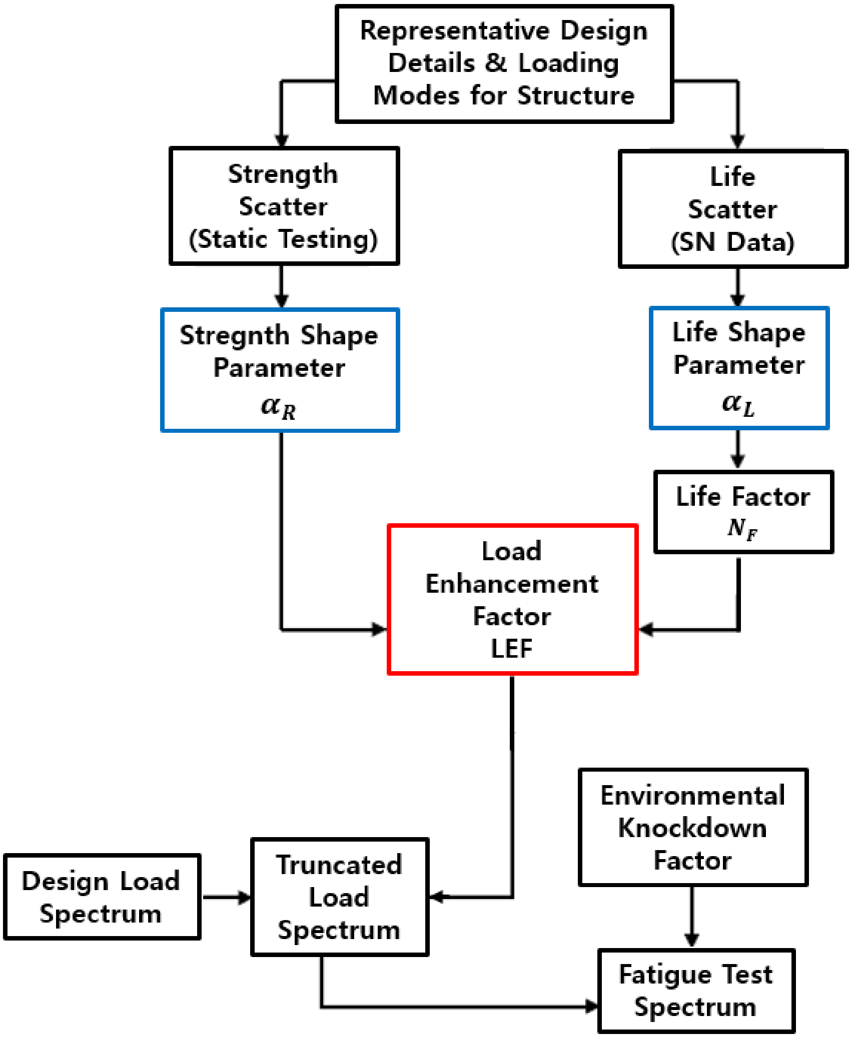


Fig. 2.2 Procedures for generating load enhancement factors [8]

Design Detail	Test Method	Loading Condition	Environmental condition	Static-Critical Design Details	Fatigue-Critical Design Detials			
					R1	R2	R3	R4
1	Method 1	1	1	B x 6				
2	Method 2	2	1	B x 6				
3	Method 3	3	1	B x 6				
4	Method 4	4	1	B x 6				
5	Method 5	5	1	B x 6				
5	Method 5	5	2	B x 6				
1	Method 1	1	1					B x 3 x F
2	Method 2	2	1					B x 3 x F
3	Method 3	3	1		B x 3 x F			
4	Method 4	4	1				B x 3 x F	
5	Method 5	5	1			B x 3 x F		
5	Method 5	5	2			B x 3 x F		

Fig. 2.3 Minimum Test Requirements for Generating Life Factors and LEFs

Chapter 3

Static and Fatigue Tests at Coupon-level

In this section, the design for application of the established airworthiness standards FAR 29.573 is selected. Based on the material system, two sets of static tests for the two environmental conditions and one set of fatigue tests are conducted. The procedures for fabricating the specimens and for conducting the static and fatigue tests are also stated.

3.1 Specifications of the Selected Rotor Blade Design

To apply the established airworthiness standards FAR 29.573, the rotor blade design is selected. The selected rotor blade is 'Seoul National University Flap (SNUF)', which is a composite rotor blade with active trailing edge flaps to reduce the forward flight induced vibratory loads on the rotor hub [10]. Presently fabricated SNUF blade is shown in Fig. 3.1 and the detailed specifications of the design are described in Table 3.1. This rotor blade is designed to use laminates with glass woven fabric and carbon woven fabric on the skin. Additionally, carbon unidirectional tape is used as reinforcement of the structure at 25% chord along the spanwise direction. Moreover, the spar is laminated with balsa wood and glass woven fabric. To establish the procedures of coupon-level testing, baseline material is selected as carbon woven fabric and this thesis will focus on the laminate-level testing.

Fig. 3.1 Fabricated Mach-scaled SNUF blade

Table 3.1 Specifications of the selected rotor blade design [10]

Properties	Value
Rotor type	Hingeless
Rotation speed	1300rpm
Number of blades	4
Blade radius	1.5m
Chord length	0.135m
Weight	1.4 ~ 1.6kg
Tip Mach Number	0.6

3.2 Static and Fatigue Tests at Coupon-level

As discussed in the previous section, this thesis focuses on the design allowables testing, which is the coupon test. In this level, statistically large amount of tests is required to address mainly on environmental effects and material / process variability issues. In order to meet the airworthiness standards described in FAR 29.573, the composite materials used in the rotorcraft structure have to be fully characterized using the building block approach in Fig. 2.1. In the coupon level, via static strength testing, ultimate load for each material is determined. Subsequently, fatigue and damage tolerance requirements enable the ultimate load capability to withstand the undetected damage for the assumed lifetime or inspection interval. However, when the damage is detected, the structure should be maintained or replaced to restore the ultimate strength capability.

In the coupon level testing, material or process variability and environmental effects such as temperature and humidity should be considered. Via the static and fatigue tests, the load enhancement factors to account for material/process variability issues should be determined for each material and failure mode.

For rotor blades where large number of cycles are loaded, fatigue issues should be addressed. Besides different failure modes from the static tests, environmental effects and material/process variability issues are considered. Fatigue enhancement factors are defined and they act as a factor for either increasing the number of cycles or overload structures with repeated loads in the higher level to achieve desired level of safety. Additionally, S-N curves for stress ratio effects should be considered. Inplane material properties can be evaluated by three stress ratios, R=0.1 or 0(tension-tension), R=10(compression-compression) and R=-1(tension-compression).

In this thesis, for the baseline considerations, static tensile tests and tension-tension for fatigue test are selected. For the static tensile tests, both temperature conditions which are room temperature dry (RTD) and elevated temperature dry (ETD) are performed. In addition, tension-tension tests with the R-ratio of 0.1 are selected for the fatigue tests.

3.2.1 Material Processing

In this section, more information about the selected material is provided. The carbon/epoxy prepreg is composed of Toray T300 3K to be a plain weave fabric and hot melt coated with thermosetting resin. Figure 3.2 (a) and Table 3.2 describes the detailed information about the carbon/epoxy prepreg, which is provided by the manufacturer, Hankuk Carbon Corporation. Furthermore, the carbon/epoxy prepreg was cured at 90℃ for 60 minutes and post-cured at 90℃ in an autoclave facility by Nexcoms, Inc. Figure 3.2(b) shows the autoclave facility used for curing the prepreg.

Table 3.2 Specifications of the carbon/epoxy prepreg

Material	Carbon Fiber Weight Density (g/m^2)	Resin Weight Density (g/m^2)	Resin Content (%)	Total Weight Density (g/m^2)	Remark
CF-3327EPC	205	150	42 ± 2	352	Toray T300 3K

a) Carbon/epoxy prepreg **b) Autoclave Facility**

Fig. 3.2 Process for curing the carbon/epoxy prepreg

3.2.2 Specimen Preparation

Material properties of the laminates depend largely on the stacking sequences, thickness, width, geometry, load angle, and etc. To consider those effects on the material property, experiments of the baseline design should be conducted and subsequently, changing those variables depending on the structure. The representative stacking sequence of the laminates is shown in Table 3.3 [8]. For the baseline design of specimens tested, quasi-isotropic laminate with 16 plies is selected, which is $[(45/0/-45/90)\ _2]_S$. The specimens are designed according to ASTM D3039/D3039M [11], and with the same design, static tensile tests and fatigue tests are conducted. The specimens are designed to be 25mm width, 250mm length and 3.75mm thickness in dimension as shown in Table 3.4 and Fig. 3.3.

3 batches of 18 specimens are required to be representative of material/process in each environment which are room temperature dry (RTD), elevated temperature wet (ETW) or elevated temperature dry (ETD). Minimum of 3 batches are needed to show the level of confidence through which the material and processes variability issues may be addressed [7]. In this thesis, test specimens are fabricated as 1 batch. Therefore, material/process variability issues are only addressed by various panels and the methodology for handling such issues is referred by pooling the results from the FAA database.

Table 3.3 Laminate configurations of FAA database [8]

Laminate	Lay-Up% $0^o/45^o/90^o$	Ply Stacking Sequence	Total Plies
Hard	40/20/40	$[0/90/0/90/45/-45/90/0/90/0]_S$	20
Quasi-isotropic	25/50/25	$[(45/0/-45/90)_2]_S$	16
		$[(45/0/-45/90)_4]_S$	32
Soft	10/80/10	$[45/-45/90/45/-45/45/-45/0/45/-45]_2$	20
		$[45/-45/90/45/-45/45/-45/0/45/-45]_{2S}$	40
All ± 45	0/100/0	$[(45/-45)_5]_S$	20

Table 3.4 Specification of the baseline un-notched tensile test specimen

Layup	Width	Length	Thickness	Load angle	RTD	ETD	Total Plies
(25/50/25)	25mm	250mm	3.75mm	0^0	6	6	16

Fig. 3.3 Unnotched fabric carbon/epoxy tensile specimen

3.2.3 Apparatus and Testing Procedures

Both static tensile tests and tension-tension fatigue tests are conducted by using the dynamic test instrument, MTS Landmark. Additionally, elevated temperature condition is simulated via an environmental chamber. The apparatus is shown in Fig. 3.4. Static tensile tests are performed at two different environmental conditions, which are RTD and ETD. Experiments of the static and fatigue tests under RTD condition are conducted at reference temperature of $23 \pm 3°\mathrm{C}$ with an as-fabricated moisture content, $50 \pm 10\%$ relative humidity. Moreover, tests under ETW condition are conducted at $82 \pm 2.5°\mathrm{C}$. The static tensile tests are performed in accordance with ASTM D3039/3039M with constant head displacement rate of $2mm/min$.

Tension-tension fatigue experiments are performed according to ASTM D3479/3479M [12]. This is done on the load control mode with frequencies of 10 Hz and with the stress ratio of 0.1, which is the representative of tension-tension stress ratio. The fatigue tests are conducted under RTD condition and on the 3 different load levels at 6 specimens. The representative specimens after the static and fatigue tests are shown in Fig. 3.5 and the test results are shown in Fig. 3.6.

a) Static and fatigue tests **b) Dynamic test instrument**

Fig. 3.4 Apparatus for static and fatigue tests

a) Specimens after static tensile tests

b) Specimens after tension-tension fatigue tests

Fig. 3.5 Representative specimens for the baseline static and fatigue tests

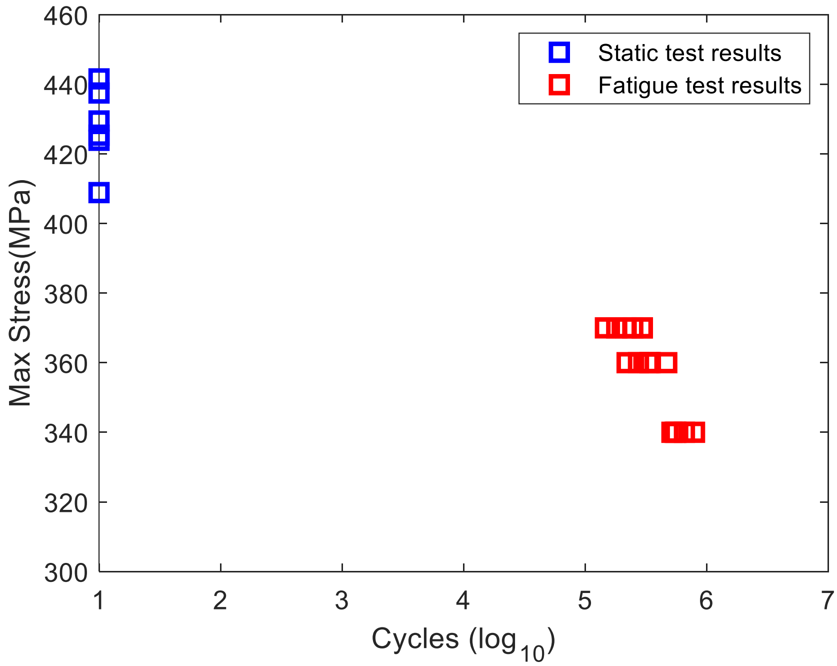


Fig. 3.6 Tensile and fatigue test results of the un-notched specimen

Chapter 4
Scatter Analysis

In this chapter, the procedures for obtaining the B-basis reliability LEFs and the life factors are discussed to consider the effects of geometry, environment, and the loading conditions in the coupon level. The strength and life shape parameters are determined from the baseline static and fatigue tests. The static strength shape parameters and the fatigue results are then pooled to obtain the reliable LEFs and life factors. Furthermore, the resulting LEFs are compared with the conservative factors reported by FAA.

4.1 Scatter Analysis of the Static Test Results

To quantify the scatter of the static test results, the test results for the two environmental conditions, which are RTD and ETD conditions, are to be analyzed. Maximum likelihood estimation is used to estimate the shape parameters of Weibull distribution. Figure 4.1 shows the results of static-strength probability and survival plots for each environmental condition. The shape parameters for RTD and ETD are estimated to be 52.464 and 64.391.

In addition, the static test results in AS4-PW are pooled to determine the static-strength shape parameter α_R. The effects of geometries, load modes, environments, and lay-ups are considered as shown in Table 4.1. In addition to the various representative lay-ups, the hole effect is considered. The harshest environment, which is elevated temperature wet (ETW), and the normal condition, which is room temperature ambient (RTA), are considered for the environmental conditions. Furthermore, tension and compression are considered to be critical and pooled.

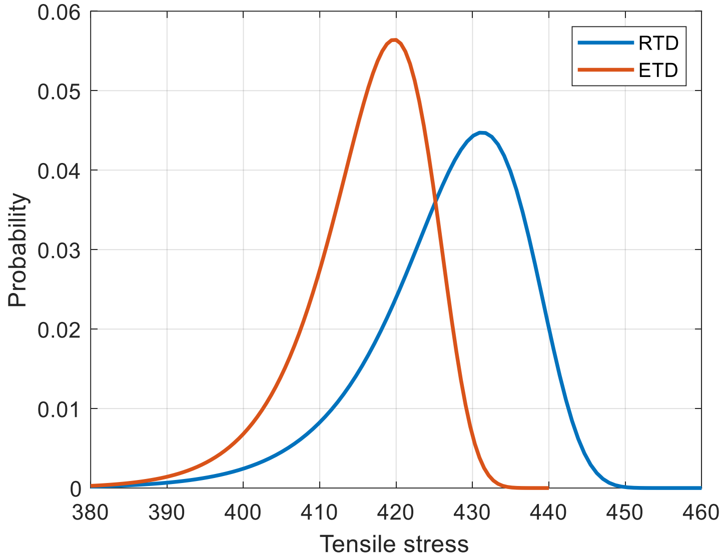
Maximum likelihood estimation is used to determine the modal or mean value of the static-strength shape parameter α_R from the shape parameters of each static test results. In addition, Anderson-Darling test is performed to examine the statistical significance from Weibull distribution with the significance level equal of 0.01. Figure 4.2 shows the probability and survival plots for the static-strength shape parameter distribution. As a result, the modal and mean values of the strength shape parameters are obtained to be 42.242 and 43.645. The modal value is selected for the conservative static-strength shape parameter. Analyzing these test results statistically in such way, the reliable strength shape parameter can be obtained and the considerations can be provided at the coupon level testing.

Table 4.1 Specifications and Weibull parameters for the pooled AS4-PW static-strength data [8]

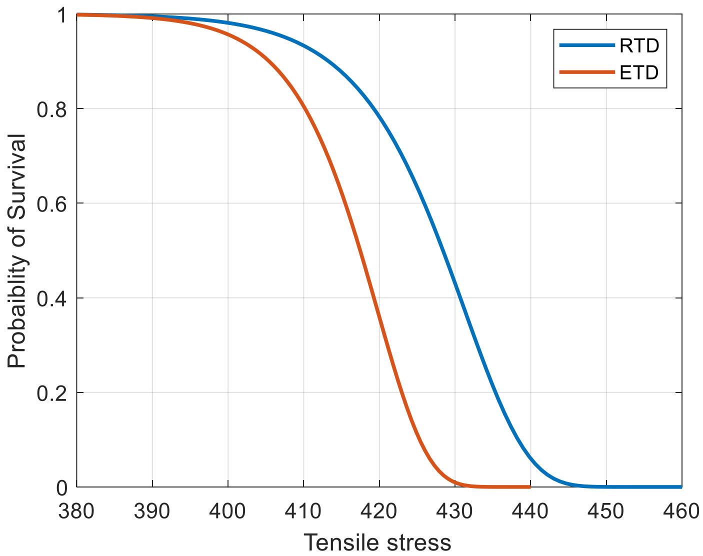
Specimen configuration		Test environment	Weibull statistics	
Lay-up % $0^o/45^o$ $/90^o$	Test description		Strength shape parameter $\hat{\alpha}$	Number of the test results N
10/80/10	OHT	RTA	58.036	6
		ETW	61.970	6
	OHC	RTA	26.930	6
		ETW	33.290	8
0/100/0	OHC	RTA	63.247	6
		ETW	11.766	5
25/50/25	OHC	RTA	33.424	6
		ETW	28.157	6
	CAI-BVID	RTA	45.777	6

* OHT : open-hole tension, OHC : open-hole compression, CAI-BVID : compression after impact-barely visible impact damage

* RTA : Room temperature ambient, ETW : Elevated temperature wet

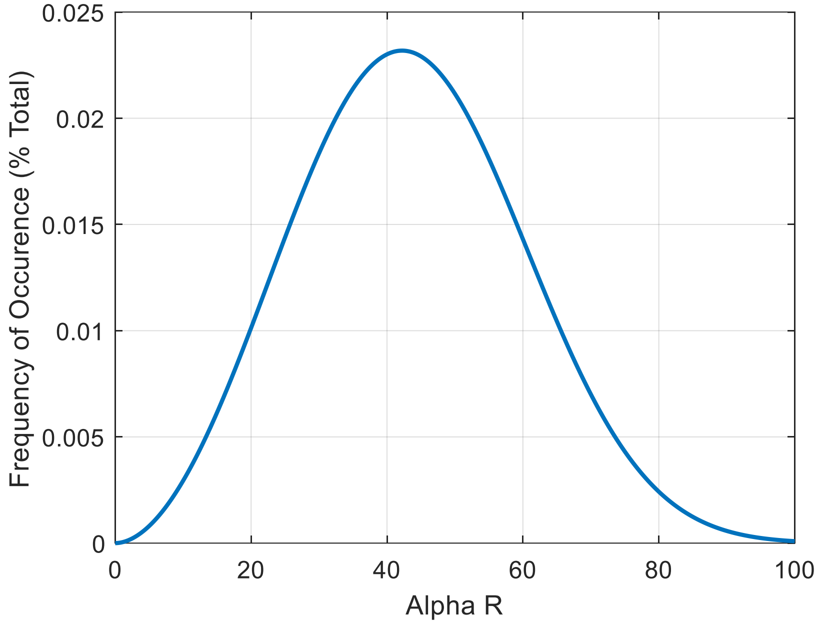


(a) Comparison of the static-strength probability plot for each environmental condition

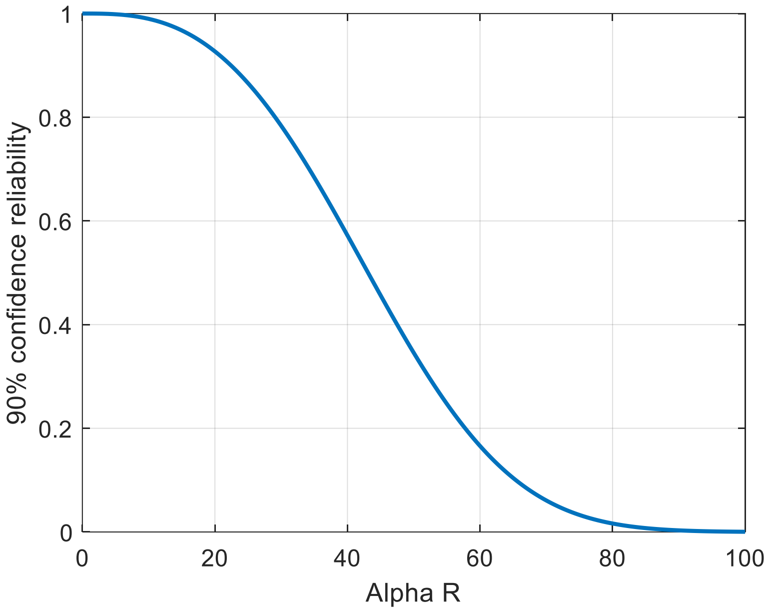


(b) Comparison of the static-strength probability of survival plot for each environmental condition

Fig. 4.1 Scatter analysis results of the static test results



(a) Static-strength shape parameter probability plots



(b) Static-strength shape parameter survival plots

Fig. 4.2 Scatter analysis results of strength shape parameters

4.2 Scatter Analysis of the Fatigue Test Results

Three methodologies are the frequently used methods for analyzing the scatter of fatigue test results: individual Weibull, joint Weibull method, and Sendeckyj equivalent static-strength model. First, by the individual Weibull method, the shape parameters are obtained for each stress level and arithmetically averaged. Second, by the joint Weibull method, the life shape parameter is estimated by using Eq. (4.1). n_i represents the number of data points in the i^{th} group of results and n_{fi} represents the number of failures in the i^{th} group of results. The detailed derivation and description are provided in Refs. [13, 14].

$$\sum_{I=1}^{M}\left\{n_{fi}\cdot\left[\frac{\sum_{j=1}^{M} x_{ij}^{\hat{\alpha}}\cdot\ln\left(x_{ij}\right)}{\sum_{j=1}^{n_i} x_{ij}^{\hat{\alpha}}}-\frac{1}{\hat{\alpha}}-\frac{\sum_{j=1}^{n_{fi}}\ln\left(x_{ij}\right)}{n_{fi}}\right]\right\}=0 \quad (4.1)$$

Finally, the life shape parameter can be estimated by using Sendeckyj equivalent static-strength model. Sendeckyj analysis is characterized the static strength, fatigue life, and residual strength into equivalent static-strength results. This is derived by assuming that the static strength depends on the particular form of the crack growth. In case of the fatigue failure, Eq. (4.2) is obtained. σ_a and σ_u represents the maximum amplitude cyclic stress and static strength, respectively, and S and C are Sendeckyj fitting parameters. The detailed derivation and description are provided in Ref. [15].

$$\sigma_a\cdot\left(1-C+C\cdot n_f\right)^S=\sigma_u \quad (4.2)$$

The life shape parameter from Sendeckyj analysis is estimated by the distribution of the fatigue lives at a given applied cyclic stress. The distribution of the life shape parameters can be represented by three-parameter Weibull distribution as in Eq. (4.3). This is obtained by assuming that the dominant cracks are present in the formulation and that the equivalent static strength results are distributed in Weibull fashion. In Eq. (4.3), α_f, β_f and A represent shape, scale, and location parameters as in Eqs. (4.4 – 4.6).

$$\mathrm{P(N)} = \exp\left\{-\left[\frac{N-A}{\beta_f}\right]^{\alpha_f}\right\} \tag{4.3}$$

where

$$\alpha_f = S\alpha \tag{4.4}$$

$$\beta_f = (\beta/\sigma_a)^{1/S}/C \tag{4.5}$$

$$\mathrm{A} = -(1-\mathrm{C})/\mathrm{C} \tag{4.6}$$

In addition to the baseline fatigue tests, the fatigue test results in AS4-PW are pooled for various conditions representing the lay-up, load mode and R-ratio to generate reliable LEFs. Table 4.2 is the detailed description for the fatigue life distributions [8]. Test Number 1 corresponds to the fatigue tests conducted in thesis and Numbers from 2 to 6 correspond to the description of the pooled fatigue tests. The R-ratios that represent tension-tension and tension-compression modes are tested and pooled. Moreover, the effects of geometry and lay-ups are considered. The fatigue results that contain more than 6 points are only pooled and analyzed. The life shape parameters are estimated by individual Weibull, joint Weibull, and Sendeckyj analysis. For Sendeckyj analysis, the maximum likelihood estimation is used to estimate the life shape parameters from the equivalent static strength results for Sendeckyj analysis. The resulting life shape parameters are summarized in Table 4.3.

Table 4.2 Specifications of the fatigue tests for the fatigue life distributions

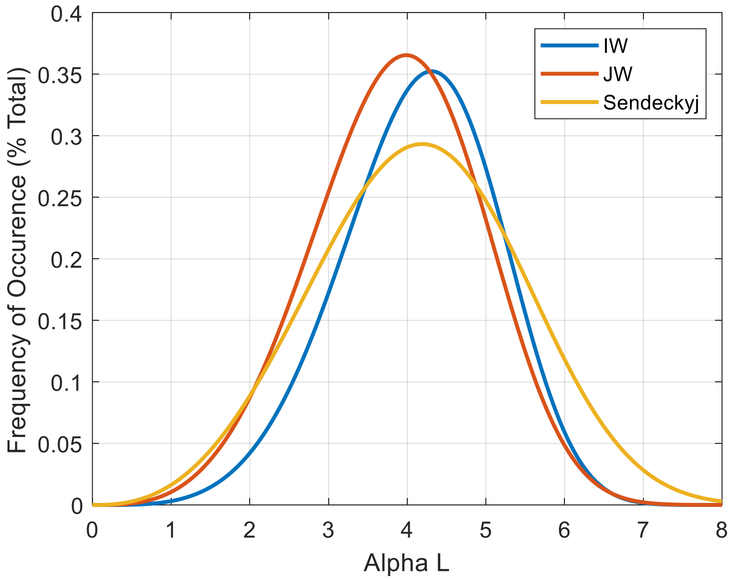
Test No.	Lay-up % $0^o/45^o/90^o$	Test description	R-ratio
(1)	25/50/25	UNT	0.1
(2)	10/80/10	OHT	0
(3)	10/80/10	OH	-1
(4)	0/100/0	OH	-1
(5)	0/100/0	TAI-BVID	0
(6)	25/50/25	OH	-1

* UNT : un-notched tension, OH : open-hole, TAI-BVID : tension after impact-barely visible impact damage

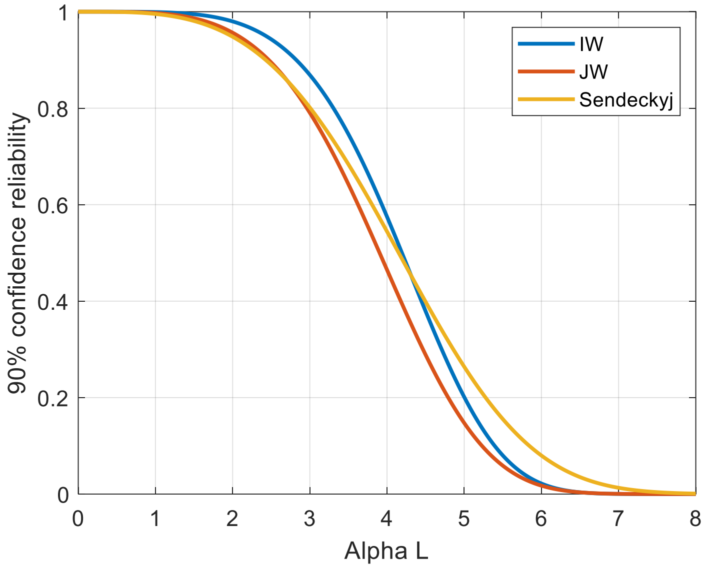
Table 4.3 Estimation of the life fatigue-life shape parameters

Test No.	Individual Weibull method	Joint Weibull method	Sendeckyj equivalent static-strength model
(1)	5.228	5.092	4.107
(2)	5.555	4.641	2.618
(3)	3.304	2.677	3.839
(4)	5.528	4.04	3.499
(5)	2.447	1.913	1.454
(6)	5.713	4.745	3.641

Maximum likelihood estimation is used to determine the modal or mean value of the fatigue-life shape parameter α_L from the shape parameters of each fatigue test results. In addition, Anderson-Darling test is performed to check the statistical significance with the significance level equal of 0.01. The tests for the significance checks shows that the shape parameter of each test result fit in the Weibull distribution of the pooled fatigue results. Figure 4.3 shows the probability and survival plots for the fatigue-life shape parameter distribution. As a result, the modal and mean values of the life shape parameters are obtained and summarized in Table 4.4. The most conservative fatigue-life shape parameter is obtained as 3.875, which is the mean value of the joint Weibull method.



(a) Comparison of the fatigue-life shape parameter probability plots



(b) Comparison of the fatigue-life shape parameter survival plots

Fig. 4.3 Scatter analysis results of life shape parameters

Table 4.4 Results of the fatigue-life shape parameters

	Individual Weibull method	Joint Weibull method	Sendeckyj equivalent static-strength model
Modal α_L	4.847	3.988	4.188
Mean α_L	4.665	3.875	4.147

4.3 Determination of the Load Enhancement Factor (LEF)

Load enhancement factor is used to meet the desired level of confidence in a shorter test duration by increasing the applied loads using Eq. (4.7). n is the number of the articles and R is the reliability. In this thesis, for γ and B-basis reliabilities, 0.95 and 0.9 are used, respectively. χ_r^2 is Chi-squared distribution with $2n$ degrees of freedom at γ level of confidence.

$$\mathrm{LEF(N)} = \frac{\dfrac{\Gamma\left(\dfrac{\alpha_L + 1}{\alpha_L}\right)^{\frac{\alpha_L}{\alpha_R}}}{-\ln(R) * N^{\alpha_L}}}{\dfrac{\chi_r^2(2n)^{\frac{1}{\alpha_R}}}{2n}} \tag{4.7}$$

Life factor approach is an alternative to the load enhancement factor approach. Life factor is used to assure the same structural durability by testing the component by the assumed loads with increased time. Life factor can be determined by using Eq. (4.8). Furthermore, LEF can be determined using the life factor as in Eq. (4.9).

$$N_F = \frac{\Gamma\left(\dfrac{\alpha_L + 1}{\alpha_L}\right)}{\left\{\dfrac{-\ln(R)}{\left[\dfrac{\chi_r^2(2n)}{2n}\right]}\right\}^{\frac{1}{\alpha_L}}} \tag{4.8}$$

$$\mathrm{LEF} = \left(\frac{N_F}{N}\right)^{\frac{\alpha_L}{\alpha_R}} \tag{4.9}$$

From the life shape parameters determined in Section 4.3, the life factor is obtained to be 2.14. Furthermore, the LEFs are generated as a function of test duration from the strength and life shape parameters obtained in Sections 4.2 and 4.3. LEF is obtained on B-basis reliability, which is defined to be 90% lower confidence limit on the tenth population percentile and Fig. 4.4 is the B-basis LEFs as a function of test duration. The LEF with the assumed usage of the fatigue loads and design lifetime (1 DLT), is obtained as 1.07. Additionally, for the test duration of two times larger than the design fatigue lifetime (2 DLT), the LEF is determined to be 1.01. LEFs based on the conservative strength and life shape parameters are obtained to be 26.31 and 1.25, respectively, as shown in the figure. These conservative factors are based on the full characterization of various material systems, loading conditions, and environment provided by FAA [13]. Table 4.5 is the summary of the factors analyzed in this thesis and the conservative factors by FAA, which are the resulting strength and life factors, LEF by 1 DLT and LEF by 2 DLT.

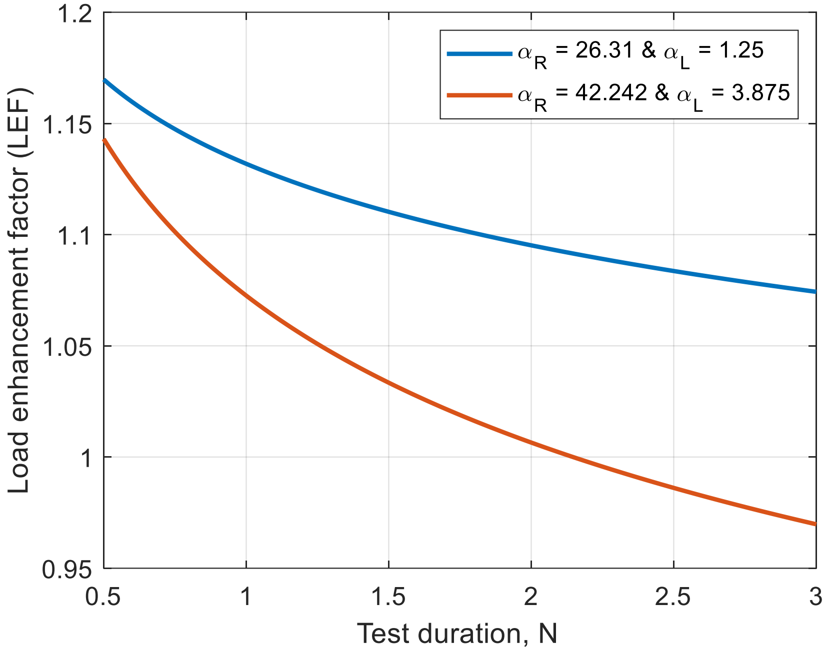


Fig. 4.4 B-basis load enhancement factors as a function of test duration

Table 4.5 Summary of the scatter analysis results

	Static-strength shape parameter α_R	Fatigue-life shape parameter α_L	Life factor N_F	LEF (1 DLT)	LEF (2 DLT)
Analyzed value	42.242	3.875	2.14	1.07	1.01
Conservative value	26.31	1.25	13.56	1.13	1.1

As shown in Eq. (4.9), LEF is a function of both strength and life shape parameters obtained from the static and fatigue tests. The strength and life parameters depend on the scatter of each test condition. In addition, life factor is a function of only life shape parameter as shown in Eq. (4.8). Therefore, life factor can be determined by the fatigue test results. Figure 4.5 shows the influence of fatigue-life shape parameters on the life factors and Fig. 4.6 shows the influence of the strength shape parameter on the LEFs along with the fixed life shape parameter. Therefore, by using load enhancement factor approach, various conditions including the effects of geometry, environment, loading mode, and lay-ups can be considered in the coupon-level testing procedure for rotorcraft fatigue evaluation. Furthermore, by taking these variables into account, the reliable load enhancement factors or the life factor can be obtained more economically than the LEFs analyzed by the conservative factors from FAA.

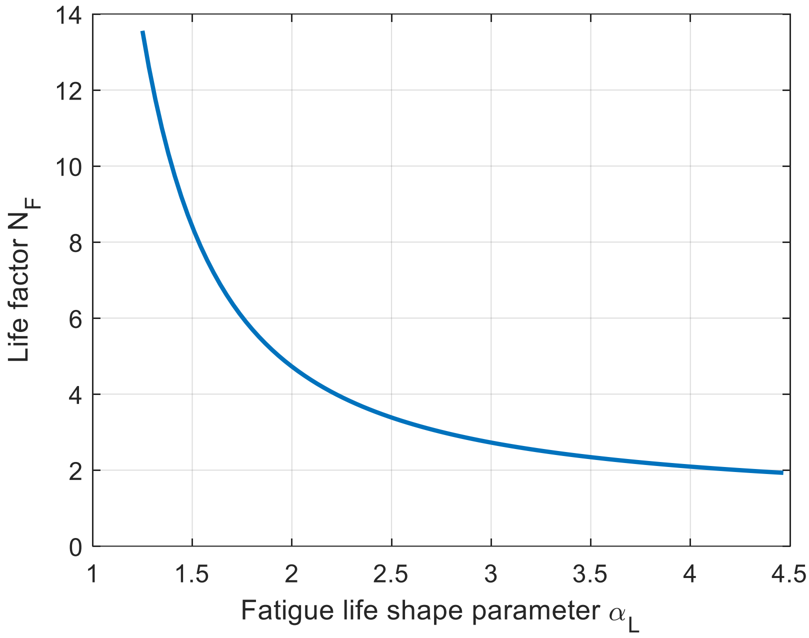


Fig. 4.5 Influence of fatigue-life shape parameter on the life factor

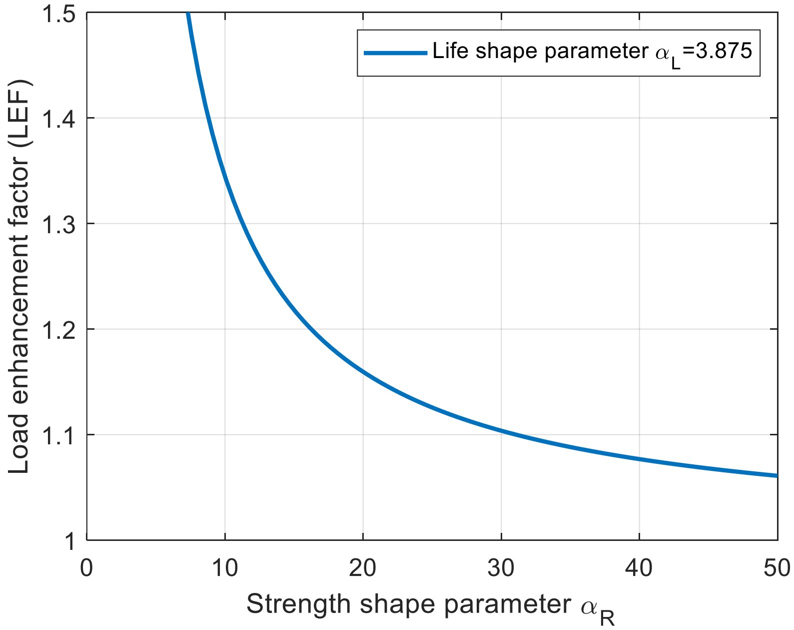


Fig. 4.6 Influence of the strength parameter on the LEFs

Chapter 5

Evaluation of Weibull Parameters for Scatter Analysis

In this chapter, further research on the evaluation of the Weibull parameter estimation methods for scatter analysis is conducted. Various Weibull parameter estimation methods are considered for the scatter analysis. In addition to the life factor and LEFs, the strength and life shape parameter are also compared with the analyzed results using MLE in Chapter 4. In Section 5.1, improved graphical and analytical procedures for estimating Weibull distribution parameters are proposed. In Sections 5.2 and 5.3, various Weibull estimation methods are implemented for scatter analysis. The smallest and the largest strength and life shape parameters are obtained. In Chapter 4, the life and load enhancement factors are established from the shape parameters obtained in Chapter 3 and the results of each procedure are compared.

5.1 Weibull Parameter Estimation

The Weibull distribution is one of the widely accepted crack initiation models for analyzing material properties scatter. Reliability analysis is conducted by using a large number of results via the shape and scale parameters of Weibull distribution estimated from the test results. However, discrepancies may exist when fitting the test results into the probability distribution. Therefore, frequently used methods are proposed and various cases for the parameter estimation are considered.

A two-parameter cumulative Weibull distribution can be described, as shown in Eq. (5.1), where α is the shape parameter and β is the scale parameter. The linearized unreliability function $F(x)$ in Eq. (5.1) can be converted into Eq. (5.2).

$$F(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \tag{5.1}$$

$$\ln(\ln(\frac{1}{1 - F(x)})) = \beta \ln(x) - \ln(\beta) \tag{5.2}$$

To estimate $F(x_i)$ of the i^{th} failure, the following three graphical methods are mainly used: the mean rank regression (MR); the median rank regression (MDR); and symmetric cumulative distribution function (SCDF). $F(x_i)$ can be obtained by using the formulae listed in Table 5.1. Subsequently, after the Weibull cumulative probability is plotted as $F(x_i)$ in terms of *x*, the resulting points can be estimated using the least squares method, which is rank regression on *X* (RRX) and rank regression on *Y* (RRY).

Table 5.1 Methods for estimating unreliability function $F(x_i)$ for probability plotting

Method	$F(x_i)$
Mean rank (MR)	$\mathrm{i}/(\mathrm{n}+1)$
Median rank (MDR)	$(\mathrm{i}-0.3)/(\mathrm{n}+0.4)$
Symmetric cumulative distribution function (SCDF)	$(\mathrm{i}-0.5)/\mathrm{n}$

In addition, MLE and method of moments (MOM) can be considered for parameter estimation. By using the MOM, an estimator of the k^{th} moment is given, as shown in Eq. (5.3), where $x_1, x_2, \ldots x_n$ represents a set of results.

$$\widehat{m_k} = \frac{1}{n}\sum_{t=1}^{n} x_t^k \tag{5.3}$$

The k^{th}moment for Weibull distribution is given by Eq. (5.4), estimated using the Gamma distribution function Γ.

$$\mu_k = \left(\frac{1}{\alpha^k}\right)^{\frac{k}{\beta}} \ \Gamma\left(1 + \frac{k}{\beta}\right) \tag{5.4}$$

By dividing the 1st moments by the 2nd ones and taking on the square root, Eq. (5.5) is derived, which is a function of only β.The shape parameter β can be estimated using Eq. (5) and the scale parameter can be estimated using Eq. (5.6) with the Gamma distribution function Γ.

$$\sqrt{\frac{\widehat{m_1}}{\widehat{m_2}}} = \sqrt{\frac{\Gamma(1+\frac{1}{\beta})\Gamma(1+\frac{1}{\beta})}{\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2(1+\frac{1}{\beta})}} \tag{5.5}$$

$$\alpha = \left\{\frac{x}{\Gamma\left[\left(\frac{1}{\beta}\right)+1\right]}\right\}^{\beta} \tag{5.6}$$

Moreover, MLE estimates the parameters by maximizing the likelihood function, as shown in Eq. (5.7), where x_i, $f(x_i)$, and *n* represent the sample result, probability density function, and the number of data sets, respectively. By taking logarithms on Eq. (5.7) and differentiating with respect to α and β, the shape and scale parameters can be estimated.

$$L(\alpha, \beta) = \prod_{i=1}^{n} f(x_i) = \alpha^n \beta^n \left(\prod_{i=1}^{n} x_i \right)^{\beta-1} \exp\left(-\alpha \sum_{i=1}^{n} x_i^{\beta} \right) \tag{5.7}$$

5.2 Determination of the Static Strength Shape Parameter

To estimate the modal or mean value for the strength shape parameters, the strength shape parameter analyzed by the static and fatigue test results in Section 4.2 and the pooled shape parameters in Table 4.1 are analyzed. Aside from the scatter analysis using MLE of the Weibull distribution as in Section 4.2. Various Weibull parameter estimation methods are implemented using the methods discussed in Section 5.1. The probability and survival plots for the static strength shape parameter are shown in Figs. 5.1 and 5.2. The results of the mean and modal values of the static strength shape parameters are listed in Table 5.2. The MLE, MOM, RRX, RRY, MR, MDR, and SCDF are used to obtain the static strength shape parameters. The static strength shape parameter varies with its smallest and largest values being 34.334 and 45.541, respectively. These are the mean and modal values estimated using the mean rank regression on *X*.

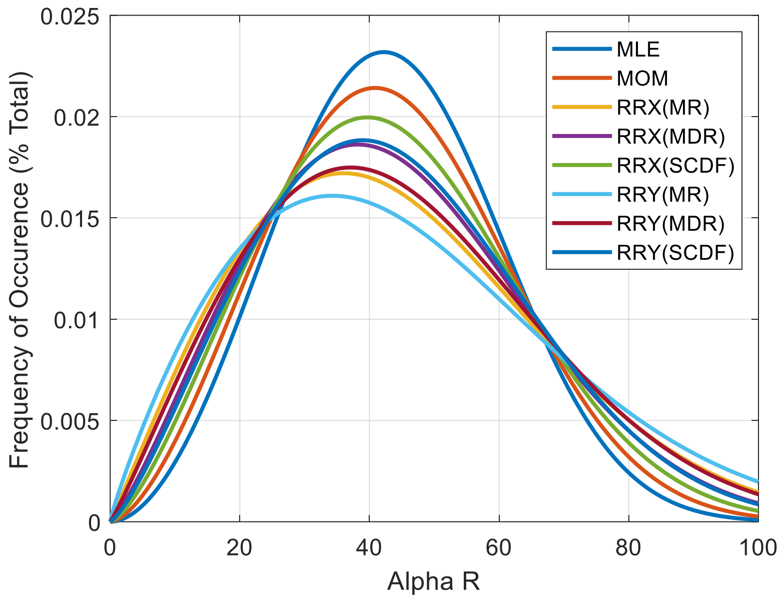


Fig. 5.1 Comparison plots of the static-strength shape parameter probability for the various parameter estimation methods

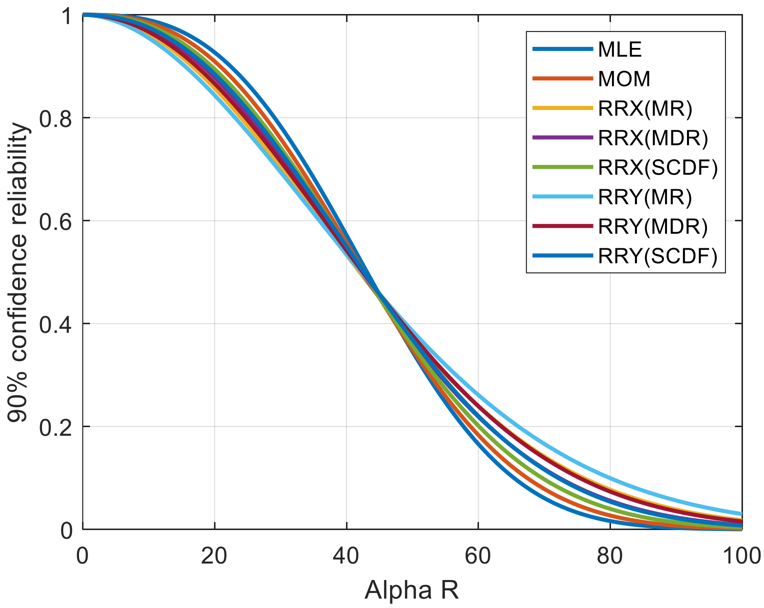


Fig. 5.2 Comparison survival plots of the static-strength shape parameter for various parameter estimation methods

Table 5.2 Results of the static-strength shape parameters for the various parameter estimation methods

	MLE	MOM	Rank regression on X (RRX)			Rank regression on Y (RRY)		
			MR	MDR	SCDF	MR	MDR	SCDF
Modal α_R	42.242	40.841	36.036	38.238	39.637	34.334	37.137	38.939
Mean α_R	43.645	43.586	44.589	44.095	43.803	45.541	44.807	44.365

5.3 Determination of the Fatigue Life Shape Parameter

To compare the results of the fatigue-life shape parameters, the procedures for scatter analysis and the fatigue result sets are implemented as stated in Section 4.3. However, in addition to MLE, various Weibull parameter estimation methods as discussed in Section 5.1 are used to estimate the life shape parameters from the equivalent static-strength results in Sendeckyj analysis. The same Weibull parameter estimation method is used to estimate the mean or modal value from the life shape parameters. As a result, fatigue-life shape parameters for various scatter analysis and Weibull parameter estimation methods are obtained using the probability and survival plots, as shown in Figs. 5.3 and 5.4. The life shape parameters estimated for the test conditions and scatter analysis methods are provided in Table 5.3. Subsequently, the shape parameters for each test condition are analyzed to be the fatigue-life shape parameters for the scatter analysis methods as shown in Table 5.4. IW and JW represent the individual Weibull and joint Weibull methods, respectively. MLE, MOM, RRX, RRY, MR, MDR, and SCDF are used to estimate the shape parameters in Sendeckyj equivalent static-strength results. The most conservative fatigue-life shape parameter is identified to be 2.891, which is the modal value estimated from the mean rank regression on Y. Further, the largest one is 4.847, which is the modal fatigue-life shape parameter estimated using the IW.

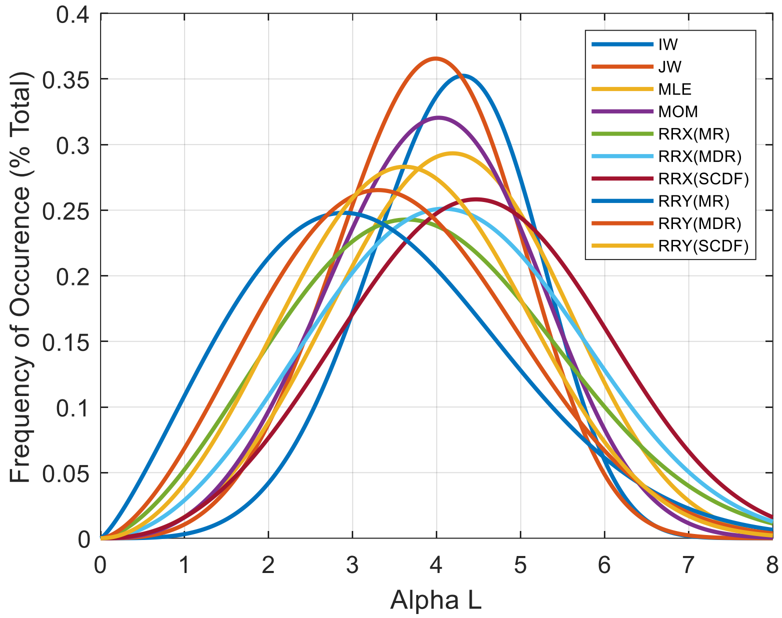


Fig. 5.3 Comparison plots of the fatigue-life shape parameter probability for the various scatter analysis methods

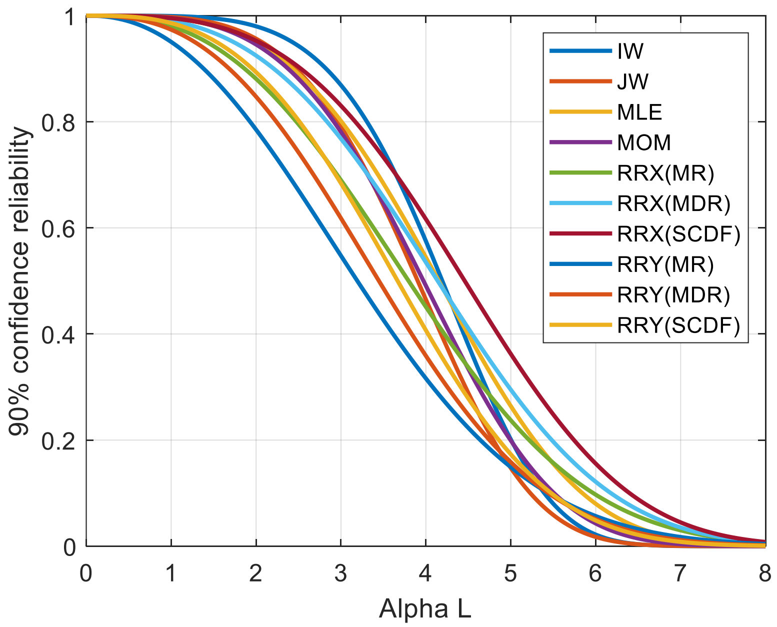


Fig. 5.4 Comparison survival plots of the fatigue-life shape parameter for the various scatter analysis methods

Table 5.3 Estimation of the fatigue-life shape parameters by the various scatter analysis methods

Test No.	Individual Weibull method	Joint Weibull method	Sendeckyj equivalent static-strength model							
			MLE	MOM	RRX			RRY		
					MR	MDR	SCDF	MR	MDR	SCDF
(1)	5.228	5.092	4.107	4.797	4.392	4.800	5.178	4.247	4.590	4.880
(2)	5.555	4.641	2.618	3.760	3.880	4.163	4.420	2.916	3.091	3.240
(3)	3.304	2.677	3.839	3.836	3.324	3.595	3.840	3.140	3.384	3.598
(4)	5.528	4.04	3.499	5.155	5.399	5.857	6.275	3.917	4.210	4.464
(5)	2.447	1.913	1.454	1.769	1.878	2.025	2.157	1.475	1.587	1.683
(6)	5.713	4.745	3.641	4.436	4.133	4.517	4.874	3.586	3.850	4.070

Table 5.4 Results of the fatigue-life shape parameters using the scatter analysis and Weibull parameter estimation methods

	Individual Weibull method	Joint Weibull method	Sendeckyj equivalent static-strength model							
			MLE	MOM	RRX			RRY		
					MR	MDR	SCDF	MR	MDR	SCDF
Modal α_L	4.847	3.988	4.188	4.028	3.644	4.084	4.469	2.891	3.299	3.620
Mean α_L	4.665	3.875	4.147	3.959	3.874	4.177	4.466	3.328	3.521	3.701

5.4 Determination of the Load Enhancement Factor (LEF)

To generate the LEFs, the static-strength and fatigue-life shape parameters need to be determined. Therefore, the smallest and largest values of the shape and life parameters, as determined in Sections 5.2 and 5.3, are used and the generated LEFs are compared. The results are compared as a function of test duration, as shown in Fig. 5.5. The LEF is obtained on B-basis reliability, which is defined as the 90 % lower confidence limit on the tenth population percentile. The values of 34.334 and 45.541 are used as the smallest and largest shape parameters (α_R), respectively. These are estimated by the RRX using the mean rank probability plot. The smallest life parameter (α_L) used is 2.891 and it is estimated by the Sendeckyj analysis fitted by the RRY plotted by the mean rank. Additionally, for the largest life parameter, 4.847 is used. These are estimated by the IW method. From Fig. 5.5, it can be noted that with the assumed usage of the fatigue loads and design lifetime (1 DLT), the LEFs range from 1.066 to 1.09. Additionally, for a test duration that is two times larger than the design fatigue lifetime (2 DLT), the LEFs range from 0.99 to 1.03.

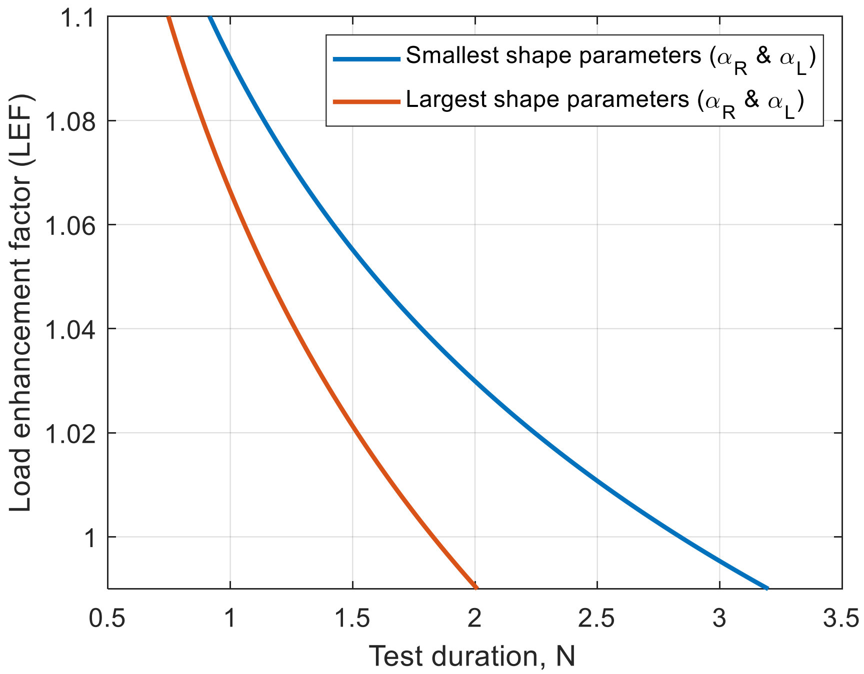


Fig. 5.5 Influence of the test duration and shape parameters on B-basis reliability of load enhancement factors

Table 5.5 Comparison of the life factors and load enhancement factors of 1 DLT and 2 DLT for the smallest and largest values of the strength and life shape parameters

	Smallest value	Largest value	Discrepancy
Strength shape parameter	34.334	45.541	24.6 %
Life shape parameter	2.891	4.847	40.4 %
Life factor N_F	2.84	1.84	35.2 %
LEF (1 DLT)	1.09	1.07	2.2 %
LEF (2 DLT)	1.03	0.99	3.9 %

MLE is one of the most frequently used robust methods that shows good correlation with large number of samples. However, most of the static and fatigue tests do not have enough number of samples. It is significantly costly to create sufficient result sets for each set of fatigue tests for the representative material system and structures. In addition, in this thesis, the Weibull parameter estimation is conducted using two static and six fatigue result sets. Thus, numerical investigation is performed to show the rationality for model selection for the parameter estimation methods. Therefore, various models are considered for estimating the Weibull parameters. The static-strength shape parameters range from 34.334 to 45.541 and fatigue-life shape parameters range from 2.891 to 4.847. The results of the smallest and largest values for the strength and life shape parameters are summarized in Table 5.5. The strength and life parameters show the discrepancy of 24.6 % and 40.4 %, respectively.

LEF can be a function of the static-strength and fatigue-life shape parameters. From Fig. 4.5, it can be noted that the evaluation of the effect of the fatigue-life shape parameter on the life factors leads to a change in the LEF. The pooled results and the tests conducted show reduced scatter for the fatigue properties compared to 1.25 by Federal Aviation Administration (FAA). In addition, in Fig. 5.6, the life shape parameters are fixed to evaluate the effect of the strength parameters on the LEF. The static-strength shape parameter shows reduced scatter compared to 26.31 by FAA. Both the strength and life shape parameters are in the insensitive region of the LEF curves with respect to the strength and life parameters. However, it is noted from Fig. 5.6 that the life factors range from 1.84 to 2.84 and the LEF by 1 DLT ranges from 1.07 to 1.09. In addition, the LEF by 2 DLT ranges from 0.99 to 1.03. The life factors and LEFs by 1 DLT and 2 DLT are summarized in Table 5.5 in accordance with the largest values for the strength and life parameters. Based on the largest value of the life factor, the smallest one shows a discrepancy of 35.2 %. In addition, the LEFs of 1 DLT and 2 DLT show discrepancies of 2.2 % and 3.9 %, respectively, based on the largest value. As a result, the conservative life factor and the LEFs are obtained by applying various Weibull parameter estimation methods for scatter analysis. From the discrepancies shown, it is shown that the Weibull parameter estimation methods need to be evaluated for the better model of distribution fitting. Therefore, various scenarios for Weibull distribution parameter estimation and scatter analysis methods need to be further evaluated.

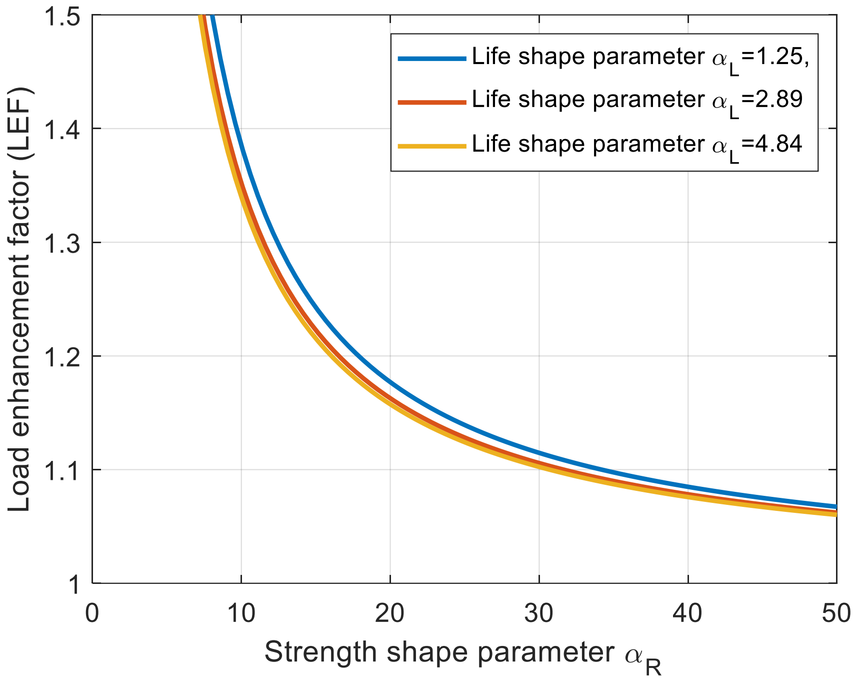


Fig. 5.6 Influence of the strength and life parameters on load enhancement factor

Chapter 6

Conclusion and Future Works

6.1 Conclusion

In this thesis, methodology for certifying the composite structures is investigated in accordance with FAR 29.573, AC 29.573, and CMH-17. The scatter analysis method which is the load enhancement factor approach is selected to comply with the procedures for fatigue and damage tolerance evaluation. For the application of fatigue and damage tolerance evaluation, the rotor blade design is selected. The baseline laminate is selected and the specimen is designed according to the rotor blade. Furthermore, the static tensile tests for the two environmental conditions and one set of fatigue tests are conducted. The scatter analysis is performed for the pooled results and the test results obtained in this thesis. From the results of the static and fatigue tests, the static-strength shape and fatigue-life shape parameters are obtained by statistical computation for different environmental conditions, geometry, loading modes and lay-ups. From the strength and life shape parameters, load enhancement factors or life factors can be generated that is used for the component level fatigue tests. The life factor and the LEF by 1 DLT and that by 2 DLT are obtained. Based on the conservative shape and life factors provided by FAA, the LEFs by 1 DLT and 2 DLT shows the discrepancy of 5.31 % and 3.18 %. In such way, the method to consider those effects such as geometry, environment can be considered on the coupon-level testing procedures for fatigue and damage evaluation.

For further research, the Weibull parameter estimation and scatter analysis methods are evaluated for establishing LEFs for composite structures. Various models of the improved graphical and analytical procedures for Weibull parameter estimation are proposed and summarized. In addition, to generate LEFs, static-strength and fatigue-life shape parameters are estimated by analyzing the static test and fatigue test results. Eight models are used to determine the strength and life shape parameters based on Sendeckyj equivalent static-strength results. In addition, the MLE determines the life shape parameters used in the individual Weibull and joint Weibull methods. The same parameter estimation method is used to determine the modal or mean value of the shape parameter. Furthermore, the life factors and LEFs including the strength and life shape parameters are evaluated based on the models used for Weibull parameter estimation and scatter analysis. As a result, the LEFs by 1 DLT and 2 DLT show a discrepancy of 2.2 % and 3.9 %, respectively, in accordance with the largest and smallest strength and life shape parameters. From the discrepancies shown, it is shown that the Weibull parameter estimation methods for the scatter analysis methods need to be evaluated for the better model for the distribution fitting.

6.2 Recommendation for Future Works

The following three items are recommended for future development.

1. Various Weibull parameter estimation methods will be applied to obtain the modal or mean value of the strength and life shape parameter for individual Weibull and joint Weibull methods in addition to Sendeckyj analysis. The discrepancies of fitting to the Weibull distribution will need to be evaluated to consider the uncertainties induced by the parameter estimation methods. As a result, the procedures for selecting the best model for evaluating the uncertainties of material scatter will be established.

2. The design load spectrum for the selected rotor blade will be determined. The load spectrum will be omitted in the lower level and the environmental knockdown factors will be derived to consider the higher level of tests.

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국문초록

하중증대계수 방법을 통한 복합재 구조의 피로 평가 절차 연구

이 창 배

기계항공공학부

서울대학교 대학원

복합재가 항공산업에서 널리 사용되고 복합재의 거동에 대한 이해가 성숙함에 따라 개정된 감항인증 기준인 손상허용 및 피로평가 절차가 정립되었다. 하지만 복합재는 용도, 하중 및 환경 조건에 따라 다르게 다루어져야 한다. 복합재 로터 블레이드에 사용된 복합재의 거동을 이해하기 위해서 본 논문은 쿠폰 단위 시험과 이때 다루어져야 하는 고려사항들에 초점을 맞추고자 한다. 이를 위해 로터 블레이드의 설계안과 해당 블레이드에서 사용되는 기준 복합재료를 선택하였다. 또한, 기준이 되는 하나의 정적 및 피로 시험을 수행하여 쿠폰 단위 시험에서 환경, 재료/공정 변동성 및 형상에 따른 영향을 고려하는 방법을 다루고자 한다. 이에 대한 영향을 고려하기 위해 분산 해석을 수행하였고, 결과 시험 시간에 따른 하중증대계수를 획득하였다.

하중증대계수는 정적 및 피로 시험 결과로부터 강도 및 수명 형상 파라미터를 예측함으로써 도출할 수 있다. 따라서 복합재 물성치의 분산으

로부터 기인하는 불확실성에 대해 고려할 수 있다. 하지만 분산 해석에서 사용되는 Weibull parameter 를 예측 방법에 따라 하중증대계수는 다른 결과를 나타낸다. 따라서 본 논문에서는 Weibull parameter 예측 기법과 분산 해석 기법이 제시되었다. 8 개의 Weibull 예측 기법과 3 개의 분산 해석 기법에 따른 강도 및 수명 형상 파라미터를 구하였고, 이에 따른 하중증대계수를 도출하였다. 가장 작은 형상 파라미터들과 가장 큰 형상 파라미터들로 얻은 하중증대계수를 비교하였으며, 마지막으로 물성치의 분산을 보다 현실적인 분포 피팅을 통해 해석하기 위해 하중증대계수에 대한 강도 및 수명 계수의 영향과 파라미터 예측과 분산 해석에서의 모델 선택에 따른 결과를 평가하였다.

주요어 : 피로 평가, 회전익기 구조, 감항인증, 분산 해석, 하중증대계수 방법, Weibull parameter 예측

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