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Acceleration of Service Life Testing by Using Weibull Distribution on Fiber Optical Connectors

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Abstract: The service life assessment of previous fatigue stress has a fundamental role in estimating the reliability of products like fiber optical connectors, and should replicate use in severe environments in telecommunications systems. However, the vibration prediction models used in the literature present limitations in vibration life prediction. In this paper, we propose using the insertion loss fatigue life and including it in the Weibull distribution to determine the Weibull parameters η and β to evaluate fiber optic connector reliability $R(t)$ under environmental and mechanical testing stress. We analyzed the failure data of a standard telecommunication fiber optical connector under a program of service life stress testing against that of a fiber optical connector under only mechanical vibration stress testing. The fiber connectors were monitored during the vibration testing to review the transient change of the optical signal. Their results showed that the reliability of the fiber connectors submitted to the service life program was $R(t) = 0.694$, while that of the fiber connectors submitted to mechanical vibration only was $R(t) = 0.970$. In addition, the analysis showed that the service life testing consumed 70.2% of the product's lifetime. We present in Numerical Validation the steps to determine the acceleration factors of the vibration test developed.

Keywords: accelerated life testing; vibration stress; reliability; Weibull distribution

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1. Introduction

Structural vibration loads encountered in the field of operation are among the mechanisms most widely responsible for failure of mechanical, electronic and telecommunication systems [1,2]. Most failures in fiber optical connectors are from high attenuations and insertion loss [3]. A defect or a high attenuation may cause malfunction and even lead to serious failures in telecommunication fiber optic connections. Thus, to prevent failures and defects while the product is in service, an analysis should be performed to detect them early [4,5]. The detection can be carried out by testing the failure regression time, using a tool that obtains data from failure times observed of products that are submitted to stress such as vibration load, to procure estimated reliability as a remnant lifetime [6,7]. With that purpose, accelerated life testing (ALT) is applied to collect experiment data of the product of interest submitted to higher stress than when it is in operation; thus, the reliability under operational stress can be determined [8]. Regarding product operation, fiber optic connectors that are used for telecommunication systems are subjected to vibrations during their operational life [3] and these may induce dynamic loads and potentially lead to an early failure due to fatigue damage [9]. Thus, the fiber optical connectors must be designed to withstand the induced vibration damage [10]. During the product development it may be necessary to validate the most critical components through durability/validation tests to avoid the risk of failure [11]. The industrial standards based on fatigue damage stress are applied to perform tests representative of the conditions of application [12], then the environmental and mechanical conditions that affect the fiber optical connectors are measured and evaluated. However, reliability issues must be addressed for fiber optical connectors operating under mechanical vibration conditions, since fiber optics are increasingly used in harsh environments. Thus, reliability models for fiber optical systems submitted to mechanical stress have been generated [13], but while there is a need for information on mechanical vibration loads induced, no extensive experimental essay has been found in the literature on mechanical vibration as an accelerating parameter. Currently, vibration tests are carried out on new samples, but this is not efficient in determining the reliability of the product or its remaining life because the service life tests consume a significant percentage of its useful life (strength to support stress). Thus, in this article we determine the reliability and the remaining life of (1) samples subjected to service life tests [14], and (2) samples subjected only to vibration, finding that results for the samples subjected to service life tests, on average, were lower than those of samples subjected to vibration only. We note that lifetime assessment is related to operation and environmental stresses like temperature and vibration that cause fatigue in the component's material capability due to degradation and aging [15].

The paper is organized as follows. Section 2 includes the generalities of the fiber optic connector measurements, vibration tests, and Weibull distribution model. Section 3 includes a numerical validation. In Section 4, the results are presented. Finally, in Section 5, the discussion is provided.

2. Theoretical Background

2.1. Fiber Optical Connector Measurements

When testing fiber optic functionality, performance is divided into multimode and single-mode fiber [16], and since in practice the single mode fiber is widely employed, this investigation focused on single mode fiber. The main fiber optic measurement test applied to evaluate fiber optics is called attenuation [5], which is caused mainly by bending that can be micro bending or macro bending. The attenuation provokes an exponential loss of the optical power of the fiber, denoted by

$$P(x) = P_o \exp(-\propto z) \quad (1)$$

In practice, it is applied by using the unit dB (decibel) and Equation (1), rewritten as,

$$P(z) = P_o \times 10^{-\propto z/10 \text{ dB}} \quad (2)$$

where $P(z)$ is the optical power at distance z from the input. P_o is the optical power at the fiber input and $\propto$ is the attenuation coefficient [dB/km]. On the other hand, in fiber optic single-mode connectors, the insertion loss is among the most critical parameters [10] and it is defined as

$$IL = 10\log\left({}^{P_{in}}\!\big/_{P_{out}} \right) \quad (3)$$

Insertion loss (IL) is measured in dB; P_{in} is the power input and P_{out} is the power output.

Thus, in this investigation the diagnosed failures obtained during the service life and ALT experiments are denotated by their IL measurements requirements. According to the international telecommunication association (UIT) [17], the maximum IL value in a graded index fiber optical connection after environmental or mechanical stress is about $\leq$0.4 dB, and for monitoring during stress applied it is about $\leq$0.5 dB. The graded index fiber optical connectors are usually measured at the wavelength of 1310 and 1550 nanometers (nm) for IL [3], because for communications applications these are the wavelengths at which single-mode fibers transmit optical power. Here, it is noted that for an optimized fiber connection/coupling that is not submitted to any stress, the IL requirement is about 0.35 dB [18].

Now, we proceed to review the proportional hazard models that can incorporate the effect of the stress induced in a fiber optical connector while it is performing its function of communication.

2.2. Proportional Hazard Models

Proportional hazard models are regression models used to incorporate the effect that a set of external variables has on the base hazard function of the process or system analyzed [19]. There are two types of proportional hazard models, parametric and semi-parametric. Parametric models are suitable for describing the behavior of lifetime data. In the literature, there are exponential, Weibull, gamma and lognormal models. However, only the exponential and the Weibull models can be considered as proportional hazard models and accelerated life models at the same time [6]. Since the Weibull model has been suggested as an accelerated life model [20] and proportional as well [21], it was applied in this investigation, and the following power function gives its hazard rate [20]:

$$h(t, z_t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp(\gamma \times z_t) \quad (4)$$

where t is the time, z_t represents a row vector at time t, γ is a column vector of the variables, β is the shape parameter, and η is the scale parameter of the Weibull distribution. This represents the hazard function of the Weibull proportional hazard model. Now, let us present the generalities of the Weibull distribution model.

2.3. Weibull Statistics Analysis

The two-parameter Weibull distribution is used to statistically analyze fatigue behaviors [22]. It has the capability to perform accurate fatigue failure analysis. The probability density function $f(t)$ and cumulative distribution function $F(t)$ are described by the Equations (5) and (6), respectively [23].

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\} \quad (5)$$

$$F(t) = 1 - exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\} \quad (6)$$

where t is the selected random variable (stress load). The corresponding reliability function $R(t)$ [23] is given as

$$R(t) = exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\} \quad (7)$$

From [24], the Weibull fatigue damage β and η parameters are determined as

$$\beta = \frac{-4\mu_y}{0.995 \times ln\left(\frac{\sigma_1}{\sigma_2}\right)} \quad (8)$$

$$\eta = exp(\mu_x) \quad (9)$$

where μ_y represents the mean of the Y vector (see Equation (13)), and μ_x represents the log-mean of the failure-time data [24], which here is determined directly from the monitoring variable (insertion loss measured in dB). Thus, μ_x is determined as

$$\mu_x = ln(\sigma_1\sigma_2)^{\frac{1}{2}} \quad (10)$$

Here, note the efficiency of the Weibull parameters β and η depends only on the accuracy by which the values are determined by Equation (3). In this paper, they were determined using an Agilent N7745A instrument (Keysight, Kimballton, IA, USA) with an 8-channel optical multiport power meter. Once the β and η values were known, the Weibull stress random analysis was performed as shown in the next section.

2.4. Weibull Stress Random Analysis

By using the n value from Equation (3) in the median rank approach function stated by Equation (11) [25], the corresponding cumulated failure percentile $F(t_i)$ is determined as

$$F(t_i) = \frac{i - 0.3}{n + 0.4} \tag{11}$$

Now, by using the $F(t_i)$ elements in the linearized form of the reliability function given in Equation (7), determine the corresponding Y_i elements as in Equation (12), and then compute its corresponding arithmetic mean value as in Equation (13) [24],

$$Y_i = LN(-LN(1 - ((i - 0.3)/(n + 0.4)))) \tag{12}$$

$$\mu_y = \sum_{i=1}^{n} \frac{Y_i}{n} \tag{13}$$

Additionally, the reliability index that corresponds to the Y_i value [24] can be determined as

$$R(t) = exp\{-exp\{Y_i\}\} \tag{14}$$

By using the β and η parameters, the $\sigma_{1\mathrm{i}}$ values can be calculated using the t_{0i} value that corresponds to each Y_i element as

$$t_{0i} = \exp\{Y_i/\beta\} \tag{15}$$

Next, the $\sigma_{2\mathrm{i}}$ value is determined as

$$\sigma_{2i} = \eta \times t_{0i} \tag{16}$$

And the $\sigma_{1\mathrm{i}}$ value is determined as

$$\sigma_{1i} = \eta / t_{0i} \tag{17}$$

Since the Weibull ALT presented in this investigation is based on the stress induced by the mechanical vibration in the fiber optic connectors. Now let us review the vibration analysis.

2.5. Vibration Analysis

When the assessment of fiber optical connectors is conducted by vibration analysis, different signal processes can be considered; this can be performed within either the time or the frequency domain. Among these techniques, the PSD analysis is widely used [26]. In the analysis we must consider that the product being vibrated responds to the input vibration as a function of the product's resonant frequency, where the amplification factor of the response Q is expressed as the transmissibility of the vibration amplitude at the resonance frequency [26], and it is given by

$$Q = \frac{f_n}{\Delta f} \tag{18}$$

where f_n is the natural frequency in Hz, and it is determined either by Equation (19) or Equation (20) [27],

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{19}$$

$$f_n = \frac{W_n}{2\pi} \tag{20}$$

where m is the mass; k is the material's stiffness and W_n is the natural frequency in Rad/Sec. When an oscillatory excitation force acts on the element under analysis, this is led by Equation (21) [28].

$$m\ddot{x} + c\ddot{x} + kx = F_0 \tag{21}$$

m, c, and k are the mass, damping, and stiffness of the system, which represent its inertial, dissipative and elastic properties, respectively, while F_o, represents the force applied to the element's mass. In the case of a fiber optical connector, the signal measured in dB can be monitored by using fiber measurement equipment (see Figure 1) when it is submitted to the stress of vibration PSD load by a period of time stated.

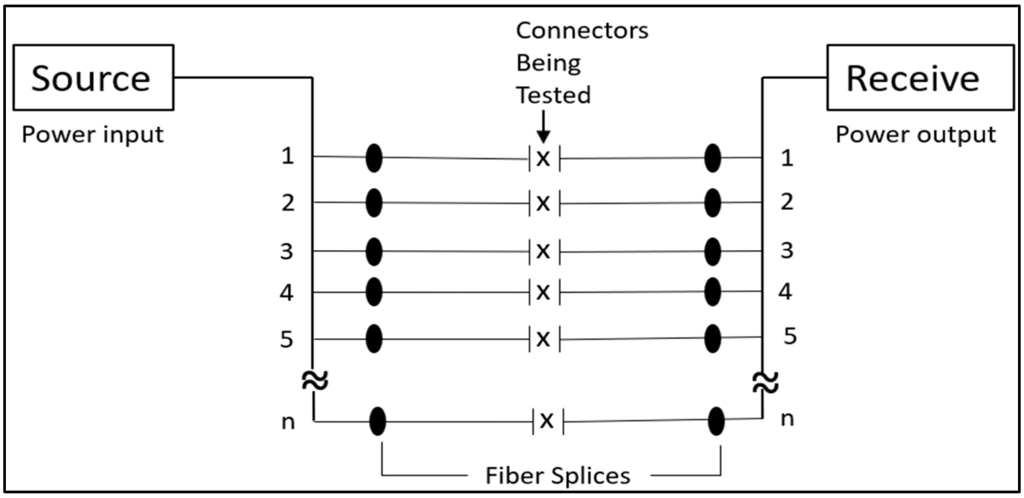


Figure 1. Insertion loss (dB) measurement of an optical signal with fiber optical connectors. Note: the same system of measurements was applied to monitoring the fiber optic behavior while it was being submitted to either environmental or mechanical load of stress.

Now, the steps to determine the percentage of product life consumed by the service life testing and the vibration ALT performed in fiber optical connectors are presented in the diagram in Figure 2.

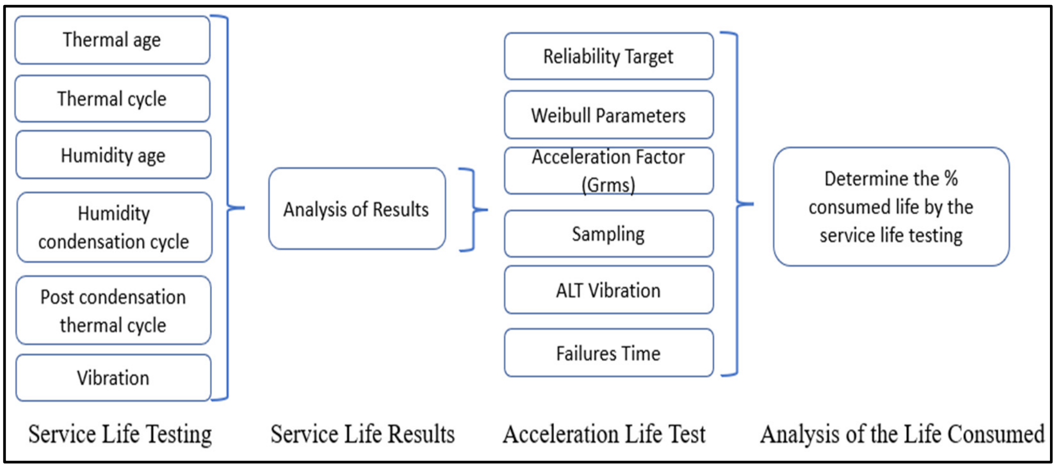


Figure 2. Service life testing and ALT analysis.

Here, note that from the proposed analysis, the corresponding Weibull reliability is estimated. Next, a numerical application is presented.

3. Validation of the Procedure

An experimental application was performed using optical angled PC polish fiber endface connectors, which are shown in Figure 3. Fiber optics are connected to obtain a signal in the telecommunication industry, and their alignment must be in a range designed to avoid failure due to high insertion loss, even when submitted to environmental or mechanical stress during their function in service of field applications. For this purpose, the thermal and humidity tests were performed using an environmental chamber. In contrast, the vibration tests were carried out using an electromechanical PM250HP shaker and power amplifier with an MB dynamic controller. The fixture on the vibration shaker allowed the fiber adapters used for connecting the fiber connectors to be mounted on the three mutually perpendicular axes. Both the chamber and the shaker provided the load and stress of the profiles performed on the fiber optic connections and its signal under test. The main idea was to determine the percentage of life consumed by the service life testing in terms of time to failure, as defined in Figure 2.

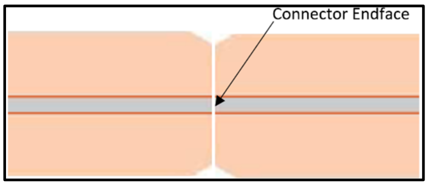
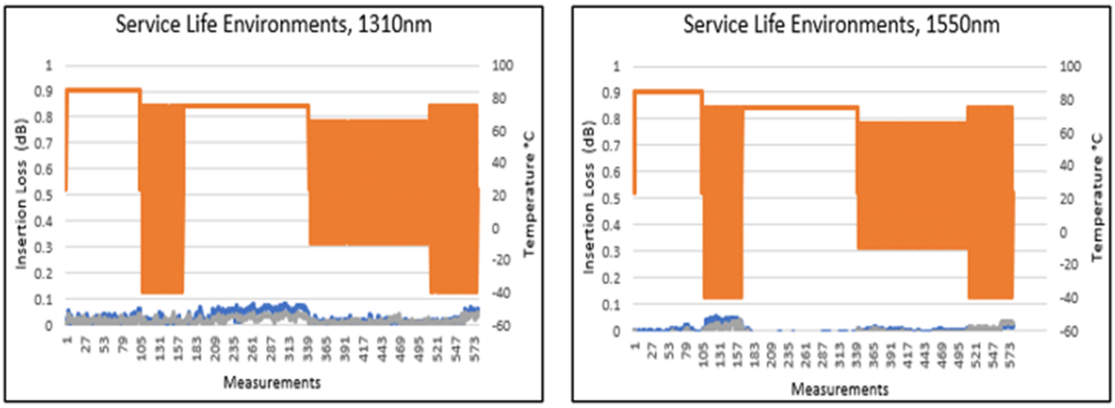


Figure 3. Single fiber alignment by two connectors.

3.1. Numerical Validation

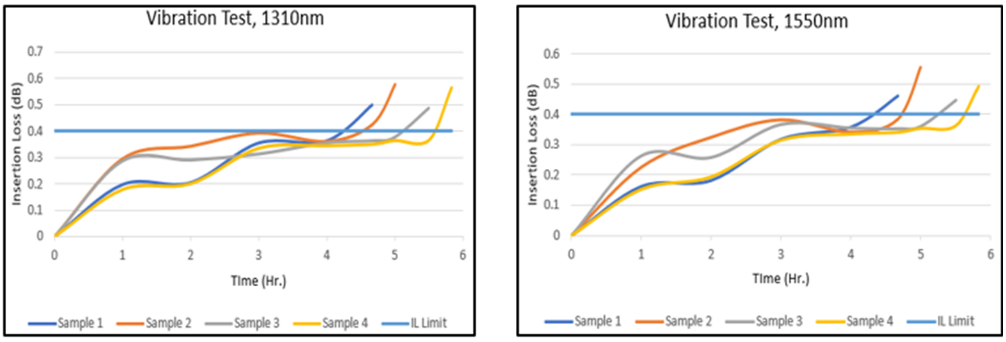
A numerical comparison of the failure times between the service life tests and an accelerated vibration test were performed, as outlined in Figure 2. The two fiber optic connectors that implied a connection were submitted to the GR-326 [14] service life program testing in the order and sequence shown in Figure 2. As per GMW 3172 in Appendix D [26], six samples were tested with no fiber damage in 864 h of service life testing of the temperature profiles. In Figure 4, the orange line shows the temperature profiles applied, and the lines at the bottom represent the insertion loss measurements of the six samples that were stable. The insertion loss requirement limit was 0.4 (dB).



(**a**) (**b**)

Figure 4. GR-326 service life insertion loss measurements (**a**) at 1310 nm; (**b**) at 1550 nm.

Next, the service life vibration test with the following experimental setup was performed. The samples were vibrated for 2 h on each of the third principal axes at an amplitude of 1.5 mm with a frequency between 10 and 55 Hz, and the insertion loss was measured during the test using Agilent N7745A equipment with an LED source at 1310 and 1550 nm, with the connections shown in Figure 1. The insertion loss failure times induced by the vibration load are shown in Figure 5 and Table 1.



(**a**) (**b**)

Figure 5. Vibration test insertion loss results with wavelengths (**a**) at 1310 nm; (**b**) at 1550 nm.

Table 1. Vibration test insertion loss results.

Failure Times in Vibration Service Life Test			
Sample ID	**Failure Time (h)**	**Insertion Loss Requirement (dB)**	**Insertion Loss Result (dB)**
1	4.670	0.400	0.501
2	5.000	0.400	0.576
3	5.500	0.400	0.485
4	5.830	0.400	0.566
5	12.289	0.400	0.464
6	13.861	0.400	0.561

Four of six samples (1–4) failed the service life vibration test. The two remaining samples (5–6) that met the requirement were still used, but under vibration ALT analysis that is presented in the next section. However, the failure times of samples 5–6 are included in Table 1 due to the purpose to calculate the Weibull β and η parameters of the service life testing program.

3.2. Acceleration Coefficients Estimation

To estimate the acceleration factors for the evaluation, a model that represents lifetime use and stress, and a test plan, are required [17,29]. For this paper, in which the stress was applied by the induced vibration, the reliability target was $R(t)$ = 0.97 with a confidence level C = 0.90. The test required 15 samples, the time of the vibration applied was 2 h per axis (6 h total), and the PSD generated 2.306 Grms to represent the stress level of the vibration, which was calculated by Equation (22) [9].

$$A_i = 10log(2)\frac{PSD_i}{10\log(2) + m}\left[f_i - f_{i-1}\left(\frac{f_{i-1}}{f_i}\right)^{m/10\log(2)}\right] \quad (22)$$

where A_i is the area of the *th* row, PSD_i is the amplitude and f_i is the frequency of the *i*th row of the vibration profile applied, while f_{i-1} is the frequency of the (th − 1) row of the testing profile, and m is the slope given as follows [9]:

$$m = {}^{dB}\Big/_{Octavas} \quad (23)$$

and

$$dB = 10log\left({}^{PSD_i}\Big/_{PSD_{i-1}}\right) \quad (24)$$

$$Octavas = \frac{log\left({}^{f_i}\big/_{f_{i-1}}\right)}{\log(2)} \quad (25)$$

$$Grms = \sqrt{\sum A} \tag{26}$$

Table 2 shows the features of the vibration profile and its results.

Table 2. GR-326 vibration profile applied.

f_i (Hz)	PSD_i (G^2/Hz)	dB	Oct	m (dB/Oct)	Area (A_i)	Grms
10	0.004	0.000	0.000	0.000	0.040	
20	0.02	6.990	1.000	6.990	0.108	
30	0.06	4.771	0.585	8.156	0.377	
40	0.14	3.680	0.415	8.866	0.963	
50	0.30	3.310	0.322	10.282	2.129	
55	0.4	1.249	0.138	9.086	1.742	
					5.320	2.306

The next step corresponds to the Weibull probabilistic analysis, with the shape factor β = 2.500 and fatigue constant m = 4 [26]. Here, because the testing of 15 samples was not desirable, it was reduced to 6. The increased over-stress factor is given by Equation (27) [26].

$$Accelerated\ Factor = \left\{ \frac{ln[1-c]}{n_{reduced} \times \ln[R(t)]} \right\}^{1/\beta} \tag{27}$$

where using the known values, we have

$$Accelerated\ Factor = \left\{ \frac{ln[1-0.90]}{6 \times \ln[0.97]} \right\}^{1/2.5} = 2.755$$

Due to the reduced sample size, the time for testing increased, and was calculated as per Equation (28).

$$Time_{new} = Time_{old} \times \left\{ \frac{ln[1-c]}{n_{reduced} \times \ln[R(t)]} \right\}^{1/\beta} \tag{28}$$

After replacing the known values, the new time for testing was

$$Time_{new} = 2 \times \left\{ \frac{ln[1-0.90]}{6 \times \ln[0.97]} \right\}^{1/2.5} = 5.510$$

Then, the vibration stress level (Grms) required increasing to reduce the test time to a desired time, as given by Equation (29) [26], and using the known values, the Grms accelerated was calculated as

$$Grms_{accel} = Grms_{normal} \times \left[\sqrt[m]{Time_{new} / Time_{old}} \right] \tag{29}$$

$$Grms_{accel} = 2.306 \times \left[\sqrt[4]{5.510 / 2} \right] = 2.971$$

Finally, the adjustment factor required to accelerate the vibration profile given was applied as in Equation (30):

$$Adjusment\ Factor = \left[\frac{Grms_{accel}}{Grms_{normal}} \right]^2 \tag{30}$$

$$Adjusment\ Factor = \left[\frac{2.972}{2.306} \right]^2 = 1.572$$

The new accelerated vibration profile used for testing, including the adjustment factor, is shown in Table 3. This profile is applied in the next section.

Table 3. GR-326 accelerated vibration profile.

f_i (Hz)	PSD_i (G^2/Hz)	dB	Oct	m (dB/Oct)	Area (A_i)	Grms
16.599	0.004	0.000	0.000	0.000	0.000	
33.197	0.020	6.990	1.000	6.990	0.180	
49.796	0.060	4.771	0.585	8.156	0.626	
66.394	0.140	3.680	0.415	8.866	1.599	
82.993	0.300	3.310	0.322	10.282	3.534	
91.292	0.400	1.249	0.138	9.086	2.891	
					8.833	2.972

3.3. Accelerated Vibration

Once the vibration ALT was defined (see Table 3), it was carried out by the same PM250HP shaker and power amplifier with an MB dynamic controller, using the same fixture on the vibration shaker that held the fiber optical connections. The fiber connectors submitted to testing were the two samples that met the completed service life testing, and two new samples without any previous stress that were indicated as per the standard GMW8758 [30]. The samples were tested to failure at the vibration ALT stress and the time to failure was recorded for each sample. The insertion loss measurements of the fiber optical connectors under test were taken by making the connections as per Figure 1, with the fiber optic connectors in a mated pair configuration formed by standard fiber angled PC adapters. The samples were connected to the Agilent N7745A equipment with an 8-channel optical multiport power meter, with a speed measurement data acquisition and transfer of 5 kHz per channel and with event detection in a wavelength range from 1310 to 1550 nm.

The vibration ALT is performed to demonstrate the product's reliability when it has not been submitted to previous service life testing. With that information, the accelerated vibration test was conducted, and its results are presented in Table 4.

Table 4. Accelerated vibration failure times.

Sample ID	Failure Time (H)	Requirement (dB)	Result (dB)
1 (service life survived)	4.00	0.400	0.464
2 (service life survived)	5.00	0.400	0.561
1 (new Sample without service life)	66.00	0.400	0.876
2 (new Sample without service life)	63.00	0.400	0.509

To determine a product's Weibull reliability, the failure time needs to be deaccelerated. This test was conducted using Equation (31), which multiplies the adjustment factor 1.572 from Equation (30) by the failure time in Table 4. The results are shown in Table 5.

$$\text{Time deaccelerated} = \text{adjusment factor} \times \text{failure time} \tag{31}$$

The experimental results are presented in the next section.

Table 5. Deaccelerated vibration failure time.

Samples ID	Failure Time (h) Deaccelerated
1 (service life survived)	6.639
2 (service life survived)	8.299
1 (new Sample without service life)	109.550
2 (new Sample without service life)	104.571

4. Results

Regarding the Weibull service life program testing from Table 1, from the corresponding cumulated percentile $F(t_i)$ elements in the linearized form of the reliability function stated in Equation (7), the corresponding Y_i elements are determined as in Equation (12), where $n = 6$. Thus, from Equation (13), the mean is $\mu_y = -0.501$, and with the failure times $\sigma_1 = 13.861$ and $\sigma_2 = 4.670$ we proceeded to use the Weibull distribution to obtain the reliability. From Equation (8), the Weibull shape parameter β value is

$$\beta = \frac{(-4)(-0.501)}{0.995 \times \ln\left(\frac{13.861}{4.670}\right)} = 1.850$$

From Equation (10), the log-mean is $\mu_x = 2.085$, and from Equation (9), the Weibull scale parameter η is

$$\eta = \exp(2.085) = 8.045$$

With the Weibull family results, the random behavior of the failure times σ_1 and σ_2 is determined by following the next steps. The random behavior of σ_1 and σ_2 is determined by Equations (16) and (17). Then, by using the β and the Y_i values in Equation (15), the basic Weibull elements t_{0i} for each Y_i are obtained, whereas by using the η and σ_1 values in Equation (32), the Weibull t_{01} values from the σ_1 and σ_2 failure time values are reproduced. These value is calculated as

$$t_{01} = \eta / \sigma_1 \tag{32}$$

By replacing the known values of η and σ_1, in Equation (32), we have

$$t_{01} = \frac{8.045}{13.861} = 0.580$$

And by using the β value in Equation (33), the Y_1 value that belongs to the t_{01} value is determined as

$$Y_1 = \ln(t_{01}) \times \beta \tag{33}$$

$$Y_1 = \ln(0.580) \times 1.850 = -1.008$$

Finally, by substituting the Y_1 value in Equation (14), the reliability $R(t)$ that belongs to the t_{01} element is

$$R(t) = exp\{-exp\{-1.008\}\} = 0.694$$

These results are shown in Table 6.

Next, the Weibull vibration ALT analysis in Table 5 was performed. In this case, since the value $\beta = 2.500$ was used to develop the acceleration test, this value was maintained. From the corresponding cumulated percentile $F(t_i)$ elements in the linearized form of the reliability function stated in Equation (7), the corresponding Y_i elements were determined as in Equation (12), where $n = 4$. Thus, from Equation (13), the mean is, $\mu_y = -0.617$, and with the failure times $\sigma_1 = 109.550$ and $\sigma_2 = 6.639$, we proceeded to use the Weibull distribution to obtain the reliability.

Table 6. Weibull service life program testing statistics analysis.

n_i	Y_i Equation (12)	μ_y Equation (13)	$R(t)$ Equation (14)	t_{oi} Equation (15)	σ_{2i} Equation (16)	σ_{1i} Equation (17)
1	−2.156	−0.359	0.891	0.312	2.509	25.803
2	−1.175	−0.196	0.734	0.523	4.262	15.188
	−1.008	**−0.544**	**0.694**	**0.580**	**4.670**	**13.861**
3	−0.602	−0.100	0.578	0.722	5.812	11.138
4	−0.147	−0.025	0.422	0.924	7.429	8.712
5	0.282	0.047	0.266	1.165	9.370	6.908
6	0.794	0.132	0.109	1.536	12.361	5.237

BOLD: The failure times from service life testing.

From Equation (10), the log-mean is, $\mu_x = 3.295$, and from Equation (9) the Weibull scale parameter η is

$$\eta = \exp(3.295) = 26.967$$

Using the η and σ_1 values in Equation (32), the Weibull t_{01} value from the σ_1 and σ_2 failure time values was reproduced. This value is calculated as

$$t_{01} = \frac{26.967}{109.550} = 0.246$$

Using the β value in Equation (33), the Y_1 value that belongs to the t_{01} value is determined as

$$Y_1 = \ln(0.246) \times 2.500 = -3.503$$

By substituting the Y_1 value in Equation (14), the reliability $R(t)$ that belongs to the t_{01} element is

$$R(t) = exp\{-exp\{-3.503\}\} = 0.970$$

These results are presented in the Table 7.

Table 7. Weibull vibration ALT statistics analysis.

n_i	Y_i Equation (12)	μ_y Equation (13)	$R(t)$ Equation (20)	t_{oi} Equation (15)	σ_{2i} Equation (16)	σ_{1i} Equation (17)
	−3.504	**−1.402**	**0.970**	**0.246**	**6.639**	**109.550**
1	−1.753	−0.438	0.841	0.496	13.377	54.371
2	−0.717	−0.179	0.614	0.751	20.247	35.922
3	−0.050	−0.013	0.386	0.980	26.432	27.516
4	0.609	0.152	0.159	1.276	34.405	21.139

BOLD: The failure times from vibration ALT.

The failure times from vibration ALT.

The results of the service life program testing and the vibration ALT by following the formulation given in Section 2.4 are presented in Table 8.

Table 8. Weibull comparison statistics results.

Weibull	Service Life Testing	Vibration ALT
Shape parameter (β)	1.850	2.500
Scale parameter (η)	8.045	26.967
Mean (μ_y)	−0.501	−0.617
$\text{Log} - \text{mean}\ (\mu_x)$	2.085	3.295
Reliability $[R(t)]$	0.694	0.970

To determine the percentage of the life consumed by the service life testing, the following relation of the η failure times was applied: $\frac{8.045}{26.967} = 0.298$. Thus, the percentage consumed is defined by $1 - 0.298 = 0.702$. It was determined that the service life testing does consume 70.2% of the total fiber optic connector's life. Equivalently, this implies that the observed life without considering the service life load (only vibration) is 3.352 times higher than when the service life testing load is applied. Therefore, we recommend conducting service life program testing instead of vibration testing only to determine the reliability and remnant life of the product.

5. Discussion

In this investigation, a Weibull probabilistic alternative to determine the fiber optical connector's reliability is presented. The reliability was estimated based on the service life testing GR-326 and an accelerated vibration test developed. Vibration stress was employed to determine the failure times of the product. In regard to the reliability results obtained by using the steps in Figure 2, they are based on the insertion loss measurements. This proposal predicts a reliability of $R(t) = 0.694$ for service life testing and a reliability of $R(t) = 0.970$ for single vibration ALT. It is important to note that service life testing does consume 70.2% of the connector's lifetime. However, we know the product's reliability data when they are submitted to the whole service life testing program or individual vibration testing.

The proposed analysis is useful and can be applied in environments where fiber optical connectors are installed in telecommunications. The importance of these results lies in the increased application of fiber optic connectors that has emerged in telecommunications technology, since it uses digital encoding of data streams for telephone, video and data services and internet for homes and businesses, applications in which reliability is key. Finally, the reliability of a fiber optical connector is of high importance in telecommunications applications where long connections represent a large investment and high reliability is required, and therefore, more research must be pursued.

6. Conclusions

1. A vibration ALT was developed using the probabilistic Weibull distribution and acceleration coefficients to estimate the reliability of the fiber optic connectors. According to the samples tested, the reliability R(t) was 0.970.
2. The reliability was determined by the fiber optical connector failure times obtained from the insertion loss measurements performed during testing. The measurements were performed using Agilent N7745A equipment with an 8-channel optical multiport power meter, with a speed measurement data acquisition and transfer of 5 kHz per channel and with event detection in a wavelength range from 1310 to 1550 nm, as shown in Figure 1.
3. This investigation can be applied to fiber optical connectors used in the telecommunications industry to assist in real and practical reliability analysis. An experiment by using the service life testing program from GR-326 was performed and its reliability R(t) = 0.694 was determined.
4. By using the relation of the scale Weibull parameter data from each experiment, (1) service life testing program, and (2) vibration ALT, the percentage of the product's service life consumed was obtained.
5. Finally, to determine the reliability and the remaining life of a product, we recommend, based on the statistical Weibull analysis conducted, performing the service life tests, because each test of the service life consumes a percentage of the product's life.

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