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Air-Vessel Corrosion Damage Distribution and Reliability Modeling

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Existing research on structural reliability affected by corrosion has a primary focus on structure failure due to inadequate residual structural strength. However, some corrosion-induced failures are not critically dependent on stress or fatigue: examples include leakage from fluid lines or containers, air cabin and landing floats, and/or degradation of the externally smooth surface. Based on data collected from passenger aircraft Y-7 inspections and maintenance, this paper will propose some concepts and relevant failure criterion based on the functionalities of the structure. Additionally, this paper will propose a few corrosion probabilistic models for reliability assessments.

I. Introduction

CORROSION is one of the most serious safety problems in aviation, and it gives rise to extensive maintenance costs. Although a large amount of polymers and composites have been employed in aircraft in recent years, metallic materials remain important, as they are still commonly used due to their strength, stiffness, toughness, and tolerance of high temperatures. In aircraft, high-strength aluminum alloys are the material of choice, and corrosion of this material manifests itself in many ways, including stress corrosion cracking, pitting corrosion, exfoliation corrosion, crevice corrosion, and galvanic corrosion. Corrosion leads to deterioration of structural strength and stiffness and to degradation of the appearance of surfaces. Corrosion can lead to failure through initiation and propagation of fatigue cracks; in turn, fatigue can damage the protective coat on the structural surface, thereby promoting further progression of corrosion (Schweitzer [1]). For example, a crash of Boeing 747 aircraft caused by stress corrosion occurred in August 1985 in Japan, in which 520 persons lost their lives (Job [2]). In 1998, the total annual direct cost of corrosion to U.S. aircraft industries was estimated at $2.225 billion, the corrosion maintenance was estimated at $1.7 billion, and downtime due to corrosion was estimated at $0.3 billion (Agarwala [3]). NASA has outlined approximately $70 million and a 19-year program to assess and mitigate corrosion in their space program (Curtis [4]).

In recognition of the many forms of corrosion, including those that are not related to residual strength, it is proposed here that failure criteria of aircraft parts should be defined in relation to their specific functions. Parts such as spars, beams, and ribs are designed for carrying loads, and so the failures are traditionally, and reasonably, judged in relation to residual strength of the part. For other parts, strength is not the primary design requirement; for example, parts such as oil pipes, containers, and reservoirs are measured by their integrity (within the condition of adequate strength). In another example, some parts of an aircraft (such as mirrors, engine blades, and wing surfaces) are considered to be sufficiently degraded to justify repair or replacement when their surface finish impedes their ability to perform their required function. The reliability modes of components affected by corrosion therefore need to be constructed on the basis of structural function, which means the failure criteria are not necessarily structural but functional and would be subject to the number, size, and depth of corroded areas.

Based on data collected from inspections and maintenance conducted in China on the passenger aircraft Y-7, this paper discusses several corrosion-induced failure criteria and proposes a number of corresponding corrosion probabilistic models. A few examples are also demonstrated.

II. Corrosion Investigation and Data Collection

The Y-7 is a twin-engine turboprop 55-seat airliner developed in China based on the Russian Antonov An-24. Its maiden flight was on 25 December 1970, and it has now been developed in a family series, such as cargo Y7H, Y7H-500, Y7-200A, Y7-200B, MA60, etc. There were more than 150 Y-7 aircraft in operation, and it used to be the largest fleet in the Chinese aviation market.

In the early 1990s, widespread and serious corrosions were found in the overhauls (C and D checks), during which the aircraft had actually flown about 4084 cycles and 4174 flight hours, over a calendar period of 60 months. A special investigation was therefore conducted among the fleet, and thousands of corroded spots were found to be extensively located on the wings, rudders, fuselage, etc. (Che [5]). The material of the corroded panel of Y 7 aircraft is LY12CZ aluminum alloy. After cleaning up all corroded surface spots of the panel with chemical and physical methods that included tearing down some assembly, the surface areas (width by length) and depths of the corroded spots were measured. There were a total of about 5500 spots recorded in a database (Fan [6]). The schematic description is shown in Fig. 1.

III. Model 1: Nonstress Uniform Corrosion

Nonstress uniform corrosion is typified by the corrosion of metal and refers to the relatively uniform reduction of thickness over the surface of a corroding material. It is relatively easy to measure, predict, and design against this type of corrosion damage. When the residual thickness (or size) of the structural element becomes less than the minimum allowable thickness, failure is deemed to have occurred. The life of components can be estimated based on relatively simple immersion test results.

Investigations have found that the actual residual thickness C after corrosion at time t is a random variable and follows a normal distribution (Pidaparti et al. [7]). Accordingly, based on the function of the component in the structure, the allowed corroded thickness threshold C^* of the panel is also a random variable and complies with normal distribution. The corrosion failure criteria can be defined as the actual residual thickness C after corrosion becoming equal to the allowed thickness-loss threshold C^*. The equation for the safety margin M of the targeted structure can then be expressed as

$$M = C - C^* \leq 0$$

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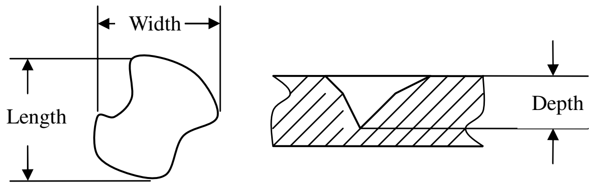


Fig. 1 Schematic description of the area and depth of corroded surface.

Therefore, the reliability of the structure induced by uniform corrosion is

$$R(C) = 1 - P(C \leq C^*) = 1 - \int_{-\infty}^{\infty}\left[\int_0^{c*} g(c^*).\mathrm{d}c^*\right] f(c).\mathrm{d}c \quad (1)$$

Here, $f(c)$ and $g(c^*)$ are the probability density functions of the actual thickness C and the allowed corroded thickness threshold C^* of the structure, respectively.

Assume that U_C, U_{C^*}, σ_C, and σ_{C^*} are the means and variations of C and C^*. Then the reliability index [8] of the structure induced by uniform corrosion will be

$$\beta = \frac{U_C - U_{C^*}}{\sqrt{\sigma_C^2 + \sigma_{C^*}^2}} \quad (2)$$

Accordingly, the reliability of the structure induced by uniform corrosion will be

$$R(c) = 1 - \Phi(-\beta) \quad (3)$$

Example: Sampling 10 liquid containers/reservoirs (aircraft parts) as an example, assume that the anodized coatings and painted protection on the surface are completely damaged, and the primary failure criterion of the container is the container wall reduced to a critical thickness by the uniform corrosion. It is assumed that the uniform corrosion rate is linearly proportional to time (in hours). The thicknesses of the walls before use were initially measured, and which were gauged again at 500 flight hours. The detailed data are shown in Table 1.

In practice, the required minimum thickness of the walls is $X_{\min} = 1.424$ mm, and the reliability of the containers at 2000 h can be calculated as follows.

The mean and variance of the initial wall thickness and corrosion volume are calculated in Table 2.

Because of the assumption that uniform corrosion is linearly proportional to time, the mean and variance of corrosion volume at 2000 h usage time will be

$$\mu_{c_{2000}} = \mu_{c_{500}} \times \frac{2000}{500} = 0.752 \text{ mm}$$

$$\delta_{c_{2000}} = \delta_{c_{500}} \times \frac{2000}{500} = 0.2308 \text{ mm}$$

Then the mean and variance of wall thicknesses at 2000 h will be

$$\mu_{x_{2000}} = \mu_x - \mu_{c_{2000}} = 1.534$$

$$\delta_{x_{2000}} = \sqrt{\delta_x^2 + \delta_{C_{2000}}^2} = 0.2369$$

Then the reliability index

$$\beta = \frac{\mu_{x_{2000}} - x_{\min}}{\delta_{x_{2000}}} = 0.4643$$

And the reliability of the container at 2000 h $R(2000) = 1 - \Phi(-\beta) = 0.677$.

IV. Model 2: Failure of High Smooth Surface Finish

Corrosion not only harms the strength of structure but also degrades the surface finish of the product. This may become critical when effective performance of the primary design function depends on a highly smooth surface. Examples of parts for which this will be a major factor include linings of journal bearings, mirrors, surfaces of aircraft wings, turbine blade surfaces, and so on. In these cases, once the surface roughness exceeds an allowable level, they may be considered to have failed to perform function adequately through, respectively, increase in rolling resistance and associated power loss, reduction in optical function, increase in aerodynamic drag, and reduction of the design stall resistance. Once these failures have occurred, repair or replacement maintenance must be immediately applied.

Pitting is an often-seen failure mode of corrosion in aviation aluminum alloys. A large number of investigations indicate that the probability of occurrence of active pitting spots follows the Poisson distribution (Ren et al. [8]):

$$P(n, x) = \frac{x^n e^{-x}}{n!} \quad (4)$$

where k is the number of active pitting spots, $P(n, x)$ is the probability of n active pitting spots that occur on specific area of the sample skin, and x is the average (or expected) number of occurrences on the same area. The Poisson cumulative probability function is

$$F(n,\ x) = \sum_{j=0}^{n} \frac{\boldsymbol{x}^j}{j!} \boldsymbol{e}^{-x} \quad (5)$$

where $F(n, x)$ gives the probability of occurrence of up to n active pitting spots on the same specific area of the sample skin, and x is the average (or expected) number of occurrences on the same area.

Example: During the Y-7 aircraft C check inspections, an average of 107 active pitting spots were found on the wing panels (at the time, the total flight hour was about 4000 h/5 years; see Fig. 2).

Based on the model proposed above, the average occurrence of active pitting spots, x, on wing panels will be $x = 107$, and the probability of occurrence of exactly n pitting spots for this specific case will be

$$P(n, 107) = p(n) = \frac{107^n}{n!} \cdot e^{(-107)} \quad (6)$$

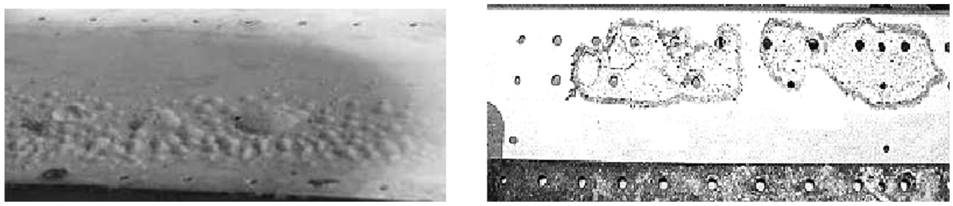
This model is applicable to cases that require a high-quality smooth surface.

Table 2 Mean and variance of initial wall thickness and corrosion volume

Mean	Variance
$\mu_x = 2.286$ mm	$\delta_x = 0.0563$ mm
$\mu_{c_{500}} = 0.188$ mm	$\delta_{c_{500}} = 0.0577$ mm

Table 1 Container uniform corrosion test data (mm)

Container No.	1	2	3	4	5	6	7	8	9	10
Initial thickness X	2.388	2.261	2.286	2.337	2.184	2.261	2.286	2.311	2.311	2.235
Thickness at 500 h $-X_{500}$	2.184	2.007	2.184	2.108	1.930	2.108	2.134	2.210	2.083	2.032
Corrosion volume $-C_{500}$	0.204	0.254	0.102	0.229	0.254	0.153	0.152	0.101	0.228	0.203



a) b)

Fig. 2 Example photographs of Y7 wing panel a) corrosion and b) after cleaning.

V. Model 3: Failure of Airtight Chamber/Cabin

The most common result of corrosion is deterioration of vessel strength and stiffness. However, for parts such as pipes, pumps, aircraft cabins, and tanks or reservoirs, the most serious corrosion-induced failure is the corrosion pit or crack, such as a corroded pore. Integrity of flight-critical systems can be severely undermined if pits or cracks cause leakage or unpressurized; in extreme cases, such failure could lead to fatal accidents. In this category, the operating life of the part will therefore depend on the depth of such defects (see Fig. 1).

Taking the sampling data from aircraft Y-7 inspection, the five deepest corroded spots are recorded as samples in Table 3.

A. Spot Depth Distribution

The correlation test with a computer program (linear correlation with the F distribution) found that the best-fit distribution of spot depths is Gumbel (Ren et al. [8]). The probability density function for the Gumbel distribution is as follows:

$$f(y) = \frac{1}{\sigma}\exp\left(-\frac{(y-\mu)}{\sigma}\right)\cdot\exp\left(-\exp\left(-\frac{(y-\mu)}{\sigma}\right)\right) \quad (8)$$

where μ and σ are, respectively, the location and scale parameters, and the variable y represents the depth of the corrosive spot.

The probability function for the Gumbel distribution is

$$P(y) = \int_0^y f(y)\,\mathrm{d}y = \exp\left(-\exp\left(-\frac{(y-\mu)}{\sigma}\right)\right) \quad (9)$$

The defining parameters of the Gumbel distribution were found as 1) location parameter $\mu = 1.1703$, 2) scale parameter $\sigma = 0.7055$, and 3) correlation coefficient $|r| = 0.961$.

B. Airtight Chamber/Cabin Reliability Model

The variable y represents the depth of the corrosive spot, and we may denote the maximum allowed depth (threshold) of corrosive spots as y_m. Of course, in some cases, y_m is the thickness of the skin panel; in this case, a corrosive spot of this depth would penetrate through the material thickness and be referred to as a *pore*. We can interpret failure to have occurred when $y \geq y_m$.

The reliability computational model of no-pore in the wing panel follows as

$$R(y_m) = P(y \leq y_m) = \exp\left(-\exp\left(-\frac{(y_m-\mu)}{\sigma}\right)\right) = \exp\left(-\exp\left(-\frac{(y_m-1.1703)}{0.7055}\right)\right) \quad (10)$$

Table 3 Top-five deepest corroded spots

Spots	Max depth, y/mm
1	1.39
2	2.15
3	2.28
4	2.35
5	2.50

For example, suppose the thickness of the wing panel and skin of Y-7 aircraft is 4 mm thick and this is equal to the maximum allowable depth of a corrosive spot. Then the probability of there being no corrosive pore in a typical Y-7 wing panel is

$$R(4.0) = P(y \leq 4.0) = \exp\left(-\exp\left(-\frac{(4.0-1.1703)}{0.7055}\right)\right) = 0.982 \quad (11)$$

Figure 3 shows the reliability with the wing panel thickness.

VI. Model 4: Failure of Surface Area

For some products, only very limited surface-area corrosion can be tolerated, either for aesthetics or for functional requirements. Components such as the aircraft wings and fuselage require a smooth surface to allow for proper performance of their aerodynamic function. When such components have an insufficiently smooth surface, drag will increase and the margin against aerodynamic stall may be reduced. From a maintenance perspective, corrosion spots that are shallow or small in area can be ignored. Therefore, for a component such as a wing panel, the corroded area would be the key parameter in the failure criteria. Accordingly, a reliability model for this case can be constructed on the basis of corrosion area. Following similar reasoning to that used in model 3 above, failure can be said to have occurred when $S \leq S_m$, where S and S_m, respectively, are actual corrosion surface size and the maximum permitted corrosion surface size.

Table 4 shows the five largest corrosion surface sizes of wing panels, obtained from Y-7 aircraft maintenance data.

It has been found that the corrosion spots have surface areas that comply with the Weibull distribution [8]. The Weibull probability density function is

$$f(x;k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}\exp\left(-\left(\frac{x}{\lambda}\right)^k\right) \quad (12)$$

for $x \geq 0$ and $f(x;k,\lambda) = 0$ for $x < 0$, where $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution.The Y-7 maintenance data gave a good fit to a Weibull distribution, with $k = 0.818$, and $\lambda = 5616$.

The Weibull probability density function specific to the corrosion data was therefore

$$f(S) = 1.4564 \times 10^{-4}\left(\frac{S}{5616}\right)^{0.182}\exp\left(-\left(\frac{S}{5616}\right)^{0.818}\right) \quad (13)$$

Figure 4 shows the corrosion-spot area Weibull density distribution.

Table 4 Top-five largest corrosion surface sizes

Location i	Area S_i, mm^2
1	3925
2	4239
3	4710
4	5652
5	7850

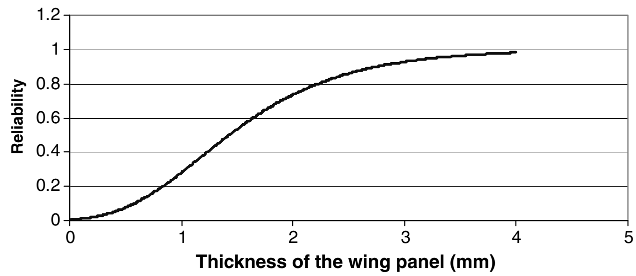


Fig. 3 Wing structural reliabilities with the thickness of the wing panel.

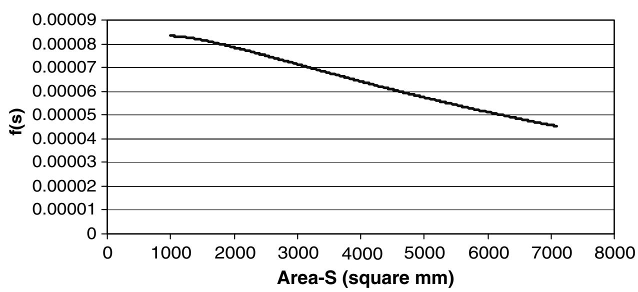


Fig. 4 Corrosion-spot area Weibull density distribution.

The area-based reliability criterion will be

$$R(S_m) = P(S \leq S_m) = \int_0^{S_m} f(S_m)\,\mathrm{d}S_m$$
$$= \int_0^{S} 1.4564 \times 10^{-4} \left(\frac{S_m}{5616}\right)^{0.182} \exp\left(-\left(\frac{S_m}{5616}\right)^{0.818}\right) \cdot \mathrm{d}S_m \quad (14)$$

VII. Corroded-Spot Characteristics

All reliability models established in this paper are based on characteristics of corrosion pits. The structural component function requirement is the primary parameter of the failure criteria. Some parts, such as cabin, oil pipe, and fuel container, will be considered to have failed if corrosion pits develop through the thickness of the material. Other parts, such as engine blades (mirror surface), may only allow limited areas of corrosion before they are considered to have failed.

Corrosion spots appear in a range of geometries: some are shallow with large surface area, and some are deep but with small surface area (e.g., pits). To simplify failure analysis, a characteristic geometrically based parameter was introduced: the corrosion-spot index (CSI). The CSI is a simple relationship between the depth and the area of a corrosion spot. Let the CSI be given the symbol η, and let $\eta = y/s$.

Calculation was made based on the data used in the above example, and it is found that η is not a constant value, but a variable. The mean and the variation of the CSI η using the Y-7 wing panel maintenance data set were found to be

$$\mu_\eta = 7.864 \times 10^{-4} \qquad \sigma_\eta = 7.44 \times 10^{-4}$$

It is also found that the CSI η follows an exponential distribution of the form $f(x;\lambda) = \lambda e^{-\lambda x}$ for $x \geq 0$, where λ is called the rate parameter for the distribution. For the above data set, λ is found to have a value of 0.1272. The probability density function of η is then best modeled as

$$f(\eta) = 0.1272 e^{-0.1272\eta} \quad (15)$$

VIII. Conclusions

Causes and mechanisms of aircraft skin corrosion have been studied for many decades. A large amount of this research has focused on the physical and chemical interactions of the materials involved and the environment within which they operate. This paper proposes a number of probabilistic reliability models, based on a large set of corrosion-related maintenance data for one aircraft type, in an attempt to provide theoretical solutions to practical corrosion-induced reliability problems.

The research in this paper demonstrates that corrosion-induced failure criteria depend on function requirements of the containment. Some functionalities are affected by the depth of corrosion spots, whereas others are more affected by the total corroded surface area or the number of surface corrosion spots. It has been found that the Gumbel distribution is the optimal distribution for corrosion-spot depth, and the Weibull distribution is the most suitable for the distribution of corrosion-spot surface size. A corrosion-spot index has been proposed as a characteristic parameter. This was defined as the ratio between spot depth and area, and it was found that its value was variable and followed an exponential distribution.

The models proposed in this paper can be used in a range of situations for aircraft reliability prediction and risk assessment induced by corrosion. However, due to the differences of vessel materials and service environments, the parameters of the reliability models proposed likely need be changed to suit the specific practice.

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