Reliability evaluation method of LED lighting matrix considering degradation and catastrophic failure

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Abstract. Aiming at the current situation of degradation and catastrophic failure of weaponry, a reliability modelling method considering performance degradation (lumen degradation) and catastrophic failure (nonluminous) is proposed with LED lighting matrix as the research object. First, for the degradation of lumen, the failure mechanism analysis is carried out, the thermal resistance model of lighting matrix and radiator is established, and the overall model of the degradation of the LED lighting matrix is realized. For the catastrophic failure, based on the uncertainty of the logic relationship of catastrophic failure of lighting matrix and the polymorphism of individual fault events, the method of combining fault tree and Bayesian network is used to realize the analysis of failure evolution and reliability modelling. Finally, the validity of the proposed method is verified with a case study.

1. Introduction
Nowadays, light-emitting diodes (LEDs) have been widely used in many engineering fields such as national defense and military, aerospace, urban construction, communication network, automobile industry, etc. In the field of missile weapon, it is often used in ground and vehicle equipment. For high-power LEDs, due to the characteristics of high power, high heating and long working time, their life and reliability have been paid great attention.

As an important part of the LED system, LED lighting matrix is composed of chip, phosphor, silica gel, solid crystal solder and substrate. In response to various failure modes and mechanisms, researchers have carried out a lot of basic research work \cite{2-4}, which provides strong support for the reliability prediction and life assessment. In the reliability research of LED lighting matrix, Narendran et al. \cite{5} have initially discussed the standardized measurement process of LED technology and the standardized definition method of effective life. Based on this, fault diagnosis technology can be used to improve the ability of life and reliability prediction. For example, Yanagisawa et al. \cite{6} conducted reliability tests under accelerated current conditions, and estimated the average half-life of white LEDs. Elsayed, Nelson, and Turner \cite{7-9} analyzed and summarized the general process and model of accelerated testing. In addition, some scholars have realized the analysis of reliability and life of lighting matrix from the perspective of accelerated test based on physics of failure (PoF) \cite{6,10-11}.

Due to the long service life of LED, it is difficult to predict the reliability directly by the actual life test method, and the data obtained by the accelerated test method is also limited, so the predicted results will have a large deviation from the actual. At present, the studies from the perspective of physics of failure are mostly empirical models and general models with a single module or a single
failure mode as the research object, which are difficult to realize the quantitative evaluation of the reliability of the whole lighting matrix. Therefore, based on the component structure and functional characteristics of the lighting matrix, this paper determines two kinds of failure judgment: nonluminous and lumen degradation reaching the threshold value, and then the reliability model of the lighting matrix is established from the perspective of considering the catastrophic fault transmission of multi-level structure and the degradation of the overall performance of the module level. Finally, the two parts are integrated to realize the quantitative evaluation of the reliability of the lighting matrix.

2. Reliability modelling technology framework of LED lighting matrix

According to the connotation of reliability, reliable lighting matrix should ensure that it can light up and the luminous flux meets the specified requirements. Therefore, reliability analysis of lighting matrix should be carried out from two aspects of performance degradation and catastrophic failure. Performance degradation is the degradation of lumen, which is aimed at the whole module. For catastrophic failure, it can be analysed step by step according to the typical multi-level structure of LED lighting matrix, as shown in Fig.1.

![Figure 1. LED lighting matrix reliability modeling framework](image)

First of all, the failure mechanism of each key failure mode leading to the degradation of LED lighting matrix performance is analyzed. According to its main external performance characteristics, lumen degradation [12], a comprehensive representation model is established. According to the function structure of LED lighting matrix, a fault tree with nonluminous as the top event is established, and a Bayesian network model of LED lighting matrix is established based on the fault tree. Then, the conditional probability of fault evolution between hierarchies is analyzed, and the probability of catastrophic failure (nonluminous) of lighting matrix is predicted. Finally, the reliability model of LED lighting matrix is established based on the prediction results of two kinds of failure modes.

$$R = R_D \times R_C$$  \hspace{1cm} (1)

where $R_D$ is the degradation failure reliability model and $R_C$ is the catastrophic failure reliability model.

3. Degradation mechanism analysis and modelling of LED lighting matrix

The degradation of LED lighting matrix performance is mainly manifested as the decrease of luminous flux with the increase of service time, that is, lumen degradation.

Based on the analysis of the failure mechanism of lumen degradation, it can be seen that the main cause of lumen degradation is the increase of temperature, such as the increase of thermal resistance caused by poor chip bonding and impurity diffusion, the rise of junction temperature, and the
generation of temperature related failure mechanisms such as electromigration; the increase of thermal resistance and junction temperature caused by the yellowing and layer of packaging materials and solid solder. Therefore, analysis of lumen degradation can be transformed into the thermal analysis of illumination matrix. It includes thermal resistance produced by chip, packaging material, solder connection and substrate. Generally, in order to study the thermal model of the whole system, the cooling system should be considered.

According to the composition of the lighting matrix, the thermal resistance model is established, as shown in Fig.2. According to IES LM-80-80[13], taking 70% lumen maintenance as the criterion to judge whether it works reliably. Therefore, the overall model of LED lighting matrix lumen degradation is established according to the reliability standard that the lumen degradation rate is less than 70%.

![Figure 2. Thermal resistance model of lighting matrix](image)

**TR** represents thermal resistance, where **TRc**, **TRp**, **TRs**, and **TRsub** represent the thermal resistance of chip, packaging material, solder connection and substrate respectively.

According to the lumen degradation model and the thermal resistance model, the reliability-related parameter model of the lighting matrix is established, as shown below.

\[
L_m = \frac{L_{output}}{L_0} = e^{-a(T_j)} = 0.7
\]

(2)

\[
T_j = f\{A, R_\phi, I_c, T_0\}
\]

(3)

\[
TR_{sub} = \sum_{i=4}(TR_c + TR_p + TR_s) + TR_{sub} - E
\]

(4)

\[
E = \frac{Q_1}{Q_2}
\]

(5)

\[
TTF = \frac{-\ln 0.7}{-a(T_j)}
\]

(6)

where \(T_j\) is the junction temperature, \(A\) is the non-radiation coefficient that causes internal heat, \(T_0\) is the ambient temperature, and \(I_c\) is the forward current. \(Q_1\) and \(Q_2\) are heat transfer and natural transfer respectively.

The degradation of lumen is mainly affected by the temperature of junction, which is determined by the non-radiation coefficient that causes internal heat, thermal resistance, ambient temperature and forward current. Different lighting matrix and using environment will lead to different parameter results.

Therefore, it is necessary to test the specific research object, and analyze the parameters of the lumen degradation model according to the sample data of the lumen test results to get the specific model of the lumen degradation model. Then, through the analysis of a series of TTF (Time to failure) values, the failure probability distribution of the lumen degradation is finally obtained, and then the reliability model is obtained.

The quantification methods of model parameters are as follows: firstly, the regression of multiple groups of lumen degradation data obtained from the experiment is carried out according to
\[ L_m = be^{-at} \] to obtain the values of parameters \( a \) and \( b \) in the mode. Then, the TTF value of LED lighting matrix can be predicted according to the lumen degradation model according to the failure criterion when the lumen maintenance is less than 70%. Finally, the TTF value is fitted with the time and failure probability, and the mathematical model according to the data distribution type is selected to fit the failure probability of the lighting matrix.

4. Catastrophic failure evolution modelling of LED lighting matrix based on Bayesian network

In order to represent the uncertainty of the random failure logic relationship and the polymorphism of individual fault events, Bayesian network method is used to analyse the fault evolution of LED lighting matrix. In order to establish the Bayesian network model of the catastrophic failure, the traditional fault tree and Bayesian network are combined to establish the failure-Bayesian network of LED lighting matrix, and then the process of catastrophic failure evolution is modeled and analyzed.

In the fault tree, the basic events are usually regarded as binary state objects. In the Bayesian network, the polymorphism of events can be considered to expand into multi-dimensional variables according to the specific situation of events, and the uncertainty can be expressed by probability distribution. The transformation of the basic logic relationship in the fault tree in the Bayesian network is shown in Fig.3. When event \( C \) occurs, it is represented by \( C = 1 \), otherwise, it is represented by \( C = 0 \), which corresponds to the same value in the Bayesian network. In the fault tree, the occurrence probability of the basic event corresponds to the prior probability of the parent node in the Bayesian network.

\[
\begin{align*}
P(C=A=0, B=0) &= 0 \\
P(C=A=1, B=0) &= 1 \\
P(C=A=0, B=1) &= 1 \\
P(C=A=1, B=1) &= 1
\end{align*}
\]

**Figure 3.** Bayesian network expression of basic logic relationship in fault tree

According to the failure analysis of LED lighting matrix, the catastrophic failures are mainly substrate failure (fracture, metallization), packaging device failure (chip failure, solid crystal failure, gold wire burning, packaging material failure), among which chip failure includes chip burning, electrode peeling, chip damage, etc. According to the relationship of these failure modes, the fault tree of catastrophic failure of lighting matrix is established, as shown in Fig.4. The meanings of the symbols in the figure are shown in Table 1

According to the transformation relationship between fault tree and Bayesian network, the fault tree in Fig.4 is transformed into failure-Bayesian network model, as shown in Fig.5.
The events in the failure-Bayesian network are sorted and classified as shown in Table 1.

### Table 1. Basic events of lighting matrix and its prior probability distribution

| Events (High-level) | Events (Lower level) | Basic events | Prior probability distribution $\pi(x_i)$ |
|---------------------|----------------------|--------------|----------------------------------------|
| Chip failure $B_3$  |                      | Chip burning $x_5$ | $(\alpha_5, \beta_5)$                  |
|                     |                      | Electrode peeling $x_6$ |                                            |
|                     |                      | Slight $x_{61}$ $(\alpha_{61}, \beta_{61})$ | $(\alpha_6, \beta_6)$                    |
|                     |                      | Serious $x_{62}$ $(\alpha_{62}, \beta_{62})$ |                                            |
| Packaging device failure $B_1$ |                      | Chip damage $x_7$ | $(\alpha_7, \beta_7)$                  |
|                     |                      | Slight $x_{71}$ $(\alpha_{71}, \beta_{71})$ | $(\alpha_7, \beta_7)$                    |
|                     |                      | Serious $x_{72}$ $(\alpha_{72}, \beta_{72})$ |                                            |
| Solid crystal failure $B_4$ | Delamination $x_3$ | $(\alpha_3, \beta_3)$ |                                            |
|                     | Lift-off $x_9$ | $(\alpha_9, \beta_9)$ |                                            |
|                     |                      | Packaging material failure $x_1$ | $(\alpha_1, \beta_1)$                   |
|                     |                      | Gold wire burning $x_2$ | $(\alpha_2, \beta_2)$                   |
|                     |                      | Fracture $x_3$ | $(\alpha_3, \beta_3)$                  |
|                     |                      | Metallization $x_4$ | $(\alpha_4, \beta_4)$                  |

In Table 1, the prior distribution $\pi(x_i)$ is expressed in the form of $(\alpha_i, \beta_i)$. $\alpha_i$ is the probability of the occurrence of the basic event, and $\beta_i$ represents the probability that the basic event does not occur; there are three states of electrode peeling and chip damage, i.e. intact, slight damage and serious damage. For slight damage, "with damage" does not affect the work, it can still be regarded as able to complete the specified requirements.
According to the Bayesian network diagram and Table 1, according to the logical relationship between the basic events \( x_5, x_6, \) and \( x_7, \) the conditional probability table of the chip failure \( B_3 \) is obtained as shown in Table 2.

**Table 2** Conditional probability table of events \( x_5, x_6, x_7 \) and \( B_3 \\

| Basic events | \( B_3 \) |
|--------------|------------|
| \( x_5 \) \( x_6 \) \( x_7 \) \( x_{61} \) \( x_{62} \) | \( B_3 \) |
| 0 0 0 0 0 0 | 0 |
| 0 1 0 0 0 0 | 0 |
| 0 0 0 1 0 0 | 0 |
| 0 1 0 1 0 0 | 0 |
| 1 0 0 0 0 1 | 1 |
| 1 1 0 0 0 1 | 1 |
| 1 1 0 1 0 1 | 1 |
| 1 1 0 0 1 1 | 1 |
| 1 0 1 0 0 1 | 1 |
| 1 0 1 0 1 1 | 1 |
| 0 1 0 0 0 1 | 0 |
| 0 1 0 0 1 1 | 1 |
| 0 0 0 1 0 0 | 1 |
| 0 0 1 1 0 1 | 0 |

According to the Table 2, the conditional probability distribution of events \( B_3 \) is:

\[
p(B_3 = 1 | x_5 = 0, x_{61} = 0, x_{62} = 0, x_{71} = 0, x_{72} = 0) = 0 \quad p(B_3 = 1 | x_5 = 0, x_{61} = 1, x_{62} = 0, x_{71} = 0, x_{72} = 0) = 0
\]

\[
p(B_3 = 1 | x_5 = 0, x_{61} = 0, x_{62} = 0, x_{71} = 1, x_{72} = 0) = 0 \quad p(B_3 = 1 | x_5 = 0, x_{61} = 1, x_{62} = 0, x_{71} = 1, x_{72} = 0) = 0
\]

\[
p(B_3 = 1 | x_5 = 1, x_{61} = 0, x_{62} = 0, x_{71} = 0, x_{72} = 0) = 1 \quad p(B_3 = 1 | x_5 = 1, x_{61} = 1, x_{62} = 0, x_{71} = 0, x_{72} = 0) = 1
\]

\[
p(B_3 = 1 | x_5 = 1, x_{61} = 1, x_{62} = 0, x_{71} = 1, x_{72} = 0) = 1 \quad p(B_3 = 1 | x_5 = 1, x_{61} = 1, x_{62} = 1, x_{71} = 0, x_{72} = 1) = 1
\]

\[
p(B_3 = 1 | x_5 = 1, x_{61} = 0, x_{62} = 1, x_{71} = 0, x_{72} = 0) = 1 \quad p(B_3 = 1 | x_5 = 1, x_{61} = 0, x_{62} = 1, x_{71} = 1, x_{72} = 0) = 1
\]

\[
p(B_3 = 1 | x_5 = 1, x_{61} = 1, x_{62} = 1, x_{71} = 0, x_{72} = 1) = 1 \quad p(B_3 = 1 | x_5 = 1, x_{61} = 1, x_{62} = 1, x_{71} = 1, x_{72} = 0) = 1
\]

\[
p(B_3 = 1 | x_5 = 0, x_{61} = 0, x_{62} = 1, x_{71} = 0, x_{72} = 0) = 1 \quad p(B_3 = 1 | x_5 = 0, x_{61} = 0, x_{62} = 1, x_{71} = 1, x_{72} = 0) = 1
\]

Then the probability distribution of \( B_3 \) can be obtained.

\[
\pi(B_3) = \sum_{x_5, x_6, x_7} [p(B_3 | x_5, x_6, x_7) \pi(x_5) \pi(x_6) \pi(x_7)]
\]

\[
= \begin{pmatrix}
\alpha_1 \alpha_{61} \alpha_{62} \alpha_{71} \alpha_{72} + \alpha_3 \beta_6 \alpha_{61} \alpha_{62} \alpha_{71} \alpha_{72} + \alpha_5 \alpha_{61} \alpha_{62} \beta_1 \alpha_{71} \alpha_{72} + \alpha_5 \beta_1 \alpha_{61} \alpha_{62} \beta_1 \alpha_{71} \\
1 - (\alpha_3 \alpha_{61} \alpha_{62} \alpha_{71} \alpha_{72} + \alpha_3 \beta_6 \alpha_{61} \alpha_{62} \alpha_{71} \alpha_{72} + \alpha_5 \alpha_{61} \alpha_{62} \beta_1 \alpha_{71} \alpha_{72} + \alpha_5 \beta_1 \alpha_{61} \alpha_{62} \beta_1 \alpha_{71} \alpha_{72})
\end{pmatrix}
\]

Similarly, the probability distribution of events \( B_4, B_1, \) and \( B_2 \) can be obtained separately
Finally, the probability distribution of the top event $T$ is calculated according to the probability distribution of the obtained events $B_1$ and $B_2$.

$$
\pi(T) = \sum_{B_1, B_2} \left[ p(T/B_1, B_2) \pi(B_1) \pi(B_2) \right]
$$

$$
= \left( \alpha_4 \alpha_4 + \alpha_4 \beta_4 + \alpha_4 \beta_4 \right) = \left( \alpha_4 \alpha_4, 1 - \alpha_4 \alpha_4 \right)
$$

5. Case study

The case study of the LED lighting matrix is also divided into two parts: performance degradation and catastrophic failure.

5.1. Performance degradation

For the analysis of the lumen degradation of the lighting matrix, firstly, based on the lumen test data of Philips lm-80 test report, the parameters of the established lumen degradation model are analysed, and the test data set is selected as an example. The test conditions of the data set are: node temperature 68 °C, ambient temperature 55 °C, forward current 350 mA. The data set contains 80 groups of sample test data, and gives the lumen test results of each sample between 0h and 6000h. 80 groups of sample data are regressed according to the form $L = be^{-at}$, and the model parameters $a$ and $b$ are obtained.

By averaging the fitting results of 80 groups of sample data, the lumen degradation model of the LED is obtained. Based on the model, the TTF value of the LED is predicted according to the reliability standard that the lumen degradation rate is less than 70%.

Fig. 6 shows the lumen test data points of the selected samples and the lumen degradation curve from the final regression.
The curve is the average result of 80 groups of sample data after fitting. The final model parameter values are:

\[
\alpha = 4.96 \times 10^{-6}, \quad b = 1.0064
\]

According to the lumen degradation curve, the time when the lumen degradation rate reaches 70% is 73200h, according to Eq.(1), 80 TTF data of 80 groups of sample test data can be obtained.

The failure rate curve of the whole test group is obtained by statistics of TTF data. After inspection, the life distribution of the sample does not reject the Weibull distribution. The failure probability distribution function form of the Weibull distribution is shown in the following formula, and the parameter value obtained by fitting is shown in Table 3.

\[
F(t) = 1 - \exp \left[ -\left( \frac{t}{\lambda} \right)^\delta \right], \quad R(t) = \exp \left[ -\left( \frac{t}{\lambda} \right)^\delta \right]
\]

**Table 3. Values of fitting parameters of lumen degradation life distribution**

| Parameter | Fitting result | Upper limit (95% confidence interval) | Lower limit (95% confidence interval) |
|-----------|----------------|--------------------------------------|--------------------------------------|
| $\lambda$ | 70794          | 78746                                | 63644                                |
| $\delta$  | 2.1909         | 2.5410                               | 1.889                                |

Therefore, the reliability model of lumen degradation can be determined. The failure probability distribution curve and reliability curve of lumen degradation are shown in Fig.7.
5.2. Catastrophic failure

Similar to the above methods, analyse the catastrophic failure mechanism, obtain TTF sample data of each failure mode under the same test conditions, and then carry out statistical analysis on its occurrence probability, and fit the probability distribution of each failure mode to obtain the specific failure probability distribution model of each failure mode, as shown in Table 4.

Table 4. Fitting distribution of failure probability of each failure mode

| Failure mode | Failure probability distribution (fitting) | Distribution type | Parameter |
|--------------|------------------------------------------|-------------------|-----------|
| $x_1$        | $1-\exp\left(-2.5 \times 10^{-12} t^{2.25}\right)$ | Weibull           | $\eta=205587.48$, $m=2.25$ |
| $x_2$        | $1-\exp\left(-3.4 \times 10^{-13} t^{2.4}\right)$ | Weibull           | $\eta=127485.57$, $m=2.4$ |
| $x_3$        | $1-\exp\left(-7.4 \times 10^{-7} t\right)$ | Exponential       | $\lambda=-7.4 \times 10^{-7}$ |
| $x_4$        | $1-\exp\left(-3.3 \times 10^{-14} t^{2.55}\right)$ | Weibull           | $\eta=279437.57$, $m=2.55$ |
| $x_5$        | $1-\exp\left(-2.5 \times 10^{-18} t^{3.32}\right)$ | Weibull           | $\eta=287603.79$, $m=3.32$ |
| $x_6$        | $\beta_6 = 1-\exp\left(-6.5 \times 10^{-20} t^{3.5}\right)$ | Weibull           | $\eta=433983.05$, $m=3.5$ |
| $x_{61}$     | $\beta_{61} = 1-\exp\left(-3.5 \times 10^{-19} t^{3.3}\right)$ | Weibull           | $\eta=433983.05$, $m=3.5$ |
| $x_{62}$     | $\beta_{62} = 1-\beta_{61}$ | Weibull           | $\eta=433983.05$, $m=3.5$ |
| $x_7$        | $\beta_7 = 1-\exp\left(-9.5 \times 10^{-23} t^4\right)$ | Weibull           | $\eta=452985.29$, $m=4$ |
| $x_{71}$     | $\beta_{71} = 1-\exp\left(-5 \times 10^{-25} t^{4.3}\right)$ | Weibull           | $\eta=452985.29$, $m=4$ |
| $x_{72}$     | $\beta_{72} = \beta_7 - \beta_{71}$ | Weibull           | $\eta=452985.29$, $m=4$ |
| $x_8$        | $1-\exp\left(-1.55 \times 10^{-19} t^{3.5}\right)$ | Weibull           | $\eta=338562.58$, $m=3.5$ |
| $x_9$        | $1-\exp\left(-1.1 \times 10^{-15} t^{1.75}\right)$ | Weibull           | $\eta=397421.09$, $m=2.75$ |

The probability of catastrophic failure is obtained based on Eq.(7), as shown in Fig. 8.

In conclusion, the reliability of LED lighting matrix can be obtained based on Eq.(1), as shown in Fig. 9.
6. Conclusions

In this paper, the mechanism of performance degradation and catastrophic failure is studied, and the reliability evaluation model is established. The lumen degradation trend of lighting matrix and the hierarchy transfer mechanism of catastrophic failure mode are analyzed quantitatively. A typical LED is selected to analyze the performance degradation and catastrophic failure. Finally, the reliability under various failures is obtained and the reliability curve is given to verify the effectiveness of the model.

However, based on the absolute influence of temperature in the lumen degradation effect, this paper established a lumen degradation model by analyzing the junction temperature and heat dissipation mechanism of related devices, but it does not exclude other noise factors that affect lumen degradation, such as such as voltage, environmental humidity and other uncertain factors. Therefore, in subsequent studies, a deeper exploration of the mechanism of lumen degradation is needed.

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