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# Reliability modeling for dependent competing failure processes of damage self-healing systems

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ABSTRACT

Systems experiencing multiple dependent competing failure processes (MDCFP) have attracted much attention in the recent years. Similar to the biological systems, which have the ability to heal after being wounded; damage self-healing exists in many systems and products due to the intrinsic resistance to abrupt damage. The earlier research assumed the dependence between shock process and random shock but didn't take the damage self-healing process into consideration, which occurs in many engineering systems. In the paper, a new reliability model subject to MDCFP by considering the damage self-healing phenomenon is developed. For each random shock, we propose healing time and healing level concept to describe the self-healing process. The model is practical and realistic for many complex systems such as electrical devices or microelectronic polymeric components. Due to complexity of the model, there is no analytical form of the reliability function. However, we estimate the system reliability efficiently by using simulation method. Furthermore, it is shown that the proposed model is general model that can be transformed into many classical degradation and shock models in different parameter settings.



## 1. Introduction

Competing failure modes involving performance degradation and random shocks can be found in many complex systems. Those failure modes are often caused by internal and external sources, such as corrosion, fatigue, wear, and external shocks. Those failure processes are competing to cause the system failure and are also dependent which means one process may influence the others. For instance, if a random shock occurs in the system, it will cause a sudden decrease in the system performance, equivalently, a jump increase in the degradation path. The amount of increase is also depending on the shock load. Modeling the system subject to multiple dependent competing failure processes can provide a better understanding of the mechanism of failure and offers an indirect method to predict the system reliability. However, recent literatures (Kessler, 2007; Davis et al., 2009; Li and Nettles, 2010; Zhong and Post, 2015) developed the damage self-healing materials, which are widely used in polymer matrix composites products. It is natural to understand self-healing process as the system itself has resilience to failure and can recover part of the performance from shock. In this article, we develop a new reliability model subject to the multiple dependent competing failure processes by considering the damage self-healing phenomenon. This model is practical and realistic for many complex systems such as electrical devices or microelectronic polymeric components.

Degradation modeling and analysis has attracted a lot of interest from researchers (Bian, Gebraeel, & Kharoufeh, 2015; Liu, Xie, Xu, & Kuo, 2016; Lu & Meeker, 1993; Ye, Revie, & Walls, 2014). For random shocks, reliability models may be classified into four categories: (i) extreme shock model: failure occurs when the magnitude of any shock exceeds a specified threshold; (ii) cumulative shock model: failure occurs when the cumulative damage from shocks exceeds a critical value; (iii) run shock model: failure occurs when there is a run of $k$ shocks exceeding a critical magnitude; and (iv) $\delta$ -shock model: failure occurs when the time lag between two successive shocks is shorter than a threshold $\delta$. Reliability analysis for systems that experience random shocks has been extensively studied in the literature (Li and Zhao, 2007; Eryilmaz, 2017). For systems experiencing degradation and external shocks, different maintenance strategies are also studied in the literature (Ruiz-Castro, 2014; Tang, Yu, Chen, & Makis, 2015; Zhu, Fouladirad, &

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Bérenguer, 2015; Liu et al., 2016). When considering complex systems experience multiple failure processes, the dependence of failure processes produced many challenge issues in reliability modeling. To model the competing degradation and shocks, some researchers consider those two processes are independent (Huang & Askin, 2003; Li and Pham, 2005). It may be more realistic to introduce the dependency between the degradation and shock processes. However, consider the dependency will generate some challenging issues for analyzing the system reliability.

Research has also been carried out on reliability analysis incorporating dependent competing failure processes. Peng, Feng, and Coit (2010) developed reliability models and preventive maintenance policies for systems subject to multiple dependent competing failure process (MDCFP). Huynh, Barros, Bérenguer, and Castro (2011) proposed a condition-based periodic replacement policy for this kind of system. Wang, Huang, Li, and Xiao (2011) studied degradation and shock models in which three failure modes are considered. Jiang et al. (2012) proposed a reliability and maintenance model for systems subject to MDCFP with a changing dependent failure threshold. Liu et al. (2013) conducted an optimum condition-based maintenance (CBM) policy for the continuously monitored systems considering multiple dependent competing failure processes. Yang et al. (2013) analyzed the partially perfect repair of the repairable MDCFP system. Jiang et al. (2015) categorized the shocks into different shock zones in which small magnitude of shock load will not influence the degradation path. Rafiee, Feng, and Coit (2014) considered the reliability model with a changing degradation rate after each shock. Song, Coit, and Feng (2014a), Song, Coit, Feng, and Peng (2014b) studied the multi-component system subject to MDCFP and also discussed the multi-component system with distinct shock sets. Song, Coit, and Feng (2016) proposed the reliability analysis of multiple-component series systems subject to competing failures with dependent shock effects. However, in all of the previous research involving degradation and shocks, there is no research taking the damage self-healing process into consideration. It motivates us to investigate the MDCFP with the damage self-healing process.

In this article, we develop the reliability models for a system experiencing MDCFP by consider the damage self-healing. We investigate two dependent failure processes: soft failure due to continuous degradation as well as sudden increases in degradation caused by random shocks and the hard failure due to the random shocks directly. In our new model, a damage self-healing process after each random shock is considered. The damage self-healing phenomenon exists in many polymer matrix composites products and materials. For example, Thostenson and Chou (2006) demonstrated that conducting carbon nanotube networks formed in an epoxy polymer matrix have the autonomic self-healing property and can be utilized as highly sensitive sensors. Toohey, Sottos, Lewis, Moore, and White (2007) reported a self-healing system capable of autonomously repairing repeated damage events. Wong et al. (2011) developed a strategy to create self-healing, slippery liquid infused porous surface with exceptional liquid, ice-repellency, pressure stability and enhanced optical transparency. Xu et al. (2012) investigated a mechanistic-based, two-stage model to study the stress and temperature-dependent crack healing of the self-healing glass materials. Chen, Ren, Yang, Jiang, and Li (2013) studied self-healing characteristics of damaged rock salt under different healing conditions.

Due to the popularity of self-healing phenomenon and no previous research taking the damage self-healing process into consideration, we aim to develop a reliability model based on MDCFP to describe the damage self-healing systems. In our proposed model, the damage self-healing process will last for a time interval and the length of this interval depends on the shock load and this is practical and realistic according to the literature. To describe this self-healing process, we introduce two new concepts that include healing time and healing level. Due to complexity of the model, there is no analytical form of the reliability function. However, we can use simulation method to estimate the reliability of the system efficiently. Furthermore, we conclude that our model is a general model that can be converted into many classical degradation and shock models in different parameter settings.

The remainder of this paper is arranged as follows. Section 2 describes the dependence between failure processes and the damage self-healing phenomenon. Section 3 discusses the modeling of systems subject to MDCFP with damage self-healing and provides comparisons of our new model with the classical degradation and shock models. Section 4 includes the simulation method to estimate the system reliability and provides an illustrative example. The sensitivity analyses of various variables are also discussed. Section 5 summarizes this paper and proposes some future potential work.

| Notations | |
|---|---|
| $D$ | Threshold for failure caused by random shock |
| $H$ | Threshold for failure caused by degradation |
| $N(t)$ | Number of shock loads arrived by time $t$ |
| $\lambda$ | Arrival rate of random shocks |
| $\delta_j$ | Size of $j$-th shock load |
| $t_j$ | Arrival time of $j$-th shock |
| $X(t)$ | Wear volume due to continuous degradation at time $t$ |
| $X_S(t)$ | Total wear volume at $t$ due to both continual wear and random shock |
| $\alpha_j$ | Instantaneous damage size caused by $j$-th random shock |
| $\tau_j$ | Healing time of $j$-th random shock |
| $\gamma$ | The ratio coefficient between $\alpha_j$ and $\delta_j$ |
| $k$ | The ratio coefficient between $\tau_j$ and $\delta_j$ |
| $s$ | Healing level of random shocks |
| $\beta$ | Slope of the pure degradation path |
| $\mu_\beta$ | Mean value of $\beta$ |
| $\sigma_\beta$ | Standard deviation of $\beta$ |

## 2. System model for dependent competing failure processes

Consider that a system may fail due to the two competing failure modes; one is the soft failure occurs when the overall degradation $X_S(t)$ exceeds the threshold (Fig. 1(a)), the other is the hard failure occurs when the shock load $\delta(t)$ exceeds the threshold (Fig. 1(b)). Those two failure processes are competing which means the system fail if one of the two modes occurs. These two processes may also be dependent, as the shock process influences both of the two failure processes.

When a shock occurs, it will cause a sudden increase in the overall degradation. As there are a variety of self-healing phenomenon in many materials and devices, it is natural to consider the damage self-healing process in the system. After a shock caused a sudden jump in the overall degradation path (see Fig. 1 (a)), there will be a damage healing process lasting for a specified time. Through this process, the system will regain some amount of performance and will be illustrated in the degradation path. The self-healing process was not considered in the previous literatures; however, adding this process will produce challenging issues in the computation.

In this paper, we will adopt these commonly and reasonable assumptions: