# Time-dependent resilience as a generalization of time-dependent reliability

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ABSTRACT: Civil structures and infrastructures are often subjected by design to the impacts of natural and human-caused hazardous events, and accordingly may suffer from damages, functionality loss, and failure. In order to quantitatively measure the associated likelihood and consequences for quantifying risks, an appropriate measure of structural reliability and resilience is essentially required. This paper presents an explicit measure for the time-dependent resilience of repairable structures as a natural extension of time-dependent structural reliability concepts, taking into account the effects of structural performance deterioration and nonstationary external loads. The proposed resilience measure is a function of the duration of considered service period, and is in a closed form. Remarkably, the time-dependent resilience can be treated as a generalized form of the time-dependent reliability. A numerical example is presented to demonstrate the accuracy and applicability of the proposed resilience measure.

## 1. Introduction

Planners and designers of civil structures and infrastructures consider the impacts of natural and human-caused hazardous events, and accordingly recognize that they may suffer as a result from damages, functionality loss and failure. For example, in the US, Hurricane Laura was the costliest disaster in 2020, causing $19.7 billion in damage after making landfall in southwestern Louisiana in August (NOAA, 2021). Reliability and resilience are two significant indicators of structural performance under the impact of hazardous events. The former is defined as the probability of structural survival (i.e., the load effect does not exceed the structural resistance). On the other hand, the resilience of a structure exposed to hazardous events is indicative of the structural ability over the entire adverse cycle to prepare for and adapt to adverse events, and to withstand and recover rapidly from disruptions (National Research Council, 2012; McAllister, 2013; Ayyub, 2014; Reda Taha et al., 2021). These notional definitions clearly indicate that the reliability is nested within resilience as a broad ability. Enhancing structural reliability and resilience could result in economic savings and risk reduction through improving the structural performance and expeditious recovery.

The aggressive environmental or operational conditions may impair structural performance significantly (Dieulle et al., 2003; Ma et al., 2013; Ayyub et al., 2015; Wang et al., 2017), resulting in deterioration of structural capacity of resisting hazardous events below a level as assumed for new ones. Furthermore, many types of natural hazards have nonstationary characteristics on the temporal scale due to the potential impact of climate change. For example, it was projected in Knutson et al. (2010) that greenhouse warming will result in an increase of 2-11% in the globally averaged intensity of tropical cyclones by the end of the 21st century. Another example is that, in California, US, the continued climate change will amplify the number of days with extreme fire weather by the end of this century (Goss et al., 2020). The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2021) warns that human-induced climate change has already been affecting many weather and climate extremes around the world, and the global surface temperature will continue to increase until at least 2050 under all emissions scenarios considered. As a result, the time-variation of both structural performance and the external hazardous events should be well captured in structural reliability and resilience analysis. Correspondingly, these two quantities would be dependent on the duration of the service period of interest. They are known as *time-dependent reliability* and *time-dependent resilience*, respectively, under this context.

The work by Mori and Ellingwood (1993) was among the first attempts to estimate the time-dependent reliability of aging structures, taking into account the uncertainty associated with the occurrence process and magnitude of load events. However, it used a homogeneous Poisson process for the load process, and thus did not consider the nonstationarity in loads on the temporal scale. An improved version was developed by Li et al. (2015) so that the nonstationarity in loads, in terms of occurrence frequency and/or magnitude, can be considered in an explicit form. An overview of assessment methods for structural time-dependent reliability can be found in Wang et al. (2021). While the main scope of this paper is on the development of a new measure for structural time-dependent resilience, it will be demonstrated later that the reliability can be treated as a specific case of resilience.

Despite of the descriptive definition of structural resilience, it is often challenging to develop a quantitative resilience measure, since some requirements drawn from the measure theory should be logically satisfied. In this paper, the focus is on the resilience of a single repairable structure, which refers to such a structure that it suffers from functionality/performance loss due to the impact of hazardous events, and can be restored (via repair measures) to the pre-hazard state or some other states to account for adaptability. Note that the definition of resilience for a structure can be naturally extended to that for a system (consisting of multiple structures), e.g., infrastructure systems, networks, and a community.

Bruneau et al. (2003) defined the resilience loss as $\int_{t_0}^{t_1}[1-Q(t)]dt$, in which $Q(t)$ is the performance/quality of a structure (taking a value between 0 and 1), $t_0$ is the occurrence time of hazard (disruption), and $t_1$ is the time of full recovery. Attoh-Okine et al. (2009) further proposed a normalized resilience model, denoted by $R_e$, as follows,

$$R_e = \frac{\int_{t_0}^{t_1} Q(t)dt}{t_1 - t_0} \tag{1}$$

which yields a dimensionless measure for structural resilience. However, the definition in Eq. (1) does not account for the random occurrence of hazardous events and the probability of performance loss conditional on the occurrence of load event. Ayyub (2015) developed a resilience measure for a planning horizon of $[0,t]$, assuming that (i) the target structure has a maintained and sustained performance level (i.e., without considering the impact of performance deterioration); (ii) the external load process is modeled by a homogeneous Poisson process with a constant occurrence rate of $\lambda$. As such, both the structural performance deterioration and the nonstationarity in external loads were not taken into account in Ayyub (2015).

This paper presents a measure for time-dependent resilience of repairable structures in the presence of nonstationary loads and deterioration. The computation formulas for structural time-dependent reliability and time-dependent resilience are compared. It is observed that the former is a specific case of the latter. As such, a linkage is established between the two key indicators of a structure: reliability and resilience. Motivated by the widely-used reliability-based design and cost optimization in the engineering practice, this paper also discusses the resilience-based design and cost optimization of structures. A numerical example is presented to demonstrate the applicability of the proposed resilience measure.

## 2. Resilience measure

### *2.1. Proposed formulation of time-dependent resilience*

In this section, a measure for structural time-dependent resilience is developed. It is representative of structural resilience within a reference period of $[0,t_l]$ in the presence of performance deterioration and repeatedly occurring load events. The following assumptions will be made: (i) The occurrence of load events is modeled by a non-homogeneous Poisson process with a time-variant occurrence rate of $\lambda(t)$ (that is, on average $\lambda(t)$ event(s) will occur within unit time at time $t$). (ii) The post-hazard structure will be fully restored/repaired to the desired state before the occurrence of next event. (iii) The recovery processes of the structure associated with different load events are statistically independent.

Fig. 1 presents a schematic representation of the resilience problem considering a reference period of $[0,t_l]$. Let $N$ be the number of load events within $[0,t_l]$, which is a Poisson random variable. The probability mass function (PMF) of $N$ is as follows for $n=0,1,2,...,$

$$\Pr(N=n) = \frac{\left(\int_0^{t_l}\lambda(t)dt\right)^n \exp\left(-\int_0^{t_l}\lambda(t)dt\right)}{n!} \quad (2)$$

A Bernoulli random variable $B_i$ is introduced for the $i$th load event (occurring at time $t_i, i=1,2,\ldots N$), which takes a value of 1 if the structure fails and 0 otherwise. With this, the PMF of $B_i$ is

$$\Pr(B_i=1)=p(t_i), \quad \Pr(B_i=0)=1-p(t_i) \quad (3)$$

in which $p(t_i)$ is the probability of failure conditional on the occurrence of one load event at time $t_i$. Similar to Eq. (2), the PMF of *effective* load events (i.e., events causing structural failure), $N_e$, is as in Eq. (2), but with $\lambda(t)$ being replaced by $\lambda_e(t)=\lambda(t)p(t)$.

Let $R_{e,i}$ be the resilience measure associated with the $i$th effective load event. Similar to the resilience model in Ayyub (2015), the resilience measure for a reference period of $[0,t_l]$ is defined as follows,

$$R_s(0,t_l)=\mu\left(\prod_{i=1}^{N_e} R_{e,i}\right) \quad (4)$$

It can be shown that the definition in Eq. (4) yields a monotone measure for structural resilience. Based on Eq. (4), using the law of total expectation, it follows that

$$\begin{aligned} R_s(0,t_l) &= \mu\{\mu(R_{e,1}\cdot R_{e,2}\cdot\ldots\cdot R_{e,N_e}|N_e)\} \\ &= \mu\left\{\left(\frac{\int_0^{t_l}\lambda_e(t)\mu(R_e,t)dt}{\int_0^{t_l}\lambda_e(t)dt}\right)^{N_e}\right\} \end{aligned} \quad (5)$$

in which $\mu(R_e,t)$ denotes the mean value of resilience measure associated with a single failure-causing event occurring at time $t$. Substituting the PMF of $N_e$ into Eq. (5) yields the following based on the law of total probability,

$$R_s(0,t_l)=\exp\left\{-\int_0^{t_l}\lambda(t)p(t)\left[1-\mu(R_e,t)\right]dt\right\} \quad (6)$$

Eq. (6) is the proposed measure for structural time-dependent resilience, where the nonstationarity in the load occurrence process, as well as the time-variation of $\mu(R_e)$ (due to, e.g, aging effect, time-variation of resourcefulness) can be taken into account.

If further taking into account the uncertainty associated with the deterioration process of structural performance, Eq. (6) can be extended by using the law of total probability. For example, in the presence of a linear deterioration process with a rate of $\Theta_a$, it follows that

$$R_s(0,t_l)= \int_0^{\infty}\exp\left\{-\int_0^{t_l}\lambda(t)p(t)\left[1-\mu(R_e,t)\right]dt\right\}f_{\Theta_a}(x)dx \quad (7)$$

in which $f_{\Theta_a}(x)$ is the PDF of $\Theta_a$ (note that in Eq. (7), $\mu(R_e,t)$ is conditional on $\Theta_a=x$). It would be more convenient, in some occasions, to use the nonresilience, denoted by $\overline{R_s}(0,t_l)$. It is the complement of structural resilience, i.e., $\overline{R_s}(0,t_l)=1-R_s(0,t_l)$.

Finally, some discussions on the proposed resilience measure (see Eqs. (6) and (7)) are presented in the following.

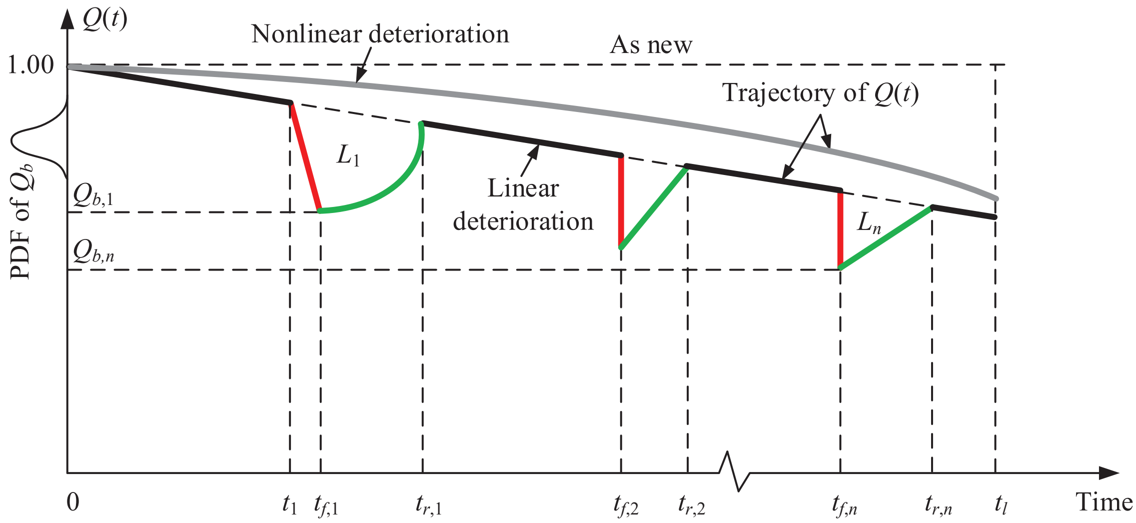


*Figure 1: Concept of time-dependent resilience over a reference period of* $[0,t_l]$.

- The item $\mu(R_e,t)$ in Eqs. (6) and (7) is representative of the time-variation of resilience measure associated with a single hazardous event, while $R_s(0,t_l)$ reflects the overall resilience of the structure within a reference period of $[0,t_l]$, referred to as time-dependent resilience.
- In Eq. (6), if there exists a function $\mu_{\max}(R_e,t)$ so that $\mu(R_e,t) \leq \mu_{\max}(R_e,t)$ holds for $\forall t \in [0,t_l]$, then an upper bound for the resilience measure would be achieved by substituting $\mu_{\max}(R_e,t)$, i.e.,

$$R_s(0,t_l) \leq \exp\left\{-\int_0^{t_l} \lambda(t)p(t)\left[1-\mu_{\max}(R_e,t)\right]dt\right\} \tag{8}$$

  The item $\mu_{\max}(R_e,t)$ is the upper bound of structural resilience subjected to one disruptive event occurring at time $t$, which corresponds to the case of the greatest residual functionality and the most expeditious recovery profile. In particular, if $\mu_{\max}(R_e,t) \equiv 1$, then $R_s(0,t_l)$ in Eq. (6) equals 1, which is consistent with the definition of resilience measure. On the other hand, the case of $\mu(R_e,t) \equiv 0$ would yield a lower bound for $R_s(0,t_l)$ in Eq. (6), and this point will be discussed in the next section.
- In Eq. (4), the resilience measure for a reference period of $[0,t_l]$ has been formulated by considering the multiplication of the resilience measures associated with individual load events. An alternative approach is to consider the summation of each $R_{e,i}$ to derive the time-dependent resilience (Yang and Frangopol, 2019; Wang and Zhang, 2020). Compared with the alternative approach, the features of $R_s(0,t_l)$ in Eq. (4) are, (i) it is more sensitive to each $R_{e,i}$ having a small value (an example is that, when $R_{e,1} \approx 0$, $R_s(0,t_l)$ is approximately 0, even if the remaining $R_{e,i}$'s are all close to 1); (ii) it establishes a unified framework for assessing structural reliability and resilience, as will be demonstrated in the next section.
- Note that the resilience measure in Eq. (6) has been formulated by considering the random variables from the physical space. Generally, resilience can also be conceptualized to encompass four dimensions: technical, organizational, societal and economic (Bruneau et al., 2003). Under this context, the limitation of the proposed resilience measure is that it does not involve the variables beyond the physical space (e.g., traffic detouring when repairing a damaged bridge). It thus needs further research to extend Eq. (6) to address all the four dimensions of structural resilience.

### 2.2. *Comparison between time-dependent resilience and reliability*

In this section, the resilience measure in Eq. (6) will be compared with structural time-dependent reliability. To this end, the reliability method proposed by Li et al. (2015) is first reviewed. Fig. 2 illustrates the time-dependent reliability problem, where the structural resistance deterioration and the randomness associated with the load process are considered. At time $t$, conditional on the occurrence of one load event, the structure fails if the load effect exceeds the degraded resistance. The load process is modeled by a non-homogeneous Poisson model with an occurrence rate of $\lambda(t)$, and the CDF of load effect is $F_S(s,t)$ at time $t$. Within a reference period of $[0,t_l]$, if a sequence of load effects $S_1, S_2, \ldots S_N$ occur at times $t_1, t_2, \ldots t_N$, the time-dependent reliability, $R_l(0,t_l)$, is defined as

$$R_l(0,t_l) = \Pr(R(t_1) > S_1 \cap \ldots \cap R(t_N) > S_N) \quad (9)$$

in which $R(t_i)$ is the resistance at $t_i$ for $i = 1,2,\ldots N$. The hazard function $h(t)$, which is defined as the probability of structural failure during $(t, t+dt]$ ($dt \to 0$) conditional on structural survival within $[0,t]$, can be linked to structural reliability according to

$$R_l(0,t_l) = \exp\left(-\int_0^{t_l} h(t)dt\right) \quad (10)$$

For the reliability problem in Fig. 2, the hazard function is computed as follows,

$$h(t) = \lambda(t)[1 - F_S[R(t),t]] \quad (11)$$

with which Eq. (10) becomes (Li et al., 2015),

$$R_l(0,t_l) = \exp\left\{-\int_0^{t_l} \lambda(t)[1 - F_S[R(t),t]]dt\right\} \quad (12)$$

Recall the item $p(t)$ in Eq. (6), which equals $1 - F_S[R(t),t]$. As such, Eq. (11) is rewritten as $h(t) = \lambda(t)p(t)$, and correspondingly, Eq. (13) becomes,

$$R_l(0,t_l) = \exp\left\{-\int_0^{t_l} \lambda(t)p(t)dt\right\} \quad (13)$$

Comparing the time-dependent reliability in Eq. (13), and the time-dependent resilience in Eq. (6), it is observed that,

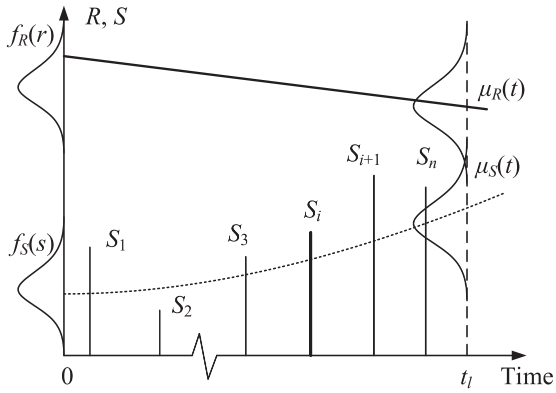


*Figure 2: Illustration of structural time-dependent reliability (Li et al., 2015, reproduced with permission from Elsevier).*

- The time-dependent reliability is a specific case of time-dependent resilience. In fact, if assigning $\mu(R_e,t) \equiv 0$, Eq. (6) reduces to Eq. (13).
- The reliability method does not account for the recovery process of a post-hazard structure; it is a lower bound for structural resilience, since $\mu(R_e,t) \leq 1$ holds for $\forall t \in [0,t_l]$.
- The resilience of a repairable structure is greater than that of a non-repairable one (i.e., the post-hazard functionality/performance loss cannot be restored) in the presence of the same configuration. For a non-repairable structure, the two quantities of reliability and resilience are consistent with each other in the context of a physical space.

## 3. Numerical example

In this section, a numerical example is presented to demonstrate the applicability of the proposed resilience measure. Consider a structure that is subjected to linear performance deterioration and a Poisson load process. The deterioration rate, $\Theta_a$, follows a lognormal distribution with a mean value of 0.003 and a coefficient of variation (COV) of 0.2. Taking into account the nonstationarity in load occurrence, assume that the occurrence rate has an initial value of 0.2/year, and doubles over a reference period of 50 year. With this, $\lambda(t) = \lambda(0) \cdot (1 + 0.02t)$ (in years), in which $\lambda(0) = 0.2$. The post-hazard performance loss increases with time according to

$$\mu(\widetilde{Q},t) = \mu(\widetilde{Q},0)(1+kt^{\alpha}) \tag{14}$$

in which $\mu(\widetilde{Q},t)$ is the mean value of fractional performance loss at time $t$, $k$ and $\alpha$ are two parameters reflecting the changing rate and shape, respectively. Assume that $\mu(\widetilde{Q},0) = 0.1$. It is further assumed that the structural resistance also deteriorates linearly with a rate of $\Theta_a$. The load effect, conditional on occurrence, follows an Extreme Type I distribution with a mean value of $0.3r_n(1+0.01t)$ (in years) and a COV of $c_S = 0.4$, in which $r_n$ is the nominal resistance. The initial resistance is deterministically $1.05r_n$. With the aforementioned configuration, Eq. (7) will be used to compute the structural time-dependent resilience (or nonresilience). Note that the structural configuration used herein is for illustration purpose. When the resilience of a real-world structure is to be estimated, the relevant parameters in Eq. (7) should be updated by considering the properties of the structure and the time-variant characteristics of the service environment (e.g., using a finite element modeling to estimate the structural resistance).

Fig. 3 presents the time-variant mean value of $R_e$ as a function of the load occurrence time (up to 50 years) in the presence of different changing patterns of $\mu(\widetilde{Q},t)$, assuming that $\Theta_a$ is deterministically 0.003, and the recovery rate is uniformly distributed within $[3,6]$. The values of $\alpha$ being equal to 0.5, 1 and 2 correspond to square-root, linear and parabolic increasing modes, respectively. It is observed that $\mu(R_e,t)$ decreases in time with an increasing performance loss. When $\mu(\widetilde{Q},50)$ is fixed, a greater value of $\alpha$ results in a larger $\mu(R_e,t)$, since the increase of $\mu(\widetilde{Q},t)$ mainly occurs at the latter stage of a reference period of 50 years. Furthermore, a greater value of $\mu(\widetilde{Q},50)$ leads to a smaller $\mu(R_e,t)$ due to the severer performance loss conditional on load occurrence.

In Fig. 4, the time-dependent nonresilience for reference periods up to 50 years is plotted. It is assumed that $\mu(\widetilde{Q},t)$ increases linearly to 0.2, 0.3 or 0.4 at the end of 50 years (i.e., $\alpha = 1$ in Eq. (14)). For comparison purpose, the nonresilience associated with time-invariant $\mu(\widetilde{Q},t)$ (i.e., $\mu(\widetilde{Q},t) \equiv 0.1$)

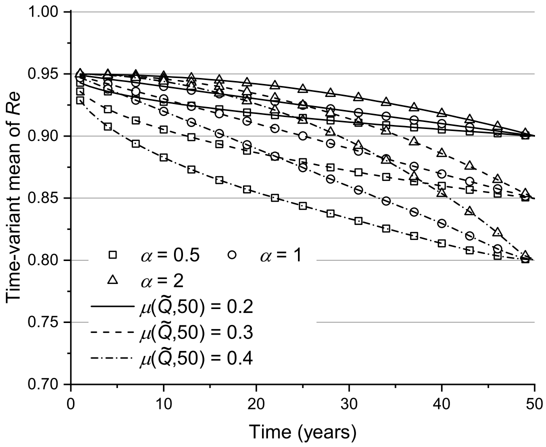


*Figure 3: Time-variant mean value of resilience measure $\mu(R_e,t)$ for different changing patterns of average fractional performance loss $\mu(\widetilde{Q},t)$.*

is also plotted in Fig. 4, which is representative of the case with no performance deterioration. The nonresilience increases with time, which is characteristic of the accumulated risk of performance loss. A greater value of $\mu(\widetilde{Q},50)$ results in a larger nonresilience, which is consistent with the observation from Fig. 3. For reference periods beyond 20 years, the nonresilience increases approximately exponentially in time. Furthermore, the structural time-dependent failure probability (i.e., $1-R_l(0,t_l)$) is also presented in Fig. 4. The failure probability is an upper bound for structural nonresilience, since the item $1-\mu(R_e,t)$ in Eq. (7) is within the range of $[0,1]$.

The dependence of time-dependent nonresilience on the changing shape of $\mu(\widetilde{Q},t)$ (i.e., $\alpha$ in Eq. (14)) is presented in Fig. 5, where $\mu(\widetilde{Q},50) = 0.3$. The nonresilience associated with $\alpha = 0.5$ is the largest, followed by those with $\alpha = 1$ and $\alpha = 2$, respectively. This is because, with fixed $\mu(\widetilde{Q},0)$ and $\mu(\widetilde{Q},50)$, a greater value of $\alpha$ leads to a smaller $\mu(\widetilde{Q},t)$ for $t \in (0,50)$ and thus larger resilience. This observation is consistent with that from Fig. 3.

In Fig. 6, the impact of load occurrence rate on structural time-dependent nonresilience is examined, where $\lambda(0)$ varies from 0.1 to 0.5. The mean of fractional performance loss ($\mu(\widetilde{Q},t)$) increases linearly from 0.1 at the initial time to 0.3 by the end of 50 years. For a relatively short reference period,

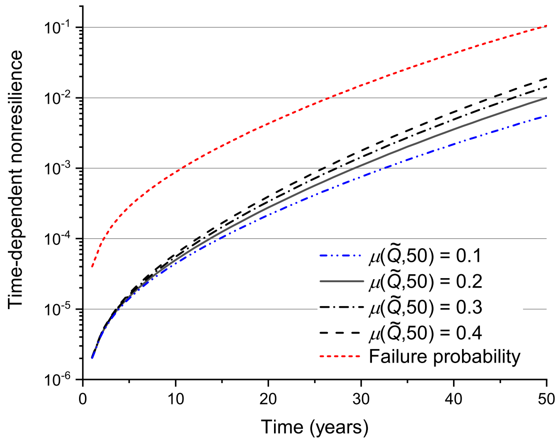


*Figure 4: Time-dependent nonresilience considering different mean values of fractional performance loss at the end of 50 years $\mu(\widetilde{Q},50)$.*

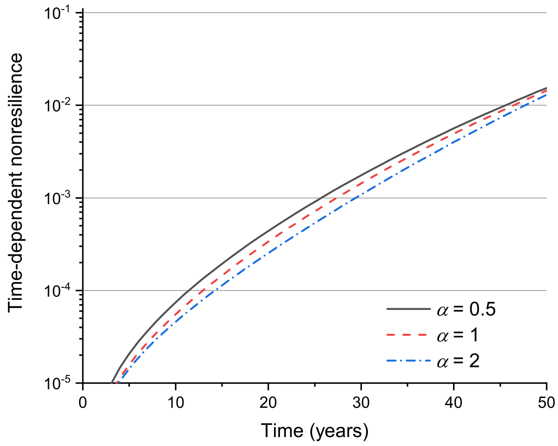


*Figure 5: Dependence of time-dependent nonresilience on the shape factor $\alpha$.*

where $\overline{R_s}(0,t_l)$ is close to 0, the nonresilience increases approximately linearly with $\lambda(0)$. This is because, in Eq. (6), as $R_s(0,t_l) \approx 1$, it follows that

$$\begin{aligned}\overline{R_s}(0,t_l) &= 1 - \exp\left\{-\int_0^{t_l} \lambda(t)p(t)\left[1-\mu(R_e,t)\right]dt\right\} \\ &\approx \lambda(0)\int_0^{t_l}(1+0.02t)\cdot p(t)\left[1-\mu(R_e,t)\right]dt \\ &\propto \lambda(0)\end{aligned} \tag{15}$$

However, this linearity is weakened by a longer reference period (e.g., the case of $t_l = 50$ years), with the nonresilience becoming greater.

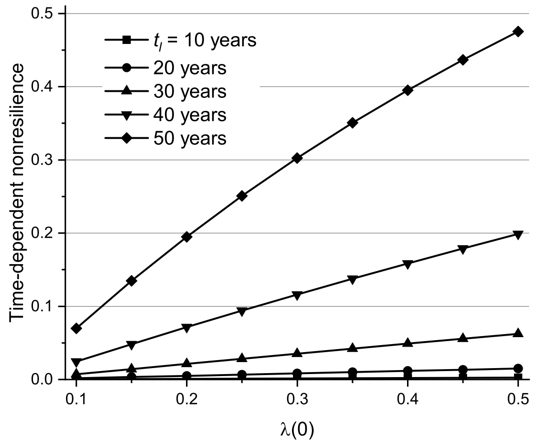


*Figure 6: Time-dependent nonresilience considering different values of the initial occurrence rate $\lambda(0)$.*

## 4. Concluding remarks

In this paper, a new resilience measure has been developed for repairable structures subjected to nonstationary loads and deterioration. The non-homogeneous Poisson process is used to describe the nonstationary load process, and the time-variation of performance loss, conditional on load occurrence, is taken into account. The resilience-based structural design and cost optimization are also studied. The following conclusions can be drawn from this paper.

- The probabilistic behaviour of resilience measure associated with a single hazardous event takes a simple, integral-free form for some specific distribution types of random variables involved, which is beneficial for use in practical engineering.
- The time-dependent resilience can be treated as a generalized form of structural time-dependent reliability, and the difference between the two quantities is whether the recovery process of the post-hazard structure is considered. Furthermore, the reliability is a lower bound of structural resilience numerically.
- A greater mean value of performance loss, or a severer performance deterioration process, leads to a larger structural nonresilience, and correspondingly a shorter predicted service life.

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