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30 June 2026

A probabilistic framework for the resilience assessment of transport infrastructure systems via structural health monitoring and control based on a cost function approach

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Abstract

The essential role of transport infrastructure systems for economic development, territorial cohesion and social transformation is widely recognized. However, key structural components of this systems, such as bridges, are rapidly aging, while the loading conditions to which they are subjected are evolving to become increasingly severe, for instance, due to changes in vehicle loads, climate crisis, etc. These circumstances contribute to reduce the level of reliability and safety of these vital infrastructure systems. Therefore, assessing the current state and predicting the future condition of transportation infrastructure, and protecting it against external hazards, proves essential. This paper focuses on an in-depth study of the role of structural control

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and monitoring in improving the structural resilience of transportation infrastructure as a life-cycle indicator. Subsequently, a novel framework based on a cost function approach is introduced, recognizing that the benefits of enhanced resilience come with associated investments. This enables stakeholders to assess the balance between initial investments and long-term gains, facilitating informed decisions on control and monitoring to ensure structural resilience.
Keywords: Resilience, Life-cycle, Monitoring, Control, Cost function, Transport infrastructure, Bridge

1. Introduction

Transport infrastructure systems are recognized as essential for communities in terms of economic development, territorial cohesion, and social transformation. Considering that a large proportion of these systems, for example, in United States (Lehman, 2022), have been in service for decades and still form the backbone for the movement of people and goods, the issue of aging of this system raises concern. In many cases, some of their key structural components, such as bridges, are getting closer to their intended life while climate changes and society evolution are driving the loading conditions to exceed those initially envisaged at the design stage (Morgese et al. , 2020). In such scenario, they can be indeed subjected to increasing hazards, such as natural events or man-made phenomena, and larger levels of traffic loads than those used in the initial design, might contribute to reducing the reliability level (Argyroudis et al. , 2019, 2020) if countermeasures are not promptly taken (Mitoulis et al. , 2023). Therefore, the assessment of the current state and the prediction of the future condition of transportation infrastructure and its components, such as bridges, as well as their protection against external hazards, has become an essential management challenge that needs to be addressed.

Management of the life-cycle of products and components has received a great deal of attention starting from the first works that appeared at the half of the last century (SAIC , 2006), evolving into a probabilistic approach for applications to structures and infrastructures (Biondini and Frangopol , 2016). As highlighted in the field of structural engineering, a proper life-cycle assessment of a structure involves taking into account several time-variant aspects. They range from the ageing of the structure itself to the evolution of the loading and the effects of maintenance and repair interventions. Besides the cost of construction and maintenance of the structure, other aspects, often of greater importance, are also of interest. E.g., the social costs associated with the presence of an infrastructure and those related to its loss of functionality can be mentioned.

With respect to a variety of causes, e.g. corrosion brought on by aggressive environment and fatigue damage, steel and steel-concrete composite structures are vulnerable to time-dependent degradation and aging effects. The implications of these consequences are especially pertinent. In addition to other things, corrosion reduces the original thickness of steel connections and profiles, such as the web and flanges of steel I-girders, or the steel bars in reinforced concrete (RC) elements. The damage affects the element's and section's structural characteristics (e.g. strength and stiffness) owing to modifications o the effective resisting geometry brought on by corrosion penetration (Biondini and Frangopol , 2016, Domaneschi et al. , 2020a).

A state-of-the-art review on the non-empirical assessment methods for time-dependent reliability of deteriorating structure is presented by (Wang et al. , 2021). Both simulation-based and analytical methods are discussed there, considering also the quantitative community resilience analysis with a focus on the infrastructure systems and the built environment.

With reference to community resilience assessment, several approaches can be found in the literature, along with the critical factors that can improve resilience. These are discussed in a recent paper by Marasco et al. (Marasco et al. , 2021), where a platform for implementing the community model through a hybrid approach is also presented.

The issue of life-cycle of bridges with respect to degradation phenomena, such as corrosion and fatigue, has been also investigated in the literature. The cumulative seismic damage and corrosion effects on bridges' life-cycle is deepened by (Kumar et al. , 2009) highlighting how the cumulative seismic damage affects the structural reliability over time more than corrosion. The issue of corrosion deterioration effects on the seismic response of RC bridge piers has been also studied by (Bartolozzi et al. , 2022). The role played by bonding in the degradation of the seismic capacity has been highlighted. Lu et al. developed a stochastic fatigue truck load model for probabilistic modeling of fatigue stresses in welded steel girder bridges. A deterministic finite-element-based hot-spot analysis and probabilistic modeling approaches have been also included (Lu et al. , 2019).

Lu et al. also studied the lifetime deflection of long-span bridges subjected to simultaneous presence of multi-heavy-duty trucks. They also revealed that the degradation of road-roughness conditions leads to more level crossings and also results in a slight increase in the extrapolation of the deflection (Lu et al. , 2017b).

With specific respect to transport infrastructure management, Kim et al. (Kim et al. , 2013) proposed a framework for structural inspection and maintenance planning, highlighting the dependence between the appropriate maintenance and the damage degree. Aspects related to analysis and decision-making for assessing bridge life-cycle performance and cost have been deepened in (Frangopol et al. , 2017), considering also climate change and structural health monitoring. Life-cycle reliability, risk and resilience-based design of transportation infrastructures have been studied by (Akiyama et al. , 2020), highlighting the importance of studying both independent and interacting hazards to assess the bridge reliability (e.g. earthquake and tsunami, or landslide).

The relationship between structural health monitoring (SHM) and the life-cycle of bridges has been discussed in the literature, e.g. in the review work by (Biondini and Frangopol , 2016) or (Orcesi and Frangopol , 2011). Focusing on railway bridges, their reliability assessment and the role played by SHM has been studied in (Vagnoli et al. , 2018), comparing different types of structural health monitoring methods (e.g. model, non-model). Considering the contributions to the relationship between structural control (SC) and life-cycle of bridges, (Hahm et al. , 2013) proposed a method for evaluating the economic efficiency of a semi-active Magneto-Rheological damper system for cable-stayed bridges under earthquake loadings by introducing the concept of life-cycle cost. Zheng et al and Forcellini (Zheng et al. , 2023, Forcellini , 2023) discussed the contribution of isolation systems to enhance the structural resilience of bridge structures.

Despite the improvements in the knowledge provided by the existing literature, the impact of SHM and SC disciplines in the life-cycle of transport infrastructure systems would need a further in-depth study. To this end, this contribution presents a conceptual framework specifically to determine how SHM and SC can positively influence the resilience and, consequently, the life cycle of transportation infrastructure and its components, such as bridge structures. Finally, a novel cost function approach is introduced as a representative index for the assessment of the most cost-effective and efficient solution towards structural resilience improvements.

The remainder of this paper is organized as follows. Section 2 presents SHM and SC contributions to the life-cycle extension of structures. Section 3 formally defines the framework. Section 4 presents the cost function approach to the framework. Finally, Section 5 draws the concluding remarks of the paper.

2. Enhancing life-cycle

The concept of life cycle for structure and infrastructure systems in civil engineering refers to the systematic evaluation and management of a construction project from its initial planning and design phases, through construction, operation, maintenance, and ultimately to its end-of-life phase, considering the economic, environmental, and social aspects at each stage (Bribián et al. , 2009, ISO15686-5. , 2008).

2.1. Contributions from Structural Control

Structural Control refers to the application of techniques oriented toward managing in real time the structural behavior with the intent to minimize some response parameter under an external (man-made or natural) excitation. Modification of the structural response can be obtained by inserting appropriate devices whose properties ideally do not change in time (passive control). Alternatively, devices whose properties change in a controlled manner in time (semi-active devices), or devices that are able to apply a force directly on the structure (active control) can be used. Such techniques can have a significant impact on the reliability, the resilience and, ultimately, on the global life cycle of a structure since it is able, as it will be proved, to substantially extend its intended life.

As noted in (Biondini et al. , 2014) as time goes by, a structure is subjected to several changes that will impact the system performance, among them important factors are the aging and the deterioration of a system and damage caused by extreme events. Also renovations, revamping or improvements before a disruptive events may affect the system performance (Figure 1). It is worth underlining the critical role of preparedness actions and their positive contributions across the entire functionality curve from the moment it is implemented (Figure 1). Indeed, preparedness actions result in an increase in the system functionality function that extends even in the moment a shock intervenes inducing a local drop down in functionality. The drop down point due to the shock would still settle at a higher level of functionality than would have occurred without the implementation of preparedness actions.

A measure of structural performance that encompasses a broad set of aspects (economic losses, casualties, recovery time etc.), usually employed to judge a structure in case of a disruptive event, is Resilience. According to a well known definition by Manyena (Manyena , 2006), Resilience is the ‘intrinsic capacity of a system, community or society predisposed to a shock or stress to adapt and survive by changing its non-essential attributes and rebuilding itself’. As Resilience is related to the capability of a system to withstand the effects of extreme events and to recover efficiently the original performance and functionality (Bruneau et al. , 2003), the impact of Structural Control on the Life-Cycle of a structure adopting Resilience (R) as a Structural Performance Indicator will be analyzed.

According to MCEER researchers (Bruneau et al. , 2003, Bruneau and Reinhorn , 2006, 2007), resilience consists of four fundamental aspects, namely robustness, resourcefulness, redundancy, and rapidity. In detail:

- Robustness pertains to the ability of a structure or element to withstand a certain level of demand, such as damage, while maintaining its typical level of functionality. Alternatively, it can be understood as the concept of damage tolerance.

- Redundancy, exemplified by load-bearing components, involves the capacity to establish alternative pathways for load support in the event of primary component deterioration. This implies having replaceable original elements that can fulfill the load-bearing role.

- Resourcefulness refers to the capacity to identify problems, set priorities, and acquire necessary materials when conditions pose a threat to the stability of a structure or its components. It involves proactive measures to ensure the availability of resources for prompt response.

- Rapidity signifies the ability to prioritize interventions and execute them promptly to minimize losses, restore normal functioning, and prevent further disruptions. Acting swiftly is essential in mitigating the impact of disruptions and facilitating a swift recovery.

Adopting the exposition and the terminology reported in (Cimellaro et al. , 2010), Resilience is the capability to sustain a level of functionality or performance for a given structure over a predefined period of time T_{LC} (the control time, which is usually the life cycle or life span of the structure) to the time evolution of the functionality function ($Q(t)$) of a system. The functionality function $Q(t)$ is a dimensionless function of time that relates the structure's performance at time t to its value in the initial state of the structure life, right after completion. Resilience is simply defined as the normalized area underneath $Q(t)$.

Structural Control has been proven capable to reduce damage in case of extreme events, as it is able to both reduce the values of the loading effects as well as the variance (see e.g. Casciati et al. , 2012). The associated damage reduction allows to improve structural resilience and to extend the service life of a structure.

An idealized representation of the life of a structure undergoing a reduction of functionality function $Q(t)$ at the initial branch is depicted in Figure 2, including also the occurrence of a shock at time t_{r0}, such as an earthquake occurrence, and the subsequent recovery phase. Time t_{d0} denotes the time at which degradation, for whatever reason, starts. For all practical purposes, it can be assumed as the time at which the structure has been completed and

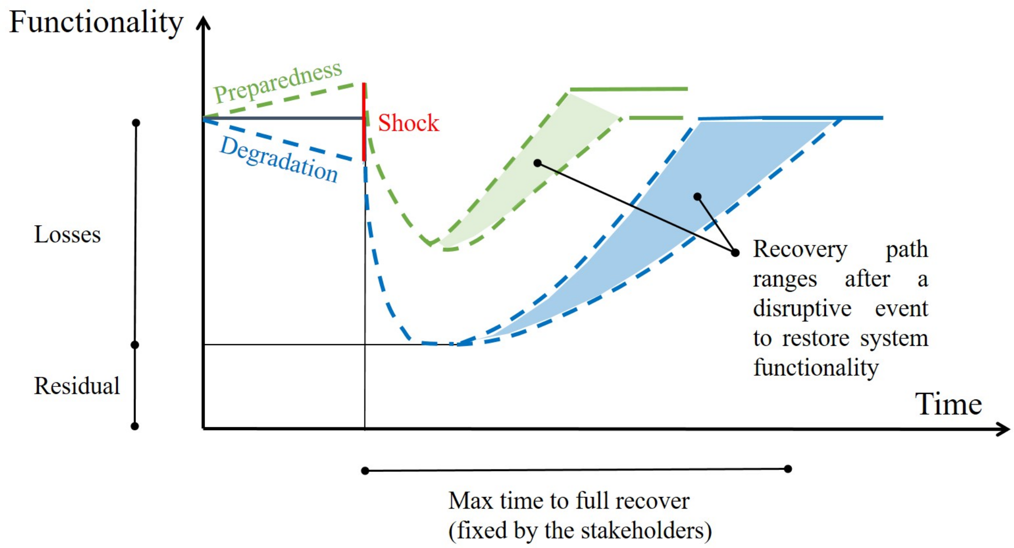

Figure 1: Functionality evolution for system resilience

first put in-service, that is the time corresponding to the initial life of the structure. Time t_{r0} is the time at which a sudden disruptive event happens, while time t_{o-o-o} denotes the time at which out-of-service for the structure is reached, as functionality reached a limit value. The other marked times are time t_{re} which is the time corresponding to the end of recovery phase, $T_{RL} = t_{o-o-o} - t_{r0}$ that is the residual service life after a shock at time t_{r0}, $T_{RE} = t_{re} - t_{r0}$ that is the time interval to recover at least the full functionality for the structure after and event happening at time t_{r0}. Finally, T_{LC} is a time interval set by the stakeholders to recover the full functionality of the infrastructure (if possible), and has been already introduced. Accordingly to (Bruneau et al. , 2003, Bruneau and Reinhorn , 2006, 2007), Resilience is defined as :

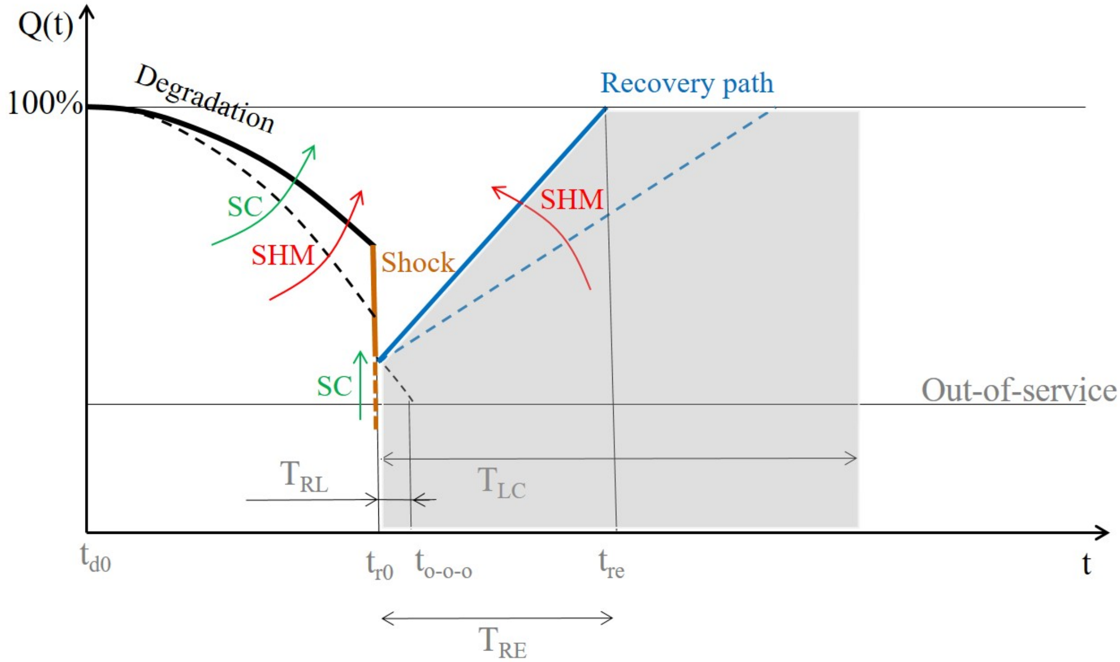

Figure 2: Effects of Structural Control (SC) and Health Monitoring (SHM) on degradation effects on the functionality function Q.

$$R = \int_{t_{r0}}^{t_{r0}+T_{LC}} \frac{Q(t)}{T_{LC}} dt \tag{1}$$

As depicted in Figures 2, SC will first reduce the structural deterioration occurring up to time t_{r0} as it has been proved that it is able to reduce internal stresses and strains in controlled structures. In this respect its action is related to the Rapidity dimension of Resilience, as it provides immediate action to improve Resilience. Secondly, SC will reduce the deterioration/damage in the final state of the structure after the extreme event occurs. This aspect is also related to the concept of "Immediate Resilience" exposed in (Domaneschi and Martinelli , 2016). This is due both to the fact that the damaging event will affect a structure that is in a better condition to absorb disturbances, i.e. in the controlled configuration, with respect to the uncontrolled one, and to the positive effects of SC in extreme events (improving the Robustness dimension of Resilience). This is also relevant even when SC was not specifically designed to cope with extreme events (Domaneschi et al. , 2016). Thirdly, also the recovery rate will be sped up, and the time to recover functionality T_{RE} will be shortened since, being the structure in a better conditions and protected before the damaging event, it will be less damaged after the occurrence of the extreme event itself, and hence faster (again, the Rapidity dimension of Resilience) and easier to repair consuming less resources in the process.

Finally, the number and arrangement of control devices is related to the Redundancy dimension of Resilience, as the loss or the damage in one control device can be compensated by the remaining ones (Domaneschi and Martinelli , 2016).

The implementation of the previously reported aspects will significantly enhance the Life-Cycle of the structure, leading to improved durability, increased efficiency, and reduced maintenance costs compared to the scenario where they would not be implemented.

2.2. Contribution of Structural Health Monitoring

Similar results can be achieved if the structure is equipped with an efficient SHM system that can provide valuable information for maintenance and repair actions, for both the initial branch of deterioration and the recovery path (Figure 2).

As it is well known, SHM can be classified, according to its performance, as belonging to several levels. The intent of SHM is to collect data on a structure trying to infer first if damage occurred (Level 1 - Damage Detection), then the location (Level 2 - Damage Localization), the intensity and the extension of damage (Level 3 - Damage evaluation), and finally to assess the remaining service life of the structure (Level 4 - Prognosis) (Doebling et al. , 1998). In this cases, the advantage in terms of Resilience is similar to what it was discussed for SC, as SHM will have several positive effects on Resilience dimensions, both in case of occurrence of extreme events as well as not.

SHM will first allow to limit the progress of structural deterioration occurring up to time t_{r0} (Figure 2) manly in relation to the "Rapidity" dimension of resilience, as an early detection of a damaged state allows to rapidly field the appropriate countermeasures. The single information about the presence of damage (Level 1) in the structures needs to be associated with the grade of redundancy of the structure ("Redundancy" dimension of resilience), as the outcome of the Polcevera's Viaduct in Italy has pointed out. For that structure, a lack of redundancy and the issue of corrosion of the steel strands inside the concrete stayed reasonably reflected in the primary cause of the disaster (Morgese et al. , 2020, Domaneschi et al. , 2020b), while SHM studies pointed out anomalous aspects worth, at least, of further investigations (Gentile , 2017, Orgnoni et al.).

Also, the second level of SHM is related to the Rapidity dimension of resilience, as the speed of the intervention and the recovery actions is improved after the pathology (the damage) has been rapidly identified by the SHM system. Thus, in this situation, SHM may aid in the decision-making to manage effectively the structure's current state by prioritizing the most appropriate interventions. As deterioration will be reduced, a damaging event will find the structure in better conditions, compared with the case where the monitoring system was not implemented, and its outcomes will be less severe.

The third level of SHM will increase the speed of organizing and implementing the recovery phases since all the involved operations will be supported by knowledge of the location and the extent of the damage, enabling the precise assessment of the resources that will be required in the repairing process and of the timing related to their implementation. Moreover, the information provided by a monitoring system can help to minimize the idle time, i.e., the time between the occurrence of the shock and the start of recovery (Argyroudis et al. , 2022).

Finally, the fourth level of SHM is connected to the "Robustness" dimension of resilience, as this SHM level attempts to predict the extent of the structural performance to withstand a given level of damage, while maintaining its normal level of functionality, offering an indirect measure of structural robustness. A comprehensive conceptual scheme is presented in Figure 3, illustrating the connections and interplay between the fields of SHM, SC, and structural resilience, aiming to summarize the mechanisms through which SHM and SC synergistically contribute to enhance the overall resilience of structures in the face of external disturbances and uncertainties.

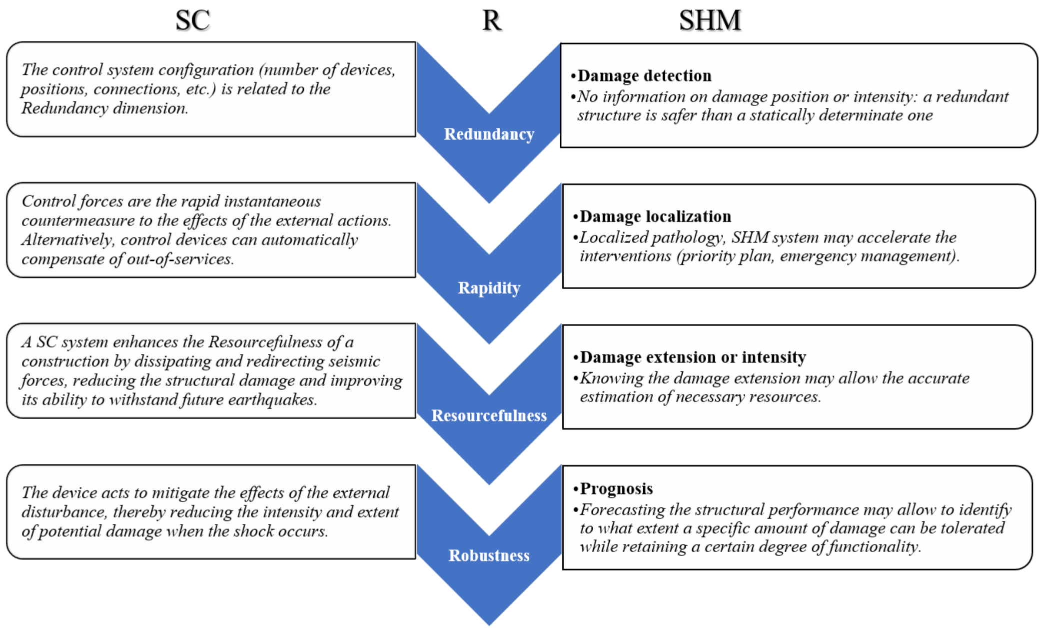

Figure 3: SC & SHM toward structural Resilience R.

3. General framework

The functionality function Q in Figure 4 serves as a comprehensive representation of the framework, providing a concise summary of how Structural Control (SC) and Structural Health Monitoring (SHM) synergistically contribute to enhancing the resilience of structures and infrastructure. Focusing on Figure 4, it is evident how SC and SHM can play a crucial role not only on the first branch of the resilience curve but also during the recovery phase. The specific type of these branches is strongly influenced by the retrofitting approaches chosen by the stakeholders or the technical approach adopted by the designers. As demonstrated in the following, analyzing this function leads to valuable insights into the underlying mechanisms that empower resilient design and operation.

The functionality function prominently showcases a distinct curve, representing the central tendency (mean values) around which data points are distributed. The dispersion surrounding this curve alludes to the inherent variability in the system response, arising from multiple factors, such as environmental conditions, material properties, and operational loads.

To further characterize this dispersion, a probabilistic perspective is adopted, with the assumption that the distribution follows a Gaussian nature. This choice is motivated by the frequent occurrence of Gaussian distributions in real-world phenomena and their convenience for mathematical modeling. Consequently, the feature function encompasses the probability density function, allowing for a quantitative assessment of the likelihood of different outcomes and performance levels.

By leveraging the SC and SHM methodologies within this framework, engineers and researchers can effectively monitor, control, and mitigate the potential risks and uncertainties associated with structures and infrastructure. Structural Control strategies, including vibration control and base isolation, enable the manipulation of the system dynamics to reduce the impact of external disturbances and enhance structural performance. Concurrently, Structural Health Monitoring techniques, such as sensor networks and data analysis algorithms, facilitate real-time monitoring of structural conditions, enabling timely interventions and proactive maintenance.

In order to elucidate the specific actions of SC and SHM on the individual components of the curve depicted in Figure 4, a comprehensive analysis is now undertaken.

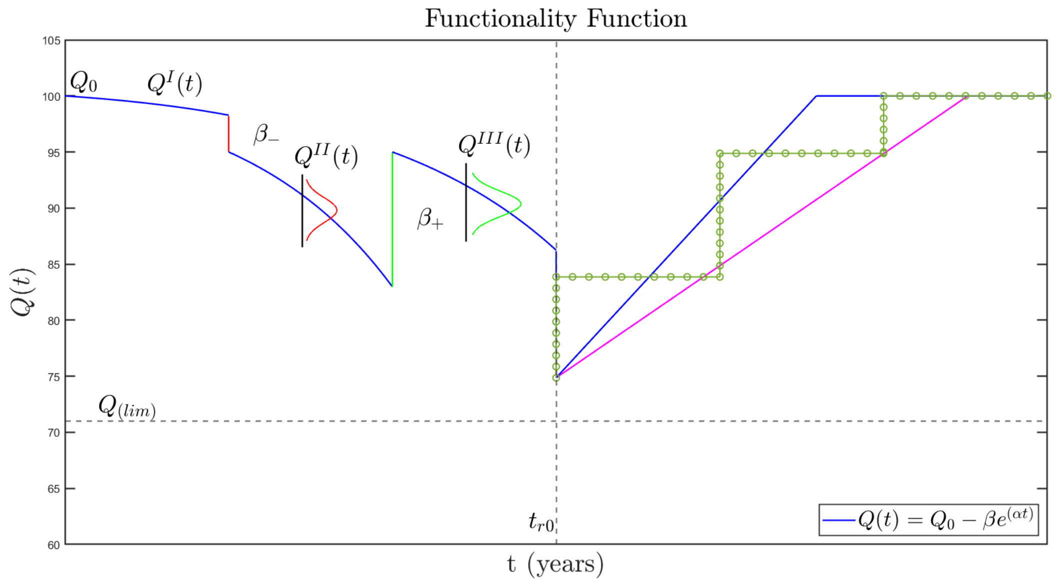

Figure 4: General framework representation via parametric curves

3.1. First branch of the functionality function and the degradation effects

The first objective is to extract and present the overarching approach for the initial segment of the functionality function, which is characterized by a decline in functionality Q during the time t attributed to degradation phenomena (Equation 2), where parameters α and β regulates the velocity and the intensity, respectively, of the degradation.

$$Q(t) = Q_0 - \beta e^{\alpha t} \tag{2}$$

More in detail, β is a coefficient that introduces discontinuity into the functionality function $Q(t)$. These phenomena are depicted in Figure 4 and, specifically, two types of jumps have been shown: the first one with a negative effect (positive value of β) on the Resilience curve due to mainly poor labour during the construction phase which leads to a loss of functionality since the first stage of the life cycle of the structure while, the second one (negative value of β), could be addressed to subsequent interventions or retrofitting procedure resulting in recovery, or even an increasing, of the structural performance.

On the other hand, α allows us to identify the velocity of the degradation phenomena. In Figure 4, three different curves $Q^{I}(t)$, $Q^{II}(t)$, $Q^{III}(t)$ with three different values of α have been shown in order to take into account several degradation phenomena with different level of damage depending to the time.

It appears evident that after the first jump, not only loss in functionality is detected but also the steepness of the curve $Q^{II}(t)$ is more pronounced. At the same time, the variability response of the system is characterized by a certain level of dispersion. After the structural interventions, an increase in the performance level is achieved with an improvement of the system's dispersion (refers to $Q^{III}(t)$).

Once the mathematical formulation of the degradation curve has been introduced and the adaptability to represent different configurations has been discussed, changes in the Functionality curve expressed in terms of the variability of its parameters or their level of dispersion will be discussed in terms of Structural Control (SC) and Structural Health Monitoring (SHM) effect.

Within this initial component of the functionality curve, the involvement of Structural Control encompasses multiple facets. For instance, in the context of damage degradation caused by fatigue cycling, the application of structural control measures has been demonstrated to effectively mitigate the adverse effects. This finding has been substantiated in relevant literature

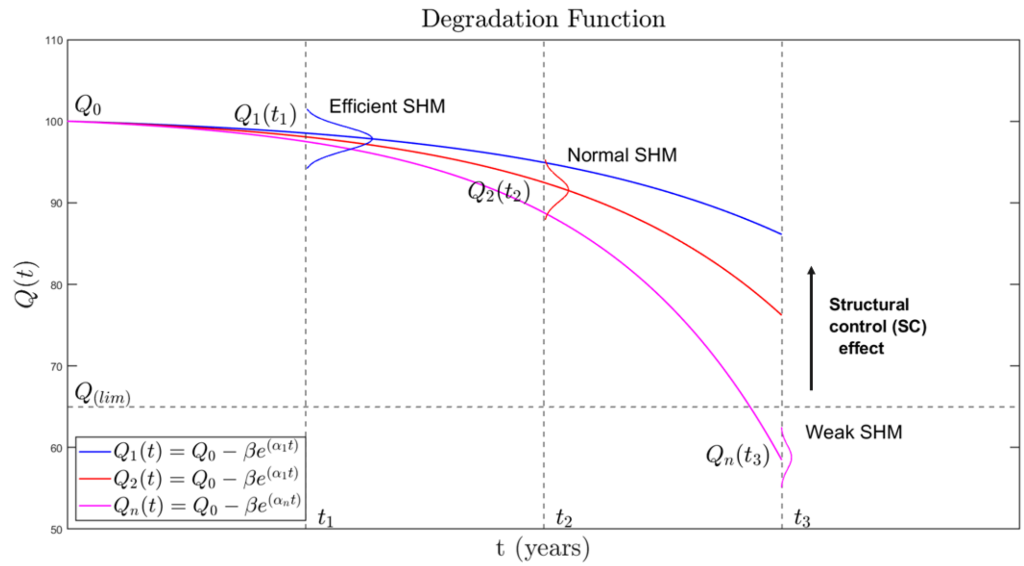

Figure 5: First component of the function: decline in functionality with the contribution of SHM and SC.

works (Pourzeynali and Datta , 2005, Domaneschi et al. , 2016). The effect of the SC can be observed in Figure 5 in which three different curves with three different evolution of the degradation have been shown. Starting from the curve $Q_n(t)$ until $Q_1(t)$ (denoted in Figure 5 by the colour magenta and blue, respectively) the level of degradation is reduced thanks to the effect of structural control systems. For the most critical degradation profile $Q_n(t)$, the functionality level at the time t_3, $Q_n(t_3)$, is even below the allowable safety threshold Q_{lim}.

Likewise, in the aforementioned initial section of the curve, also SHM assumes a notably beneficial role by providing information on the structural conditions, to implement actions (maintenance) to attenuate the rate of serviceability losses (Liu and Wang , 2022). Indeed, SHM facilitates the identification, localization, and estimation of degradation and damage, enabling the timely implementation of restoration and mitigation measures, such as maintenance activities and component replacements, to ensure efficient system performance (Zonta et al. , 2014, Memarzadeh and Pozzi , 2016, Zhang et al. , 2022). Consistently with what has been introduced before, three different configurations with an increasing level of efficiency of the SHM architecture have been reported in Figure 5. If an efficient SHM system allows for an acceptable level of dispersion resulting in a reasonable level of knowledge of the state of health of the structure, *weak SHM* leads to a significant lack of knowledge of the real structural performances Liu and Wang , 2022, Zonta et al. , 2014).

3.2. The shock effect on the functionality function

The second component of the functionality function that is here analyzed, is related to the intervention of an external shock, such as an extreme event (e.g., earthquake) that can drastically reduce functionality by the intensity of the jump ΔQ (Figure 6). Specifically, structural control (SC) exclusively plays a crucial role, mitigating the effects of the event on the structure by reducing the jump of the contribution ΔQ_{SC}. Equation 3 formalizes the relationship between the shock effects and the SC mitigation in terms of functionality function.

$$\begin{gathered} Q_{AS} = Q_{BS} - \Delta Q_{Shock} \\ Q_{SC} = Q_{BS} - \Delta Q_{Shock} + \Delta Q_{SC} \end{gathered} \tag{3}$$

In Equation 3, the subscripts BS and AS stand for "Before Shock" and "After Shock" respectively.

On the other hand, it has been demonstrated in the literature how certain

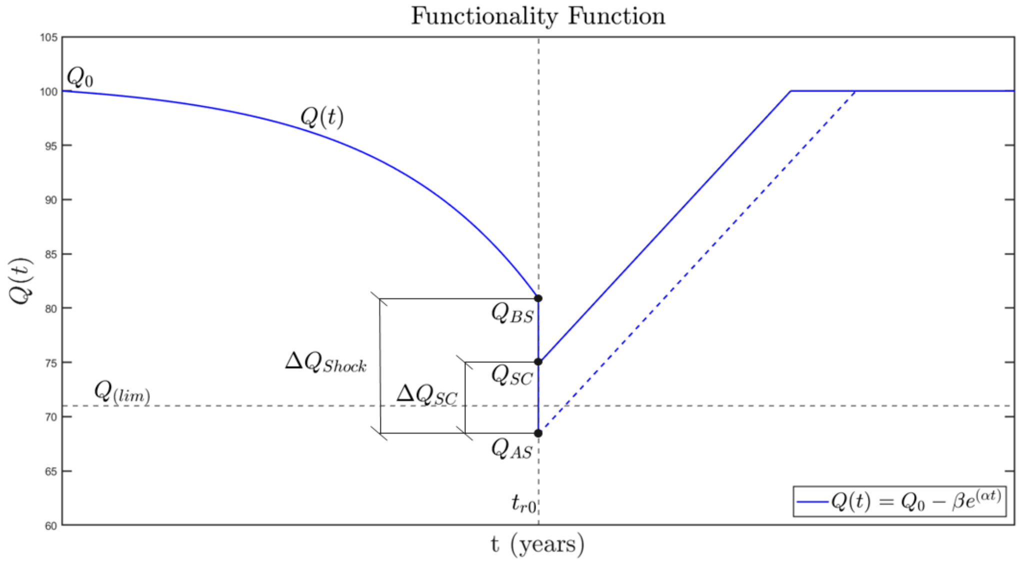

Figure 6: Second component of the function: shock effect on functionality and the role of Structural Control.

control devices (i.e. Semi-Active ones) are also able to compensate for the out-of-service of structural components realizing the property that has been termed as *Immediate Resilience* (Domaneschi and Martinelli , 2016).

3.3. Recovering the functionality

The last component of the curve that is analyzed is related to the recovery of functionality function, which can reach 100% initially as well as settle at higher or lower levels. In other words, functionality recovery interventions can also lead to improved initial functionality as well as, conversely, to lower functionality values. Different recovery functions have been described in the literature, e.g. linear, exponential, stepped, among others (Mattsson and Jenelius , 2015, Bruneau and Reinhorn , 2007). For the purposes of this study, the overall fitting function of the recovery trend has been assumed as the linear recovery function.

Within this conceptual framework, the third component of functionality recovery is exclusively influenced by the monitoring phase. Through the facilitation of damage detection, localization, and assessment of the damage magnitude, the monitoring phase significantly reduces the downtime. Specifically, structural health monitoring activities conducted on facilities and infrastructure enable the collection of comprehensive information at various time instants. Consequently, this wealth of information facilitates the prompt allocation of essential resources and implementation of appropriate measures, leading to faster restoration functionality of the facility.

Figure 7 summarizes the parameters involved in describing the process of function recovery. In particular, the parameter γ (slope of the linear fitting function) represents the variable influenced by the monitoring phase that can drastically reduce the recovery time. Equation 4, with respect to Figure 7, reports the quantification of the recovery time that represents the essential parameter for evaluating the effectiveness of the recovery phase. Indeed, resilience is quantitatively influenced by the recovery time, as the integral of the functionality function over the recovery time. Longer recovery times indicate lower resilience, while shorter times suggest higher resilience, for the same final functionality level.

$$\Delta t_k = t_{rek} - t_{r0} = (Q_0 - Q_{AS}) tan(\gamma_k) \tag{4}$$

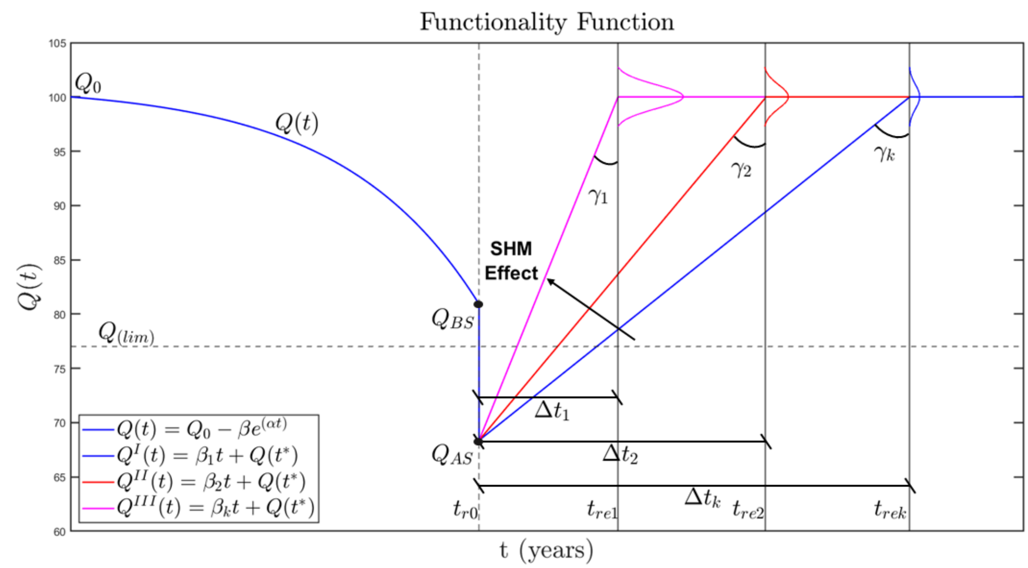

Figure 7: Third component of the function: the role of SHM in recovering functionality.

In Fig. 7, the effect of the SHM on the dispersion of the level of knowledge has been reported in terms of Gaussian distribution once the entire functionality of the infrastructure has been obtained for each proposed recovery path. It does not only affect the steepness of the recovery path as a measure of the effectiveness of the proposed interventions to restore the initial functionality but a significant effect is mainly related to the accuracy of the level of knowledge corresponding to each adopted retrofitting approach. For generality purposes, the authors assumed that the fastest consolidation approach leads to the lowest dispersion.

4. The cost function approach to the framework

This section introduces a novel approach to the proposed framework that leverages a cost function to tackle the issue of improving structural resilience through the integration of structural monitoring and control solutions.

4.1. Degradation effects on the functionality function

In the initial scenario, a deterioration process occurs gradually over time, leading to a sustained decline in functionality function. This decline persists until a certain stage at which restoration takes place and the recovery phase starts (indicated with t_{r0} in Figure 8).

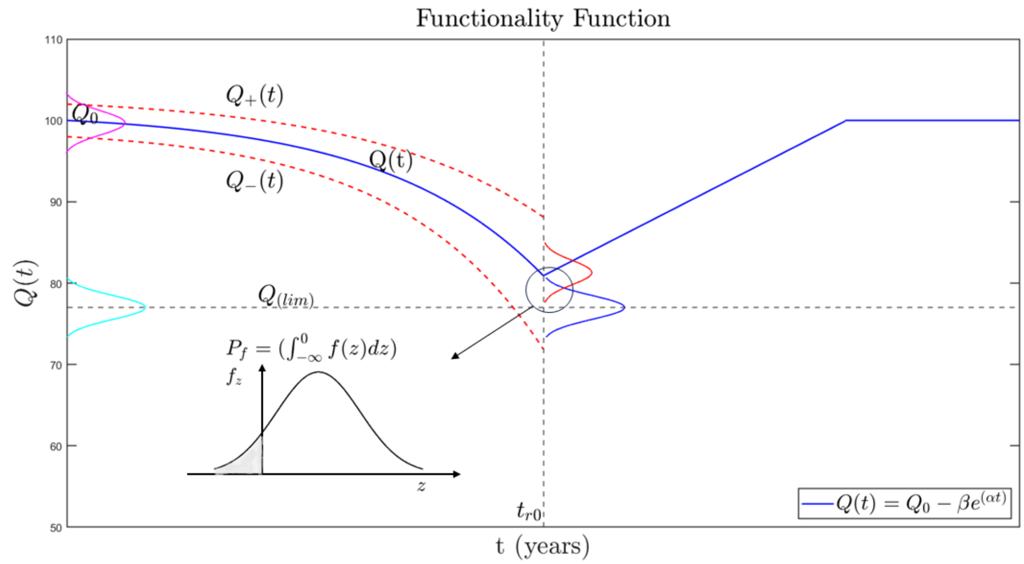

Figure 8: The degradation curve in the cost function approach. The degradation curve $Q(t)$ and the functionality acceptable limit Q_{lim} have been reported. The Red Gaussian distribution refers to the residual capacity probability function of the infrastructure after the degradation phase while the blue one represents the minimum structural and/or functionality requirements requested by Standard codes or stakeholders.

Figure 8 reports the degradation curve $Q(t)$ and the functionality acceptable limit Q_{lim}. The probability function P_f associated with the scenario where the system's functionality is decreased more than the limit can be computed as follows:

$$P_f(t) = P\Big[\frac{Q(t)}{Q_{lim}} < 1\Big] \tag{5}$$

Assuming a normal distribution for both variables, parameters $(\mu_{Q_{lim}}, \sigma_{Q_{lim}})$ are constant, (blue color in Figure 8), while $(\mu_Q(t), \sigma_Q(t))$ (red color) evolves during the service life of the structure. Thus, the probability function P_f becomes:

$$P_f = 1 - \Phi\Big(\beta(t)\Big) \tag{6}$$

Where the reliability index $\beta_{Rel}(t)$ results:

$$\beta_{Rel}(t) = \frac{\mu_Q(t) - \mu_{Q_{lim}}}{\sqrt{\sigma_Q^2(t) - \sigma_{Q_{lim}}^2}} \tag{7}$$

So the probability P_f turns out, as the reliability index, to be time-dependent with the evolutionary characteristics representing the advancement of the degradation state of the structure. This, while determined in reality, can be known at different levels by operators. With this respect, the implementation of a monitoring system can provide a reasonably higher level of knowledge for decision makers (Zonta et al. , 2014, Zhang et al. , 2022).

The functionality function $Q(t)$ has been already introduced by Equation (2) where the parameters α and β are those regulating the intensity and velocity of the degradation. In the proposed approach, both parameters can be assumed to be cost functions ($\alpha = f(cost)$, $\beta = f'(cost)$) derived from structural design aspects such as the implementation of a structural control system that can mitigate the accumulation of fatigue damage induced by cyclic loads (e.g., wind, traffic), or the quality of materials and the construction process.

However, the serviceability curve $Q(t)$ is not defined exclusively statically, at the beginning of the process, but evolves in $Q'(t)$ during the service-life of the structure due to various conditions characterized by diffuse uncertainty (e.g., changing loading conditions, such as traffic, or conditions related to climate change Lu et al. , 2017a, 2020, 2021).

$$Q'(t) = Q(t) + W(t) \tag{8}$$

Where, $W(t)$, a random function with Normal distribution, is introduced to account for such evolutionary characteristics. $W(t)$ is defined as follows:

$$W(t) = N(0, \bar{\sigma}(t)) \tag{9}$$

Parameter $\bar{\sigma}(t) = g(cost)$ represents the inherent uncertainty of the process. It is influenced by the presence of a structural monitoring system, which, through the information provided regarding the structural state (presence of damage, location, extent, and remaining useful life Morgese et al. , 2021), allows to significantly reduce the standard deviation.

Thus, the functionality function $Q'(t)$, being the sum of a deterministic function $Q(t)$ and a normal distributed function N, turns out to be equivalent to an aleatory function characterized by a normal probability distribution with mean $\mu_{Q'}$ and standard deviation $\sigma_{Q'}$ that can be defined as follows:

$$\begin{aligned} \mu_{Q'} &= Q_0 - \beta e^{\alpha t} \\ \sigma^2_{Q'} &= \bar{\sigma}^2(t) = (\sigma_0)^2 + (\sigma'_{Q'}(t))^2 \end{aligned} \tag{10}$$

Where the variance $\sigma^2_{Q'}$ represents the evolutionary inherent uncertainty of the process, which can be reduced by the information coming from an

implemented SHM system. The uncertainty is herein alternatively modelled through an elementary form consisting of two components: σ_0, the static component, and $\sigma'_{Q'}(t)$, the dynamic or evolutionary component.
The uncertainty related to the serviceability curve $Q(t)$ has been represented in Figure 8 by a maximum functionality profile, $Q_+(t)$, and a minimum one, $Q_-(t)$.

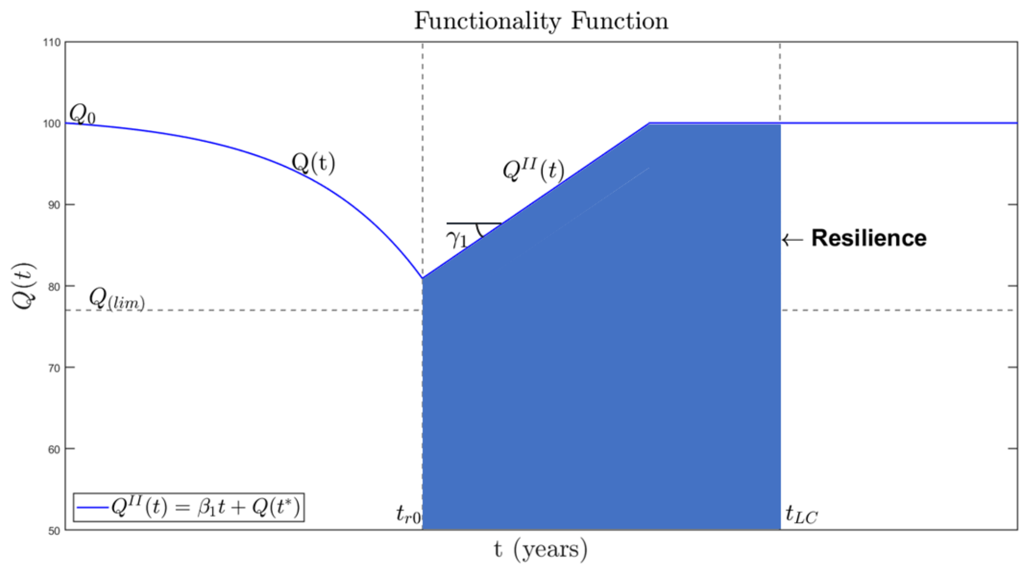

Figure 9: The recovery path in the cost function approach.

4.2. The recovery path

The recovery path $Q^{II}(t)$ is presented in Figure 9 from the recovery starting time t_{r0}. For simplicity, and without loss of generality for the proposed framework, a linear recovery path was assumed.

$$Q^{II}(t) = \gamma_1 t + Q^{II}(t_{r0}) \tag{11}$$

The slope of the recovery curve mainly drives the recovery phase and it is defined as cost function $\beta_1 = f^{II}(cost)$. In fact, assuming an effective use of available resources, the possibility of being able to face higher costs (e.g., for the implementation of a monitoring system that provides information for prognosis and diagnosis, but also for the availability of materials and work teams) may allow to optimize the recovery phase and reduce the recovery time, e.g. reducing inspection costs, increasing and improving information at the restoration project, and speeding up site activities.

4.3. The shock effect in the cost function approach

In this section, the shock effect in the cost function approach will be discussed in detail. Additionally, the role of Structural Control (SC) when a shock event occurs during the life cycle of a predetermined structure will analyzed. In the previous section 3, the capability of SC systems to reduce the instantaneous loss of functionality due to external events has been introduced. However, SC plays a crucial role also for the reduction of uncertainties induced by external shock. In Figure 10, the uncertainties at three specific points of the shock branch of the functionality curve have been depicted. Consistently with the previous treatment, Gaussian distribution has been adopted to describe the dispersion around a mean value of degradation level.

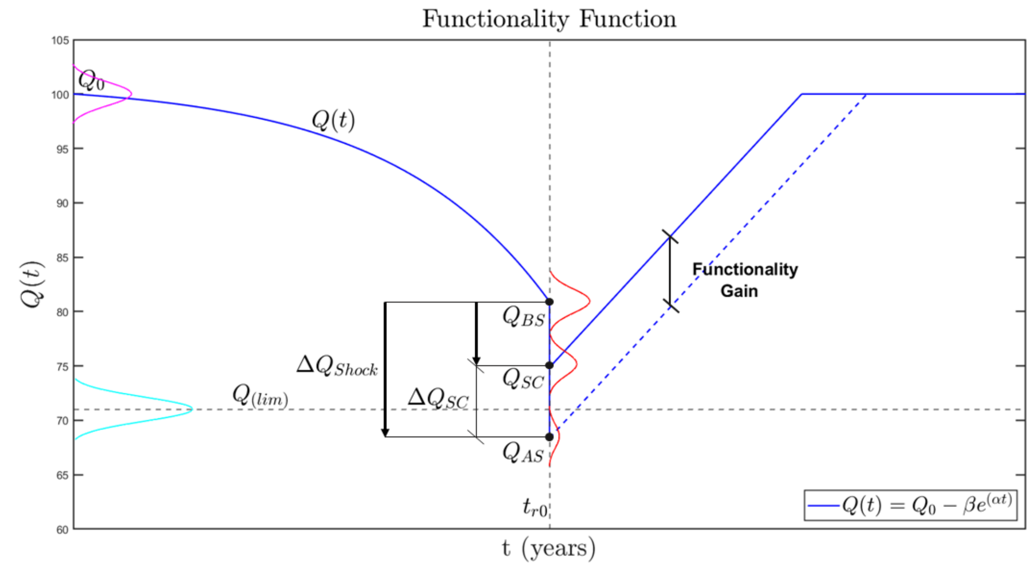

Figure 10: The shock effect in the cost function approach.

Before the shock occurrence (t_{r0}), the dispersion of the information related to the degradation level of the structure has been represented by the Gaussian distribution depicted by the curve around point Q_{BS}. As expected, the functionality of the structures decreases from Q_0 to $Q(t_{r0})$ as well as the dispersion of the information is increased due to the increasing level of damage introduced into the system. At the instant t_{r0}, two possible configurations are depicted depending on the presence or not of SC systems. From a comparison between the shape of the Gaussian distribution corresponding to a no-controlled structure, Q_{AS}, and a controlled one, Q_{SC}, it appears evident how the former exhibits a lower value of mean with a higher level of dispersion. If the mean value and the dispersion at the Q_{SC} configuration remain comparable with that one observed before the shock (Q_{BS}), a dramatic reduction in terms of mean and, subsequently, increasing of the dispersion appears at the configuration in which control is not considered

(Q_{AS}). In other words, structural control impacts directly the effective level of degradation by reducing the level of damage into the structure (minor value of Gaussian mean), while an indirect impact on the level of dispersion is produced since controlling the level of damage means avoiding important changing into the real level of information of the structural state.
In this sense, the following mathematical expression can be provided:

$$\sigma(Q_{BS}) < \sigma(Q_{SC}) < \sigma(Q_{AS}) \tag{12}$$

An efficient level of control of the structure leads to a significant gain of functionality, as shown in Figure 10. Higher the increase of resilience during the recovery phase, will be the higher the cost function, which is proportional to the efficiency of the control system. Following the scenario provided in Figure 10, the recovery curve will be written as:

$$Q^{II}(t) = \gamma_1 t + Q_{SC}(t_{r0}) \tag{13}$$

in which the cost function is expressed by $Q_{SC}(t_{r0})$ and, specifically, by the difference of:

$$f_{cost}(t) = \Delta Q_{Shock} - \Delta Q_{SC} \tag{14}$$

As provided by Equation (14), an expensive and efficient control system leads to an increased amount of functionality recovered at the time of external shock events.

It is worth underlying how the specific conditions of the facility can influence the type of investment, such as whether to implement SC or SHM, or both, along with a repair and maintenance plan. Critical factors certainly to consider include the age of the structure, and the degree of deterioration or damage. These aspects must be evaluated in a decision-making process and are specific to each considered case, taking into account the uniqueness of the structure, together with an assessment of current safety and a forecast of safety in a future service scenario. Next, the decision-making process evaluates the influence of various investments on improving safety scenario, in order to be able to identify the optimal solution, or the most cost-effective compromise with respect to the limited resources available.

To supplement the broader framework presented in this work, it is worth reporting recent applications on the practical implementation of SHM and SC in enhancing the resilience of transport infrastructure, with a particular emphasis on bridges. In (Domaneschi et al. , 2023, Martinelli et al. , 2023) valuable examples that showcase the role of SHM and SC in real-world scenarios, i.e. a viaduct and a cable-supported bridge, are reported, illustrating how these concepts contribute to improving resilience.

5. Conclusions

In this paper, the crucial role of structural resilience in transport infrastructure systems has been explored along with the contribution of monitoring and control techniques in improving this structural performance. The essential concepts related to resilience have been formerly summarized, emphasizing its multifaceted nature and diverse dimensions. Furthermore, a comprehensive overview of structural health monitoring has been presented, detailing the different phases in which it can be implemented, ranging from damage detection and localization to quantification and prognosis. The significance of structural control as a discipline capable of limiting damages in response to short-term actions (e.g., extreme events) has been highlighted, as well as of mitigating long-term effects like cyclic loading and fatigue. Although the proposed framework has been designed for the transportation infrastructure, the same lends itself to be applicable to all critical infrastructures, taking into account specific peculiarities.

Subsequently, the synergy between structural control and health monitoring has been further explored, focusing on their collective contribution to extending the service life of the infrastructure. Their effectiveness in mitigating the impacts of severe events like earthquakes and climate crises related ones demonstrates how structural control techniques can support structural resilience. Simultaneously, the role of health monitoring in providing vital information on structural health, which aids in formulating maintenance and mitigation plans, has been acknowledged. Moreover, health monitoring proves invaluable during the recovery phase, offering critical insights into damage localization and extension, and facilitating swift retrofitting and rehabilitation measures.

In an innovative step forward, a cost function approach has been introduced to address the resilience problem. Recognizing that investments are intrinsically tied to the implementation of mitigation strategies, structural control, informative techniques and health monitoring, the benefits of enhanced resilience come with associated costs. Although the integration of specialized control and monitoring systems incurs higher initial investments compared to basic structural solutions complying with current regulations, it unequivocally improves the overall resilience of the structure.

By adopting the cost function framework, stakeholders can now more effectively evaluate the trade-offs between initial investments and the long-term benefits of structural resilience. This approach fosters informed decision-making, allowing the selection of appropriate control and monitoring strategies tailored to the specific needs and criticality of each infrastructure.

In conclusion, this study underscores the indispensable role of monitoring and control in advancing the resilience of transport infrastructure systems. Through the composite of structural health monitoring and control, the infrastructure can not only withstand the impacts of adverse events but also proactively mitigate the long-term effects of degradation, e.g. corrosion, cyclic loading and fatigue. The cost-function approach offers a systematic means to weigh the benefits against the investments, paving the way for economically viable and resilient transport infrastructure systems. Facing a continuously changing climate and an uncertain future, embracing structural resilience through monitoring and control becomes imperative for safeguarding communities and promoting sustainable infrastructure development.

Future research endeavors will delve deeper into the structural reliability in association to SC and SHM, mentioned only tangentially here, thus paving the way for a more holistic understanding of the intricate interplay between these vital components of engineering design and disaster preparedness. Moreover, exploring varied recovery functions will undoubtedly be a crucial aspect of future research to understand the contribution coming from SC and SHM. With regard to the real-world application of this study, which at this stage remains at a level of abstraction and generality, future developments intend to understand and deepen the practical implications on a real transportation infrastructure and its components.

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