A Markovian framework for multi-hazard life-cycle consequence analysis of deteriorating structural systems

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ABSTRACT: Multiple-hazard (or simply multi-hazard) interactions are either disregarded or addressed inadequately in most existing computational risk modelling frameworks for natural hazards, leading to inaccurate life-cycle consequence estimates. This, in turn, can lead to ineffective risk-informed decision-making for disaster-mitigation strategies and/or resilience-enhancing policies. Probabilistic multi-hazard life-cycle consequence (LCCon) analysis (e.g., assessment of repair costs, downtime, and casualties over an asset's service life) enables optimal life-cycle management of critical assets under uncertainties. However, despite recent advances, most available LCCon formulations fail to accurately incorporate the damage-accumulation effects due to incomplete (or absent) repairs in between different hazard events. This paper introduces a Markovian framework for efficient multi-hazard LCCon analysis of deteriorating structural systems, appropriately accounting for complex interactions between hazards and their effects on a system's performance. The proposed framework can be used to test various risk management and adaptation pathways. Specifically, the Markovian assumption is used to model the probability of a system being in any performance level (e.g., damage or functionality state) after multiple hazards inducing either "shock deterioration" or "gradual deterioration", as well as after potential repair actions given such deteriorating processes. The expected LCCon estimates are then obtained by combining the performance level distribution with suitable system-level consequence models. The proposed framework is illustrated for a case-study reinforced concrete building considering earthquake-induced ground motions and environmentally-induced corrosion deterioration during its service life.

1. INTRODUCTION

As the world becomes more populated and interconnected and human settlements continue to expand, it is imperative to quantify the potential impacts that multiple natural-hazard events and their complex interactions can have on the performance of critical assets and the communities they serve. This calls for effective risk-informed decision-making on future disaster-mitigation strategies and/or resilience-enhancing policies (e.g., UNDRR, 2015). Many existing risk modelling frameworks independently analyse and aggregate the expected consequences (e.g., repair costs, downtime, and casualties) due to multiple hazards. However, it has been demonstrated that multiple, often interacting, hazards can lead to consequences greater than the sum of those related to the individual hazards (e.g., De Angeli et al., 2022). Accordingly, frameworks for multi-hazard life-cycle consequence (LCCon) analysis have gained increased attention to better quantify the expected consequences during the service life of structural systems subject to multiple hazard events (e.g., Dong & Frangopol, 2016). Nevertheless, most available frameworks assume that systems sustaining structural/non-structural damage are either instantaneously repaired or do not receive any repair actions after an event (e.g., Fereshtehnejad & Shafieezadeh, 2018). Hence, dynamic changes in the performance of the systems during their service life are not adequately tackled, preventing the accurate quantification of the associated LCCon estimates.

This paper proposes a Markovian framework for multi-hazard LCCon analysis of deteriorating structural systems (e.g., buildings and bridges), enabling the optimal life-cycle management of a structural system under uncertainties due to multiple (and often interacting) hazard events and their associated, interacting, consequences. Using the Markovian assumption (e.g., Bonamente, 2017), the framework can adequately model damage accumulation and, therefore, performance deterioration (i.e., reduction) while being computationally efficient (e.g., Iervolino et al., 2016). It is worth recalling that Markov processes have been extensively used for LCCon analysis of utility networks (e.g., Bocchini et al., 2013). Nonetheless, they have only recently been used for buildings, mainly in mainshock-aftershock-related applications (e.g., Shokrabadi & Burton, 2018). The framework proposed in this paper advances the current knowledge by including the lifetime adverse impact of multiple hazard events and their interactions on the LCCon analysis of structural systems.

2. GENERAL FRAMEWORK

The aim of the proposed Markovian framework for multi-hazard LCCon analysis (Figure 1) is to efficiently compute expected LCCon estimates of a structural system subject to multiple state-changing hazard events. The performance of the system is modelled as a discrete-time Markovian process (i.e., treating the state of the process as a discrete variable; e.g., Iervolino et al., 2016). Specifically, a structural system's performance domain is partitioned into mutually exclusive and collectively exhaustive performance states/levels. Such states should be represented using a single harmonised scale valid for different hazard types since specific hazards can cause different types of performance impairment to a system. Thus, for instance, a valid (hazard-agnostic) scale could be defined in terms of the system's functionality. In such a case, the adopted functionality states (FSs) can be defined as: 1) occupiable and fully functional; 2) occupiable and partially functional; 3) not occupiable and reparable damage; and 4) not occupiable and irreparable damage (e.g., Burton et al., 2016). If the considered hazards can cause similar damage mechanisms to a system (i.e., a consistent damage scale can be used), the performance can also be defined directly in terms of damage states (DSs), as done in the illustrative application presented later in this paper.

The transition probabilities between FSs (i.e., the probabilities that after one event, the system is in a m-th FS given that it was in a n-th FS) are derived employing state-dependent functionality models (defining the probability of exceeding a FS given a hazard intensity and the FS achieved during a prior event; e.g., fragility relationships) and hazard models (defining the probability of exceeding a hazard intensity measure –IM– given the hazard characteristics; e.g., hazard curves). The transition matrices (i.e., the stochastic square matrices used to describe the FS transitions) are assembled by collecting each (n, m) transition probabilities between FSs, also characterising the system's performance deterioration. The resulting expected consequences are obtained from suitable system-level consequence models (i.e., linking the FSs to a consequence metric of interest).

The analytical formulation to compute the expected LCCon estimates is introduced in the following section. The formulation builds upon classical hypotheses for performance-based engineering, separating the modelling of the occurrence of hazard events and the impact that those events impose on a structural system. Two modelling stages can be hence identified based on the above distinction (e.g., Zaghi et al., 2016), namely: 1) hazard modelling, considering Level I interactions through the nature of the hazards (i.e., interactions that are independent of the presence of a physical system; e.g., a landslide triggered by an earthquake event); 2) consequence modelling, considering Level II interactions as a result of the impact of the hazards on a physical system (e.g., functional impairment due to the accumulation of damage during a seismic sequence).

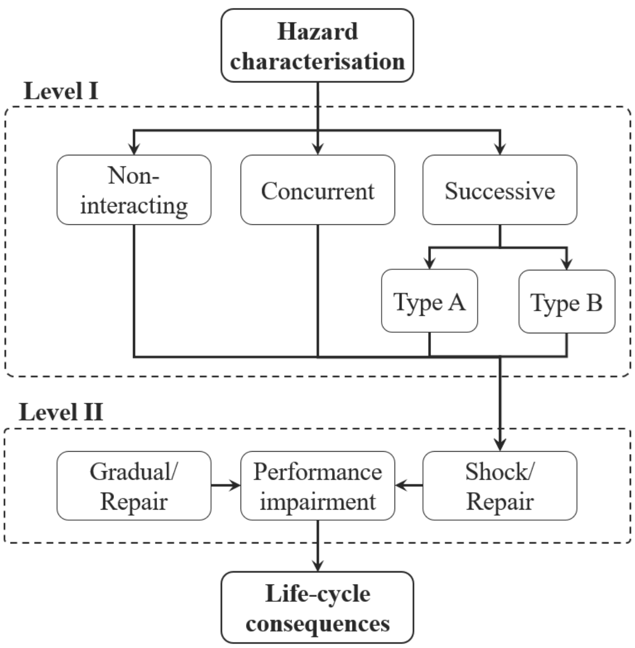

Figure 1: Markovian framework for multi-hazard life-cycle consequence analysis

The Level I interactions can be subclassified for modelling purposes (Iannacone et al., 2023) in: 1) *non-interacting*: hazards whose probability of co-occurring is negligible (e.g., earthquakes and hurricanes with a low joint probability of occurrence); 2) *concurrent*: hazards that co-occur or have a significant joint probability of occurrence in a period of time (e.g., storm surge, sea waves, and strong wind that co-occur during a hurricane); 3) *successive*: hazards having a causal relationship between a primary and secondary hazard(s); these causal relationships depend on the hazards involved, and two broad categories can be hence identified, denoted as *Type A* (i.e., a secondary hazard is triggered after the occurrence of a primary hazard) and *Type B* (i.e., the rate of occurrence of a secondary hazard increases following the occurrence of a primary hazard).

The Level II interactions are exclusively related to the performance (described by damage or functionality states) impairment of a physical system given the occurrence of hazard events. In general, the system's performance deterioration (i.e., reduction) can be caused and subclassified also for modelling purposes in: 1) "*shock deterioration*" processes (associated with hazard events occurring at a point in time; e.g., an earthquake-induced ground motion); 2) "*gradual deterioration*" processes (associated with ageing and/or deteriorating mechanisms; e.g., steel rebars corrosion). In contrast, a system's performance can be recovered (i.e., increase) due to potential repair actions executed in between hazard events. However, those actions are commonly intended to recover from shock deterioration processes rather than those due to gradual deterioration. Therefore, it is assumed that repair actions do not revert the gradual deterioration impact on the system's performance since it is continuous over time.

3. ANALYTICAL FORMULATION

The total expected LCCon estimates associated with a structural system subject to multiple hazard events can be obtained by summing the expected hazard-induced consequences during its service life, obtained as in Equation (1).

$$E[C] = \sum_{i=1}^{\infty} P(i, t_{LC}) \sum_{j=1}^{i} \boldsymbol{F_{S}}_{j} E[\boldsymbol{C_{F_S}}]^{T} \quad (1)$$

In Equation (1), $\boldsymbol{F_{S}}_{j}$ is the probability mass function (PMF) of the system's FSs after the j-th hazard event, $E[\boldsymbol{C_{F_S}}]$ is the consequence model (i.e., expected consequences associated with each FS), and $P(i, t_{LC})$ is the probability of having i hazard events during the service life (t_{LC}), obtained as in Equation (2). $\boldsymbol{F_{S_j}}$ and $E[\boldsymbol{C_{F_S}}]$ are 1xN_{F_S} vectors. N_{F_S} is the total number of FSs.

$$P(i, t_{LC}) = \frac{(\nu_T t_{LC})^i e^{-(\nu_T t_{LC})}}{i!} \qquad (2)$$

In Equation (2), ν_T is the total rate of occurrence (in a selected time unit) of N_h hazards, regardless of their type and event characteristics. It is assumed that hazard events of the same type (h) occur according to a homogeneous Poisson process with a rate of occurrence equals ν_h ($h = 1, \ldots, N_h$). Therefore, ν_T can be computed as in Equation (3).

$$\nu_T = \sum_{h=1}^{N_h} \nu_h \qquad (3)$$

It is worth noting that $P(i, t_{LC})$ can also be obtained through a simulation-based approach (e.g., Iannacone et al., 2023). The PMF of the system's FSs after the j-th hazard event only depends on the current PMF of the system's FSs and can be estimated as in Equation (4).

$$\boldsymbol{F_{S_j}} = \boldsymbol{F_{S_{j-1}}} \boldsymbol{T_{F_S}} \qquad (4)$$

In equation (4), $\boldsymbol{F_{S_{j-1}}}$ is the PMF of the system's FSs after the $(j-1)$-th hazard event and $\boldsymbol{T_{F_S}}$ is the transition matrix which quantifies the probability of transitioning between the FSs given an event, calculated as in Equation (5). $\boldsymbol{F_{S_{j-1}}}$ is a 1xN_{F_S} vector and $\boldsymbol{T_{F_S}}$ is a N_{F_S}xN_{F_S} matrix.

$$\boldsymbol{T_{F_S}} = \sum_{t_j=0}^{t_{LC}} \sum_{t_{j-1}=0}^{t_j} f(t_{j-1}, t_j | i, t_{lc}) \boldsymbol{T_S} \boldsymbol{T_{G,\Delta t}} \boldsymbol{T_{R,\Delta t}} \qquad (5)$$

In Equation (5), $\boldsymbol{T_{F_S}}$ accounts for possible repair actions and gradual deterioration in the time between the occurrence of the $(j-1)$-th hazard event and the j-th hazard event (i.e., interarrival-time), denoted as Δt_j. $f(t_{j-1}, t_j | i, t_{lc})$ is the PDF of two hazard events occurring at a time t_{j-1} and t_j, conditioned on the occurrence of i hazard events during the nominal lifetime of the system (details on how to obtain this particular PDF are shown in Fereshtehnejad & Shafieezadeh, 2018), $\boldsymbol{T_S}$ is the transition matrix associated with a shock deterioration process accounting for the possible hazard events (e.g., earthquake- and flood-related events), $\boldsymbol{T_{G,\Delta t}}$ is the transition matrix associated with a gradual deterioration process occurring in Δt_j (e.g., deteriorating mechanisms), and $\boldsymbol{T_{R,\Delta t}}$ is the transition matrix associated with the repair actions occurring in Δt_j. The matrix $\boldsymbol{T_S}$ can be obtained combining the transition matrices for individual, non-interacting, hazard types $\boldsymbol{T_{S_h}}$, as in Equation (6). $\boldsymbol{T_S}$, $\boldsymbol{T_{G,\Delta t}}$, $\boldsymbol{T_{R,\Delta t}}$, and $\boldsymbol{T_{S_h}}$ are all N_{F_S}xN_{F_S} matrices.

$$\boldsymbol{T_S} = \sum_{h=1}^{N_h} \frac{\nu_h}{\nu_T} \boldsymbol{T_{S_h}} \qquad (6)$$

A significant challenge in using Equation (1) is linked to the high computational cost of integrating all the possible outcomes for the occurrence of the hazard events and the total number of hazard events during the selected time horizon. Such a drawback is exacerbated by $\boldsymbol{T_{G,\Delta t}}$ and $\boldsymbol{T_{R,\Delta t}}$ being a function of Δt_j. Nonetheless, Equation (1) can be significantly simplified by modelling the expected LCCon estimates as the sum of the expected consequences in N_t fixed time intervals of length Δt, where $N_t = \lfloor t_{LC}/\Delta t \rfloor$. Selecting a sufficiently small Δt such that only one (primary) hazard event is likely within each interval, the expected LCCon estimates can be computed with Equation (7).

$$E[C] = \sum_{m=1}^{N_t} \boldsymbol{F_{S_{t+m\Delta t}}} E[\boldsymbol{C_{F_S}}]^T \qquad (7)$$

In Equation (7), $\boldsymbol{F_{S_{t+m\Delta t}}}$ is the PMF of the system's FSs at time $t + m\Delta t$, computed as in Equation (8). $\boldsymbol{F_{S_t}}$ is the PMF of the system's FSs at time t (i.e., the time just before $t + m\Delta t$), computed also with Equation (8) in a previous time step. $\boldsymbol{F_{S_{t+m\Delta t}}}$ and $\boldsymbol{F_{S_t}}$ are 1xN_{F_S} vectors.

$$\boldsymbol{F_{S_{t+m\Delta t}}} = \boldsymbol{F_{S_t}} \prod_{i=1}^{m} [\nu_T \boldsymbol{T_S} \boldsymbol{T_G} + (1 - \nu_T) \boldsymbol{T_R} \boldsymbol{T_G}] \qquad (8)$$

In equation (8), $\nu_T \boldsymbol{T_S} \boldsymbol{T_G}$ corresponds to the transition probability due to shock and gradual deterioration, multiplied by the probability of observing a shock-type hazard event in a selected Δt (equal to the rate ν_T under the small-interval assumption). $(1-\nu_T)\boldsymbol{T_R}\boldsymbol{T_G}$ corresponds to the transition probability due to repair actions and gradual deterioration, multiplied by the probability of not observing a shock-type hazard event in a selected Δt (equal to $1-\nu_T$ under the small-interval assumption). It is assumed that only a transition due to a hazard event or a repair action occurs in a unit of time since, commonly, repair actions will be stopped after a significant event. Nonetheless, such an assumption can be relaxed. In this case, $\nu_T\boldsymbol{T_S}\boldsymbol{T_G}$ can be written as $\nu_T\boldsymbol{T_S}\boldsymbol{T_R}\boldsymbol{T_G}$. If $\boldsymbol{T_S}$, $\boldsymbol{T_G}$, and $\boldsymbol{T_R}$ do not vary with time (i.e., are stationary), they define a homogeneous Markov process. In such a case, Equation (8) can be simplified to Equation (9). $\boldsymbol{T_S}$ (as mentioned), $\boldsymbol{T_G}$, and $\boldsymbol{T_R}$ are $N_{F_S}\text{x}N_{F_S}$ matrices.

$$\boldsymbol{F}_{\boldsymbol{S}_{t+m\Delta t}} = \boldsymbol{F}_{\boldsymbol{S}_t}[\nu_T\boldsymbol{T_S}\boldsymbol{T_G} + (1-\nu_T)\boldsymbol{T_R}\boldsymbol{T_G}]^m \quad (9)$$

The following subsections describe the derivation of the described transition matrices.

3.1. Shock Deterioration Transition Matrix

The shock-type deterioration transition matrix (i.e., $\boldsymbol{T_S}$) only has diagonal and upper-triangular entries corresponding to the probabilities of transitioning from a given FS to a higher FS (i.e., a transition between progressively worse FSs) or staying at the same FS after a hazard event. It is obtained from the transition matrix of the individual hazard types $\boldsymbol{T}_{\boldsymbol{S}_h}$ using Equation (6). In this section, the methods to assemble each $\boldsymbol{T}_{\boldsymbol{S}_h}$ are detailed for four (particular) cases, accounting for Level I and II interactions: 1) hazard type h does not interact with other hazards; 2) hazard type h induced the simultaneous occurrence of other multiple concurrent hazards; 3) hazard type h is the primary hazard of a successive Type A interaction; 4) hazard type h is the primary hazard of a successive Type B interaction. It is worth noting that equations accounting for interactions between two hazards are shown for each particular case. Nonetheless, such equations can generally be adapted for cases including more than two distinct hazard types.

3.1.1. Non-interacting hazards

If hazard type h does not interact with any other hazards, the PDF of the hazard's intensity measure, $f_{IM}(im)$, is obtained from probabilistic hazard analysis. The probability that a system in the n-th FS transitions to the m-th FS after a hazard event of intensity IM, $P(FS_m|FS_n, IM)$, is computed using state-dependent fragility relationships, as thoroughly described in Iervolino et al. (2016). The (n,m) entry of the matrix $\boldsymbol{T}_{\boldsymbol{S}_h}$ is obtained as in Equation (10).

$$\boldsymbol{T}_{\boldsymbol{S}_h}(n,m) = \int_{-\infty}^{\infty} P(FS_m|FS_n, IM)\, f_{IM}(im)\mathrm{d}im \quad (10)$$

3.1.2. Concurrent hazards

If hazard type h induced the simultaneous occurrence of other two concurrent hazards, the joint PDF of the intensity measures of the associated hazard events, $f_{IM_1,IM_2}(im_1, im_2)$, can be obtained from vector-valued probabilistic hazard analysis (e.g., by multi-variate Normal distributions or Copulas; e.g., Lan et al., 2022). The probability that a system in the n-th FS transitions to the m-th FS after the concurrent hazard events with intensities IM_1 and IM_2, $P(FS_m|FS_n, IM_1, IM_2)$, is computed using state-dependent fragility surfaces. The (n,m) entry of the matrix $\boldsymbol{T}_{\boldsymbol{S}_h}$ is obtained as in Equation (11), where $P_c = P(FS_m|FS_n, IM_1, IM_2)$ and $f_c = f_{IM_1,IM_2}(im_1, im_2)$.

$$\boldsymbol{T}_{\boldsymbol{S}_h}(n,m) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P_c\, f_c \mathrm{d}im_1 \mathrm{d}im_2 \quad (11)$$

3.1.3. Successive hazards – Type A

If hazard h is the primary hazard of a successive Type A interaction, the PDF of the secondary hazard's intensity measure given the primary hazard's intensity measure, $f_{IM_2|IM_1}(im_2|im_1)$, can be obtained from probabilistic hazard analysis that accounts for the probability of triggering a secondary event given the primary one. The probability that a system in the n-th FS transitions to the m-th FS after a primary event of intensity IM_1 and a secondary one of intensity IM_2, $P(FS_m|FS_n, IM_1, IM_2)$, is obtained using state-dependent fragility surfaces. The (n, m) entry of the matrix $\boldsymbol{T}_{\boldsymbol{S}_h}$ can be obtained as in Equation (12), where $P_A = P(FS_m|FS_n, IM_1, IM_2)$ and $f_A = f_{IM_2|IM_1}(im_2|im_1)f_{IM_1}(im_1)$.

$$\boldsymbol{T}_{\boldsymbol{S}_h}(n,m) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P_A\, f_A \mathrm{d}im_1 \mathrm{d}im_2 \tag{12}$$

3.1.4. Successive hazards – Type B

If hazard h is the primary hazard of a successive Type B interaction, the transition matrix related to the primary hazard, $\boldsymbol{T}_{\boldsymbol{S}_{h1}}$, is characterised as per Section 3.1.1. A conditional rate of occurrence is used for the secondary hazards (e.g., Iannacone et al., 2023; Iervolino et al., 2020) to obtain: 1) the PDF of the secondary hazard events given the selected primary hazard's characteristics ($\boldsymbol{\Theta}$), $f_{IM_2|\boldsymbol{\Theta}}(im_2|\boldsymbol{\Theta})$; and 2) the expected number of secondary hazard events caused by the primary hazard, $E\left[N_{h2|\boldsymbol{\Theta}}(0, \Delta t)\right]$. The (n, m) entry of the transition matrix of the secondary hazard $\boldsymbol{T}_{\boldsymbol{S}_{h2}}$ is obtained as in Equation (13), where $P_B = P(FS_m|FS_n, IM_2)$ and $f_B = f_{IM_2|\boldsymbol{\Theta}}(im_2|\boldsymbol{\Theta})$.

$$\boldsymbol{T}_{\boldsymbol{S}_{h2}}(n,m) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P_B\, f_B \mathrm{d}im_1 \mathrm{d}im_2 \tag{13}$$

The transition matrix for the entire sequence of events is finally obtained as in Equation (14).

$$\boldsymbol{T}_{\boldsymbol{S}_h} = \boldsymbol{T}_{\boldsymbol{S}_{h1}}\left(\boldsymbol{T}_{\boldsymbol{S}_{h2}}\right)^{E\left[N_{h2|\boldsymbol{\Theta}}(0,\Delta t)\right]} \tag{14}$$

3.2. Gradual Deterioration Transition Matrix

Before the gradual deterioration initiation time (t_i), there is no transition between FSs. Thus, the gradual-type deterioration transition matrix (i.e., $\boldsymbol{T}_{\boldsymbol{G}}$) is numerically equal to the identity matrix ($\boldsymbol{T}_{\boldsymbol{G}} = \boldsymbol{I}$). After t_i, the system starts transitioning from a given FS to a higher FS (i.e., a transition between progressively worse FSs) or staying at the same FS, and $\boldsymbol{T}_{\boldsymbol{G}}$ becomes an upper-triangular matrix whose entries correspond to the probability of transitioning in Δt, as in Equation (15) (which is valid for $t > t_i$). Several probabilistic models can be used to model the system's gradual deterioration (e.g., Duracrete, 2000) and, thus, to obtain the (n, m) entry of the matrix $\boldsymbol{T}_{\boldsymbol{G}}$. In the described procedure, gradual deterioration is treated for modelling purposes as the impact of non-monitored, yet frequent, small shocks.

$$\boldsymbol{T}_{\boldsymbol{G}}(n,m) = \begin{cases} P(FS_m|FS_n, \Delta t) & \text{if } n < m \\ 1 - \sum_{i=1}^{N_{P_S}} \boldsymbol{T}_{\boldsymbol{G}}(n,i) & \text{if } n = m \\ 0 & \text{if } n > m \end{cases} \tag{15}$$

3.3. Repair Actions Transition Matrix

The repair-type recovering transition matrix (i.e., $\boldsymbol{T}_{\boldsymbol{R}}$) only has diagonal and lower-triangular entries relating to the probabilities of transitioning from a given FS to a lower FS (i.e., a transition between progressively better FSs) or staying in the same FS as the structural system recovers with time. The repair actions are modelled through a Poisson process. The daily rate of occurrence of an event where the system is recovered from a worse FS to a better FS is assumed as the inverse of the difference between the repair times for each FS ($T_{n,m}$). This time difference does not necessarily correspond to the repair times associated with each state-dependent FSs; however, this is the simplest approximation to a potential recovery path between the FSs. Further details on such recovery paths can be found in Burton et al. (2016). The values of $T_{n,m}$ are only defined if $n > m$, and they can be found in the literature (e.g., HAZUS, 2003). The (n, m) entry of the matrix $\boldsymbol{T}_{\boldsymbol{R}}$ is obtained as in Equation (16). The Δt should be expressed in the same units than $T_{n,m}$.

$$\boldsymbol{T}_{\boldsymbol{R}}(n,m) = \begin{cases} \left(\frac{1}{T_{n,m}}\Delta t\right) e^{-\left(\frac{1}{T_{n,m}}\Delta t\right)} & \text{if } n > m \\ 1 - \sum_{i=1}^{N_{F_S}} \boldsymbol{T}_{\boldsymbol{R}}(n,i) & \text{if } n = m \\ 0 & \text{if } n < m \end{cases} \tag{16}$$

4. ILLUSTRATIVE APPLICATION

The proposed framework is demonstrated using an archetype four-storey, four-bay, moment-resisting reinforced concrete frame located in a seismic-prone region and subject to harsh environmental conditions. It represents a typical building vulnerability class in Southern Italy (e.g., Minas & Galasso, 2019) and is located in Ponticelli, Napoli (ν_h =0.054). The frame is characterised by a total height equal to 13.5 m (i.e., a first story of 4.5 m and upper stories of 3.0 m) and a total width equal to 18.0 m (i.e., bay spans of 4.5 m). It comprises beams and columns with 30x50 cm cross sections, designed and detailed according to the Eurocode 8 Part 3 seismic provisions for high ductility class structures (EN 1998-3, 2005). The building is assumed to undergo earthquake-induced ground motions while experiencing environmentally-induced corrosion deterioration in a marine splash exposure. DSs are used as performance states (so FS = DS in the previous equations) since a unique shock-type hazard is investigated, as in common performance-based engineering practice. The time- and state-dependent fragility relationships developed in Otárola et al. (2023) for this case-study frame are used to assemble $\boldsymbol{T_S}$ and HAZUS repair times are used to assemble $\boldsymbol{T_R}$ (HAZUS, 2003). Table 1 to 3 present the transition matrices for the case-study building. In total, four DSs are adopted, corresponding to slight (DS1), moderate (DS2), extensive (DS3), and complete (DS4) structural damage. Although the entries for $\boldsymbol{T_S}$ and $\boldsymbol{T_R}$ are obtained from fragility and recovery models, respectively; values for $\boldsymbol{T_G}$ are ideal and are used for illustrative purposes, estimating its non-diagonal entries as those corresponding to $\boldsymbol{T_S}$ divided by 100 for a Δt expressed in months.

Table 1: $\boldsymbol{T_S}$ transition probability matrix

DSs	DS0	DS1	DS2	DS3	DS4
DS0	7.69e-1	9.49e-2	6.38e-2	4.14e-2	3.12e-2
DS1	0	8.23e-1	9.77e-2	4.76e-2	3.17e-2
DS2	0	0	9.03e-1	6.42e-2	3.31e-2
DS3	0	0	0	9.61e-1	3.88e-2
DS4	0	0	0	0	1

Table 2: $\boldsymbol{T_G}$ transition probability matrix

DSs	DS0	DS1	DS2	DS3	DS4
DS0	9.98e-1	7.91e-4	5.31e-4	3.45e-4	2.60e-4
DS1	0	9.99e-1	8.14e-4	3.97e-4	2.64e-4
DS2	0	0	9.99e-1	5.35e-4	2.76e-4
DS3	0	0	0	9.99e-1	3.24e-4
DS4	0	0	0	0	1

Table 3: $\boldsymbol{T_R}$ transition probability matrix

DSs	DS0	DS1	DS2	DS3	DS4
DS0	1	0	0	0	0
DS1	3.64e-1	6.36e-1	0	0	0
DS2	1.97e-1	3.05e-1	4.98e-1	0	0
DS3	8.41-2	1.15e-1	1.53e-1	6.47e-1	0
DS4	4.82e-2	5.32e-2	6.74e-2	9.16e-2	7.40e-1

The expected LCCon is estimated in terms of expected repair costs and considering 60 years as the system's service life. The expected repair cost can be computed as in Equation (17).

$$E[C_T] = C_0 + C_{M,NPV} + E[C]_{NPV} \tag{17}$$

C_0 is the initial construction cost of the building, $C_{M,NPV}$ is the maintenance cost during the building service life actualised to the time of construction (Net Present Value, NPV), obtained from the annual cost of maintenance C_M (assumed to be $0.01C_0$ constant per year; e.g., Jalayer et al., 2011) as in Equation (18).

$$C_{M,NVP} = \sum_{t=0}^{t_{LC}-1} \frac{1}{(1+\alpha)^t} C_M \tag{18}$$

$E[C]_{NPV}$ is the expected cost (consequence) of repairs due to hazard-induced damage also actualised at the time of construction, obtained as in Equation (19) (with m=1). The discount factor, α, is illustratively assumed to be 0.05 for the adopted case-study building.

$$E[C]_{NPV} = \sum_{t=0}^{t_{LC}-1} \frac{1}{(1+\alpha)^t} \left(\boldsymbol{F}_{\boldsymbol{S}_{t+1\Delta t}} E\left[\boldsymbol{C}_{\boldsymbol{F}_S}\right]^T \right) \tag{19}$$

Figure 2 shows the expected life-cycle cost normalised with the initial cost of construction (i.e., $E[C_T]/C_0$) of the case-study building as a function of time, using the consequence model (i.e., $E\left[\boldsymbol{C}_{\boldsymbol{F}_S}\right]$ =[0,0.01,0.10,0.55,1.00], related to the mean repair-to-replacement cost ratio of the system) proposed by Di Pasquale et al. (2005) and starting in pristine conditions ($\boldsymbol{F}_{\boldsymbol{S}_0}$ =[1,0,0,0,0]). Additionally, the expected life-cycle unit (i.e., normalised) cost of a structural upgraded building at $t = 0$ years (yr) is presented. Such an upgrade is assumed to ideally cost 10.0% of the initial cost and to increase the median fragility values by

25.0% (i.e., to increase the lateral-resisting system structural capacity). The maintenance and repair costs of the upgraded and as-built configurations are assumed to be equal. Although initially much more expensive, an enhancement in the building's seismic lateral resisting system can significantly reduce its life-cycle cost, as observed in Figure 2. Given the flexibility and efficiency of the proposed framework, such improvements can be analysed at any point in time and utilised to showcase the value and/or significance of risk management and adaptation pathways.

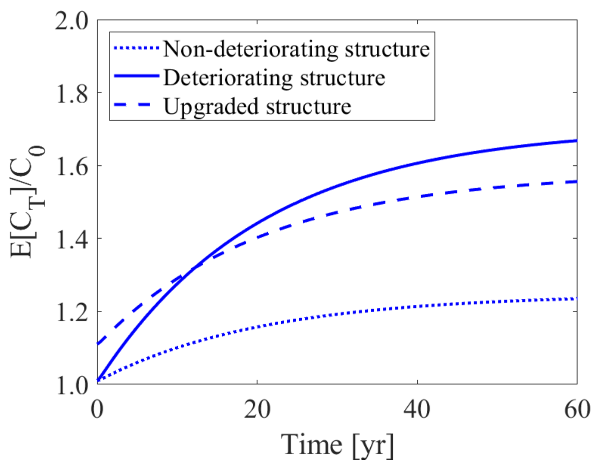

Figure 2: Normalised expected life-cycle cost of the case-study building

5. CONCLUSIONS

The study presented a Markovian framework for multi-hazard life-cycle consequence analysis of deteriorating structural systems. Consequences in terms of repair costs are obtained from the performance states of the system over time. Transition matrices for shock deterioration, gradual deterioration, and repair actions are established to model the performance state change. The framework can be used to model the time- and state-dependent deterioration and recovery processes with significantly low computational demand. A case-study moment-resisting reinforced concrete building subjected to earthquake-induced ground motions as well as corrosion-induced deterioration was presented to illustrate the proposed framework. The results showcase how the formulation can be effectively implemented in actual risk modelling practice to adequately assess the life-cycle consequences of structural systems due to multiple hazards.

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