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Abbreviation list

CC	**Climate Change**
CH	**Cultural Heritage**
FE	**Finite Element**
IM	**Intensity Measure**
ML	**Machine Learning**
UAV	**Unmanned Aerial Vehicle**

Executive Summary

Deliverable 5.2 reports how sensor data can be utilized to update the risk assessment framework within the YADES project. The framework is based on convolving hazard, exposure, and vulnerability. Hazard assessment involves identification, intensity and probability determination, and scenario development. Exposure mapping catalogs Cultural Heritage assets and their spatial distribution. Vulnerability, encompassing fragility (damage probability) and potential loss, is assessed using fragility curves derived from analytical methods and damage-to-loss relationships. Asset classification and surrogate modeling are employed for efficiency, with detailed models for critical assets.

Risk assessment updating is crucial due to changing hazards and asset conditions. YADES utilizes various sensor technologies that could be used to explore ways of dynamic updates in exposure, fragility/vulnerability, and impact. In general, hazard sensors monitor hazard intensity, response sensors track structural response, and impact sensors assess damage. Data sources include post-disaster field assessments, structural monitoring, maintenance records, and Unmanned Aerial Vehicle (UAV) observations, often used to refine Finite Element models and recalculate fragility.

Fragility curve updating in YADES occurs through damage-driven updates following hazard events (using satellite/UAV imagery and field assessments to update FE models and increase fragility) and intervention-driven updates after inspections and maintenance (using intervention records to update FE models and decrease fragility). UAV missions can also drive pre-event vulnerability updates by detecting and monitoring structural degradation, informing expert analysis and potentially shifting fragility curves to reflect increased vulnerability.

1 Introduction

YADES is a H2020 framework project funded under grant agreement 872931 which aims to introduce a research framework on the field of the resilience of Cultural Heritage (CH) areas and historic cities against Climate Change (CC) and other types of hazards. YADES will consider the local eco-systems in the areas of interest, mapping out their interactions and follow a truly sustainable reconstruction approach at technical, social, institutional, environmental, and economic levels. YADES will employ state-of-the-art numerical modelling tools for selected climate scenarios in the targeted historic areas: i) the city of Milano in Italy and ii) the archaeological area of Pafos, Cyprus, covering processes and interactions from short to the long-term (10-60 years).

The project will downscale the created climate and atmospheric composition as well as associated risk maps, and specific damage functions for CH materials perform combined hygrothermal and structural/geotechnical analysis of the CH sites and damage assessment under normal and changed conditions, based on the climatic zone, the micro-climate conditions, the petrographic and textural features of building materials, historic data for the structures, the effect of previous restoration processes and the environmental/physical characteristics of the surrounding environment.

CH assets face risks from natural hazards, such as climate-driven extreme weather events and geo-hazards like earthquakes, as well as the persistent effects of environmental degradation and lack of maintenance over time. Effectively managing these risks requires a structured and comprehensive approach. The YADES project directly addresses this challenge by introducing a detailed Risk Assessment Framework designed specifically for CH assets. This framework establishes a robust foundation by systematically evaluating risk through the convolution of three fundamental pillars: **Hazard**, involving the identification, characterization, and modeling of potential damaging events and their intensities; **Exposure**, focusing on the meticulous inventory and spatial mapping of CH assets within potentially affected areas; and **Vulnerability**, which assesses the susceptibility of these assets to damage and loss, crucially distinguishing between physical fragility and the broader consequences encompassing cultural, historical, and social values.

While establishing this baseline risk assessment is essential, the YADES framework recognizes a critical limitation of traditional approaches: their static nature. The condition of CH assets is not fixed; it evolves due to damage from hazard events, ongoing degradation processes, or conversely, improvements resulting from repair and strengthening interventions. Similarly, hazard characteristics can shift, particularly in the context of CC. Therefore, a static "snapshot" of risk quickly loses its relevance. The core innovation presented within the YADES project, and the central focus of this document, is the development and integration of **dynamic updating capabilities**. This dynamic approach aims to continuously refine the risk assessment by incorporating new information as it becomes available from diverse sources – including advanced sensor technologies, field observations, remote sensing data like UAV imagery, and maintenance records. This document will first detail the components of the foundational YADES risk assessment framework, then explore the methodologies developed for dynamically linking new data to update risk parameters, particularly asset fragility and vulnerability, ensuring the framework provides a continuously relevant and accurate tool for ongoing CH management and preservation.

2 Risk Assessment Framework in YADES

This chapter details the general risk assessment framework incorporated within the YADES project. This framework provides a structured approach for evaluating and managing the risks posed to CH assets from a range of potential hazards. It serves as the foundation upon which the dynamic updating capabilities, discussed in the next chapter, are built.

The YADES risk assessment framework is based on the fundamental principle of convolving a) **hazard**, b) **exposure**, and c) **vulnerability**. This involves systematically analyzing each of these components and then integrating them to estimate the overall risk. The framework is designed to be flexible and adaptable, allowing for the consideration of diverse CH asset types, hazard scenarios, and data sources. These three elements are presented in the following sub-chapters.

2.1 Hazard

The first step in the risk assessment process is to identify and characterize the potential hazards that could impact CH assets. This involves:

- Hazard Identification: A comprehensive list of relevant hazards is compiled, considering events such as climate-related (e.g., extreme weather) or geo-hazards (e.g., earthquakes).
- Hazard Intensity and Probability: For each identified hazard, the intensity and probability of occurrence are assessed. This may involve analyzing historical data, utilizing predictive models, and consulting with experts. Spatial and temporal variations in hazard intensity are also considered.
- Hazard Scenario Development: Representative hazard scenarios are developed to capture the range of potential events and their associated intensities. These scenarios form the basis for subsequent vulnerability and risk assessments.

2.2 Exposure

The exposure captures the extent of the asset stock/people that are exposed to a particular hazard in a certain location. The exposure mapping component involves identifying and cataloguing the CH assets within the areas of interest. This includes:

- Asset Inventory: A comprehensive inventory of CH assets is compiled, including their location, physical characteristics, and cultural significance.
- Spatial Distribution: The spatial distribution of CH assets is mapped to identify areas of high concentration and potential vulnerability.
- Dynamic Updates: The asset inventory is designed to be dynamically updated to reflect changes due to damage, restoration, or other interventions.

2.3 Vulnerability

This crucial element focuses on determining the susceptibility of CH assets to damage and loss when exposed to different hazard intensities. YADES recognizes that vulnerability is multi-faceted, encompassing not just physical damage but also the loss of cultural, historical, aesthetic, and social value. The framework will carefully distinguish between fragility (the probability of a CH asset reaching a specific damage state) and vulnerability (the potential consequences of that damage, including loss of value).

2.3.1 Vulnerability Assessment Methodology: A Deep Dive

The vulnerability component is a rather complex one to accurately define. In fact, in many cases it is used to denote "fragility" or "lack of capacity" whereas other definitions extend its meaning way beyond understanding the direct impacts of a peril. Strictly speaking, vulnerability is not fragility (Porter, 2021), since the former, at least in its basic formulation, provides the distribution of a suitable loss measure and the latter measures the probability of an asset being in a particular damage state or exceeding a certain limit state given an intensity level. However, often the term vulnerability is used in the literature to denote structural damageability, which is essentially fragility. In YADES will refrain from this confusion and the fragility and vulnerability terms will be used to denote the damage probability and the distribution of losses, respectively.

To develop vulnerability relationships, one needs to exploit fragility curves and damage-to-loss relationships that convert damage estimates to loss estimates (Galasso et al, 2021). Nevertheless, damage-to-loss models are rather scarce for CH assets, whereas, for a large portion of CH assets the models to directly associate their damage state with economic losses may not be meaningful, since their actual value extends way beyond their market one, e.g. aesthetic, social, historical, spiritual, recreational value (Romão et al, 2020). What it is relatively straightforward to define for a CH asset is the total loss of its value, associated with the collapse state of a structural asset (or complete loss of its functionality), and the no loss of value, that essentially reflects the intact state of the CH asset following the occurrence of a peril of certain intensity. The intermediate states (i.e. slight, moderate, extensive loss of the CH asset value due to the latter being in certain damage states) are more subjective and often their definition is a product of consultation with experts and stakeholders (ICCROM, 2016).

The fragility element is deemed to be key in the definition of the damage risk, and several different methodologies, of variable levels of granularity/accuracy (low, moderate, high), exist in the literature for its evaluation. By offering the probability of a structure exceeding certain damage thresholds, fragility curves serve as a useful tool in performance-based assessment for buildings with different characteristics (Bakalis and Vamvatsikos 2018; Silva et al. 2019). For estimating the fragility of structural assets, researchers can employ empirical, analytical, or expert opinion-based approaches, or even integrate these methods. Furthermore, numerous literature studies offer seismic fragility curves that researchers can utilize for risk assessment. These curves are either derived analytically through structural analyses (Erberik 2008; Kappos and Panagopoulos 2010) or directly fitted to empirical data from past events (Rosti et al. 2021; Crowley et al. 2020).

In the YADES project mostly analytical methodologies (maybe combined with expert judgement in some cases) will be utilized for estimating the fragility of the build environment in CH sites, due to the scarcity of empirical data for the spectrum of the anticipated hazards/assets and the high level of subjectively associated with expert opinion obtained data. A fragility function is defined by the expression:

$$\begin{aligned} F_{LSi}(IM) = F_{LSi}(IM = x) &= P[LS_i \text{ violated} | IM = x] \\ &= P[D > C_{LSi} | IM = x] \end{aligned} \tag{1}$$

where Limit State LS_i violation is typically defined as the seismic Demand, D, exceeding the associated limit-state Capacity, C_{LSi}, and IM denotes the Intensity Measure which is a measure of the hazard severity. Typically, fragility curves are assumed to be lognormally distributed. If θ_i is the median value and β_i is the logarithmic standard deviation (or dispersion) of DS_i, the probability of exceeding DS_i is computed as follows:

$$F_{LSi}(IM) = F_{LSi}(IM = x) = \Phi\left(\frac{ln(\,x/\theta_i)}{\beta_i}\right) \tag{2}$$

where $F_{LSi}(IM)$ is the probability of exceeding DS_i given $IM = x$ and $\Phi(\cdot)$ denotes the standard normal cumulative distribution function.

Damage States can be sequential, mutually exclusive or simultaneous. Sequential DS are the most common ones, and denote those states that occur one after the other, with DS_{i+1} always succeeding DS_i, as damage increases in the structure and more severe consequences occur. The occurrence of one damage state precludes the occurrence of the other for mutually exclusive DS, which is typical of components following one or another failure mechanism (but not both). Simultaneous DS may occur at the same time, which is typical of different components in a complex subsystem that may receive damage simultaneously. The probability of being in each DS for sequential damage states is estimated as per Eq. (3).

$$P(DS_i|IM) = F_{LSi+1}(IM) - F_{LSi}(IM) \tag{3}$$

Consequently, in their simplest expression, the vulnerability functions could be obtained by convolving system-level fragility curves with the corresponding cumulative cost/consequences of an asset’s damage state i, DS_i. Hence, the mean vulnerability curve may be calculated according to Eq. (4):

$$E(L|IM) = \sum_{i=0}^{N_{DS}} E(L|DS_i) \cdot P(DS_i|IM) \tag{4}$$

where N_{DS} is the number of damage states, $P(DS_i \mid IM)$ is the probability of being in damage state i given an IM level, $E(L \mid DS_i)$ is the expected loss (e.g. cost/downtime etc.) given DS_i and $E(L \mid IM)$ is the expected loss given the IM. An example of vulnerability curve estimation using deterministic loss data is schematically shown in Figure 1.

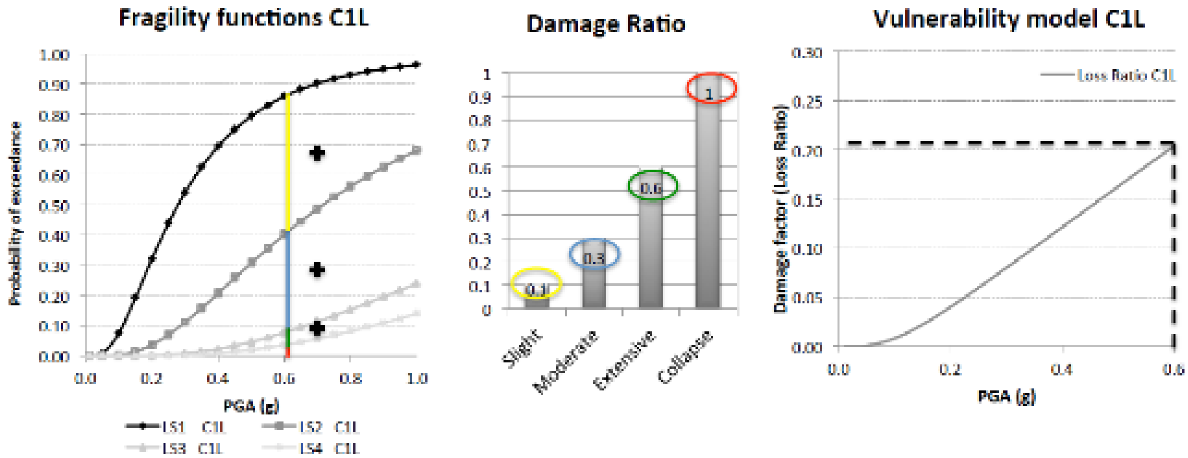

Figure 1: Example of a vulnerability assessment undertaken of the basis of the evaluated fragility and the deterministic loss data defined for the asset of interest (from D'Ayala et al, 2015)

To deliver a practical and generic disaster risk assessment framework, appropriate taxonomy methodologies (D'Ayala *et al*, 2015) and expert opinion will be utilized for identifying the characteristic classes that are deemed to compose the structural asset inventory of interest. This essentially implies that the YADES approach will refrain from addressing explicitly the fragility/vulnerability of each individual structural asset located in a CH site. Instead, clusters of structural assets that have identical or very similar key structural characteristics (structural typology, material, age of construction etc.) and hence are anticipated to have similar vulnerability when they are subjected to a specific hazard type and intensity, will be identified. Then, for each one of these classes one or a set of representative characteristic index structures will be identified. An index or a set of index structures, that could be either actual or fictitious, should, at least in a median sense, approximate the fragility/vulnerability of the structures that form the population a particular structural class. A limited number of CH-assets, in particular the important ones (in terms of their value) are expected to define a class on their own.

To alleviate the computational demands and the complexity of the modeling process and in view of the lack of details for the majority of the considered CH structures, the identified index CH assets will be modelled by surrogate structural models, but the model-type uncertainty (e.g., Lachanas and Vamvatsikos, 2021) associated with their use will be incorporated in the vulnerability assessment process. The modeling of the index structures utilizing reduced order analytical models, perfectly fits the time-limitations associated with large-scale vulnerability assessments that account for several different structural assets and the intention to quickly exploit monitoring data from variable sensors within a simplified model updating framework. In the case of exceptionally important CH assets detailed models will be utilized to validate the simplified ones.

To summarize, the vulnerability assessment focuses on determining the susceptibility of CH assets to damage and loss when exposed to the identified hazards. This involves:

- Fragility Analysis: Fragility curves, which describe the probability of a CH asset reaching a specific damage state given a hazard intensity, are developed. Analytical methodologies, tailored to the specific characteristics of different CH asset types, are primarily employed.

- Value Loss Quantification: The potential consequences of damage, including the loss of cultural, historical, aesthetic, and social value, are assessed. A structured process involving expert consultation and stakeholder engagement is used to quantify these losses for different damage states.
- Asset Classification: CH assets are grouped into classes based on shared characteristics (structural type, materials, age) to simplify the assessment process. Representative "index structures" are modelled for each class.

3 Risk Assessment Updating

3.1 Overview of Methodology

Crucially, within the YADES project there is recognition that risk assessment parameters are **not static**. They are subject to change due to evolving hazards (e.g., climate change) and alterations in the CH assets themselves due to infrastructure degradation (owing to, e.g., damage from disaster events, the effects of lack of intervention, etc.) or repair interventions.

Risk assessments typically capture a static condition (a snapshot) of assets at a specific time. Because these conditions can change over time, periodic updates to reflect changes are necessary to maintain the validity and utility of risk assessments. These updates should be conducted at regular intervals, such as every three to five years, or as otherwise specified by project requirements.

Hence, there is a need for examination of ways to ensure that the risk assessment remains current and reflects the actual state of CH infrastructure. This can be achieved by acquiring new data and establishing procedures for "linking" the data with the risk model. In general, this exploration of the "linking" process specifically investigates how data can be used to inform and update the risk model with respect to three key areas:

- **Exposure:** Updating information on the location, extent, and characteristics of assets at risk.
- **Fragility/Vulnerability:** Refining assessments of the susceptibility of assets to damage based on their current condition.
- **Impact:** Improving estimations of the potential consequences of hazard events, considering direct damage.

3.2 Data Sources for Dynamic Risk Assessment

As established in the previous section, maintaining a current and relevant risk assessment necessitates continuous updates with new data that reflect the evolving state of CH infrastructure.

The advent of affordable and readily deployable sensor technologies offers a significant opportunity to enhance data acquisition for dynamic risk assessments. These sensors enable more frequent and even continuous monitoring, expanding the capabilities for tracking changes in hazards and asset conditions. In general, sensors relevant to dynamic risk assessment can be categorized by the type of information they provide, directly aligning with the three key areas for updating the risk model discussed earlier:

- **Hazard sensors:** These instruments, such as seismographs and weather stations, provide critical data on hazard IMs.
- **Response sensors:** Sensors like accelerometers and strain gauges directly monitor the structural response of assets to environmental stressors or even minor hazard events. Data from these sensors directly informs the refinement of 'Fragility/Vulnerability' assessments, providing empirical evidence of an asset's susceptibility to damage based on its real-time condition.
- **Impact sensors:** Visual sensors, such as cameras, and other technologies capable of assessing damage states of assets fall into this category. Data from these sensors are vital for improving estimations of 'Impact,' particularly in the immediate

aftermath of an event, and can also be used to validate and refine fragility models over time.

In practice, a variety of data sources contribute to both real-time and periodic updates needed for a dynamic risk assessment framework. These sources often leverage different types of sensors and data collection methodologies, providing a comprehensive approach to data acquisition:

- **Post-disaster field assessments:** Following hazard events, structural surveys conducted in the field remain a crucial source of data. While often employing human observation, these assessments effectively act as 'impact sensors,' providing detailed information on actual damage patterns and informing immediate impact estimations as well as longer-term fragility model refinements.
- **Structural monitoring:** The continuous or periodic collection of data from sensor networks embedded within or attached to assets (sensor-based monitoring), or through remote sensing techniques, offers valuable insights into material degradation and structural changes over time. This is particularly relevant for continuously updating 'Fragility/Vulnerability' assessments by tracking the evolving condition of CH assets.
- **Maintenance and intervention records:** Systematic documentation of all repairs, retrofit, and maintenance activities undertaken on CH assets provides essential information on interventions that alter asset characteristics and reduce vulnerabilities. These records directly contribute to updating both 'Exposure' (by documenting asset modifications) and 'Fragility/Vulnerability' (by reflecting improved asset condition) components of the risk assessment.
- **UAV observations:** High-resolution imagery acquired Unmanned Aerial Vehicles (UAVs) serves as a powerful tool for wide-area monitoring. These platforms can function as 'impact sensors' for rapid damage detection following events, and also contribute to updating 'Exposure' information by tracking changes in the location, extent, and surrounding environment of assets over time.

Data from these diverse sources are then often used to refine numerical models, such as Finite Element (FE) models, of the CH assets. These updated models, in turn, allow for the recalculation and refinement of fragility assessments.

By integrating data from these diverse sources and sensor types, a dynamic risk assessment framework can move beyond static snapshots, providing a continuously updated and more accurate representation of risk to CH infrastructure. This enhanced understanding, in turn, supports more effective and timely risk management and mitigation strategies.

4 Dynamic Linking and Information Integration

This chapter focuses on the dynamic linking capabilities of the YADES framework, which represent a significant advancement in CH asset risk management. This dynamic approach allows the framework to adapt to new information and evolving conditions, leading to more accurate and timely risk assessments.

4.1 Fragility Curve Updating Methodology in YADES

Within YADES framework, the discussion focuses on continuous updating assets fragility and vulnerability to reflect the evolving condition of assets. This chapter details the specific methodology employed within YADES for updating fragility curves, as visually summarized in Figure 2.

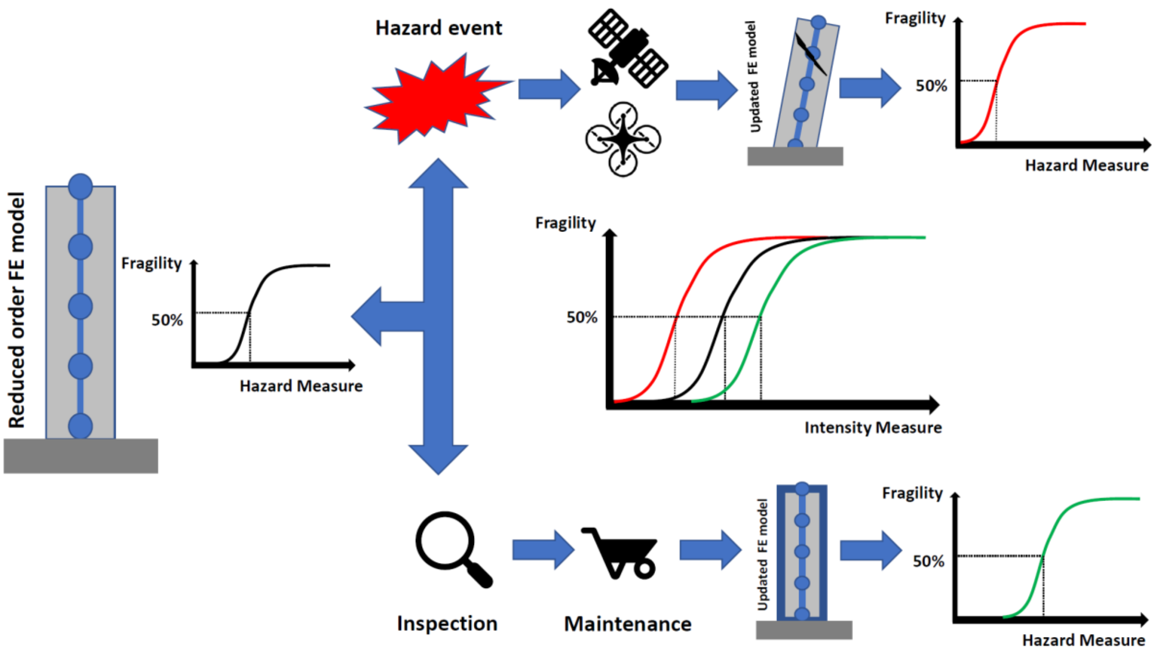

Figure 2: Schematic representation of the YADES fragility updating approach in view of the monitoring/field data following the occurrence of a peril or strengthening.

Fragility updating in YADES is primarily triggered by two key scenarios, each leading to a distinct pathway for refining fragility assessments (Figure 2):

Pathway 1: Fragility Updating Following a Hazard Event (Damage-Driven Update)

1. **Hazard Event Occurrence:** The process begins with the occurrence of a hazard event (e.g., earthquake) that potentially impacts CH assets.
2. **Post-Hazard Data Acquisition:** In the aftermath of the hazard, rapid data acquisition is crucial. YADES leverages various data sources to assess damage:
   - **Satellite and UAV Observations:** High-resolution imagery from satellites and Unmanned Aerial Vehicles (UAVs) are employed for wide-area damage detection and initial assessment of asset condition. These act as valuable **impact sensors** providing a rapid overview of the situation.

- **Post-Disaster Field Assessments:** Teams conduct on-site structural surveys to gather detailed information on damage states. These field assessments provide ground-truth validation of remote sensing data and offer in-depth insights into specific damage patterns, functioning as detailed **impact sensors**.

3. **Updated Finite Element (FE) Model Development:** The data collected from post-hazard observations is then used to update the initial "Reduced order FE model" of the CH asset. This update involves incorporating observed damage patterns and potentially adjusting material properties or structural parameters within the FE model to reflect the asset's damaged state.
4. **Recalculation of Fragility Curve:** Using the updated FE model, new fragility curves are recalculated. As depicted in Figure 2, the resulting fragility curve (shown in red) is typically shifted to the **left** compared to the original fragility curve. This leftward shift indicates an **increase in fragility**. For a given hazard intensity measure, the probability of damage is now higher because the asset has been weakened by the hazard event.

<u>Pathway 2: Fragility Updating Following Inspection and Maintenance (Intervention-Driven Update)</u>

1. **Routine Inspections and Structural Monitoring:** Regular inspections and ongoing structural monitoring are conducted to assess the condition of CH assets over time. These activities may identify signs of material degradation, structural weaknesses, or the need for preventative or corrective maintenance. **Structural monitoring** data, from sensors or remote sensing, provides continuous insights, while **inspections** are periodic but detailed.
2. **Maintenance and Strengthening Works:** Based on inspection and monitoring findings, maintenance, repair, or strengthening interventions are implemented. These works aim to address identified vulnerabilities and improve the structural performance of the CH asset. **Maintenance and intervention records** document the specifics of these activities.
3. **Updated Finite Element (FE) Model Development:** Similar to the post-hazard scenario, records of maintenance and strengthening works are used to update the FE model. This update involves incorporating details of the interventions, such as material replacements, strengthening elements, or repaired components, into the FE model. The FE model now reflects the *improved* structural condition of the asset.
4. **Recalculation of Fragility Curve:** With the updated FE model reflecting the strengthened asset, new fragility curves are recalculated. As shown in Figure 2, this results in a fragility curve (depicted in green) that is shifted to the **right** compared to the original fragility curve. This rightward shift represents a **decrease in fragility**. For the same hazard intensity measure, the probability of damage is now lower due to the maintenance and strengthening works.

Dynamic Nature of Fragility Curve: The central panel of Figure 2 is particularly important as it visually compares the original fragility curve (black), the updated fragility curve after a hazard event (red - increased fragility), and the updated fragility curve after maintenance (green - decreased fragility). This visual comparison effectively illustrates the dynamic nature of fragility and how it is modified within the YADES framework based on data and interventions.

Role of Reduced-Order Finite Element Models: It is crucial to note that in both pathways, reduced-order FE models serve as a central component of the YADES fragility updating methodology. Data acquired from sensors, field assessments, and maintenance records are not directly used to adjust fragility curves. Instead, this data is used to refine and update the underlying reduced-order FE models of the CH assets. These updated FE models, which more accurately represent the current structural condition, are then used to rigorously recalculate the fragility curves. This approach ensures that fragility updates are grounded in structural mechanics principles and reflect the actual changes in asset vulnerability.

5 Examples of Fragility Curve Updating in YADES

5.1 Example: Degradation-Driven Fragility Curve Update with UAV missions

This section explores the potential of utilizing UAV readings within the risk framework of exposed assets to natural hazards. This discussion focuses on the pre-event phase of risk assessment, where UAV-derived data can be particularly valuable for updating assets vulnerability. UAVs offer a powerful tool for efficiently capturing even subtle changes, particularly regarding structural flaws and degradation that might otherwise go unnoticed.

5.1.1 Workflow for updating vulnerability

To effectively integrate UAV findings into vulnerability updating, the following workflow is proposed:

1. **UAV Data Acquisition:** Targeted UAV missions are conducted to capture high-resolution imagery of the asset. The timing and scope of these missions should be informed by existing data and/or suspected areas of concern.
2. **Comparative Analysis:** Newly acquired UAV data is compared with previous assessments, including baseline data where available. This comparison aims to identify areas of degradation, track the progression of existing flaws, and detect new structural issues, such as corrosion, cracking, or spalling.
3. **Structural Evaluation:** Detected flaws are evaluated to determine their impact on the asset's structural integrity and potential degradation patterns. This step may involve consulting with structural engineers or other experts to translate visual observations into actionable engineering assessments. Consideration should be given to the severity of the flaw, its location, and the type of structural element affected.
4. **Fragility Model Update:** Based on the identified flaws and their structural implications, the relevant parameters of the asset's fragility model are updated. This may involve adjusting fragility curves to reflect the increased vulnerability due to detected degradation.
5. **Reporting and Documentation:** A concise report is generated summarizing the updated vulnerability state of the asset. This report should include details of the detected flaws, their impact on structural integrity, the rationale behind the fragility model updates, and the resulting changes to the model itself. This documentation ensures transparency and facilitates future assessments.

5.1.2 Conceptual example

<u>Conceptual Flaw Detection and Vulnerability Update:</u>

UAV Mission 1: An initial UAV mission (Figure 3) captures imagery revealing potential minor corrosion on exposed structural elements. Automated corrosion detection was performed using machine learning, identifying areas of interest based on visual cues such as discoloration and surface texture. These highlighted regions, while suggestive of corrosion, require further investigation to confirm the presence and extent of degradation, acknowledging the inherent uncertainties associated with automated detection methods.

Figure 3: Conceptual results from UAV Mission 1 – Asset (church in Mytilene) with defect detection using multiclass object detection model and annotations highlighting corrosion.

UAV Mission 2 (e.g., 3 years later): Three years after the initial UAV survey, a follow-up mission (Mission 2) was conducted. The resulting data (Figure 4) documents a notable increase in both the area affected by corrosion and the severity of the degradation. This progression suggests a decline in the warehouse's structural integrity and warrants further investigation to assess the potential reduction in load-bearing capacity.

Figure 4: Conceptual results from UAV Mission 2 – Asset (church in Mytilene) with defect detection using multiclass object detection model and annotations highlighting corrosion areas. The increased number and extent of these areas in comparison with the results of UAV Mission 1, suggest a potential worsening of the asset's condition.

Fragility Update: Figure 5 demonstrates the impact of corrosion progression on the fragility curve for DS3 (extensive damage). While computer vision facilitated the detection of increased corrosion between UAV Missions 1 and 2, the resulting shift in the fragility curve is a consequence of expert analysis informed by this data. The observed corrosion suggests a potential reduction in structural capacity, prompting a detailed assessment, potentially including on-site inspections and material testing. This assessment quantifies the corrosion's impact, leading to the updated fragility curves. For instance, at 0.35g PGA, the probability of exceeding DS3 increased from 10% to 18.2% due to the building's deterioration. The conceptual shift in Figure 5 illustrates how UAV data, combined with expert judgment, refines vulnerability estimates.

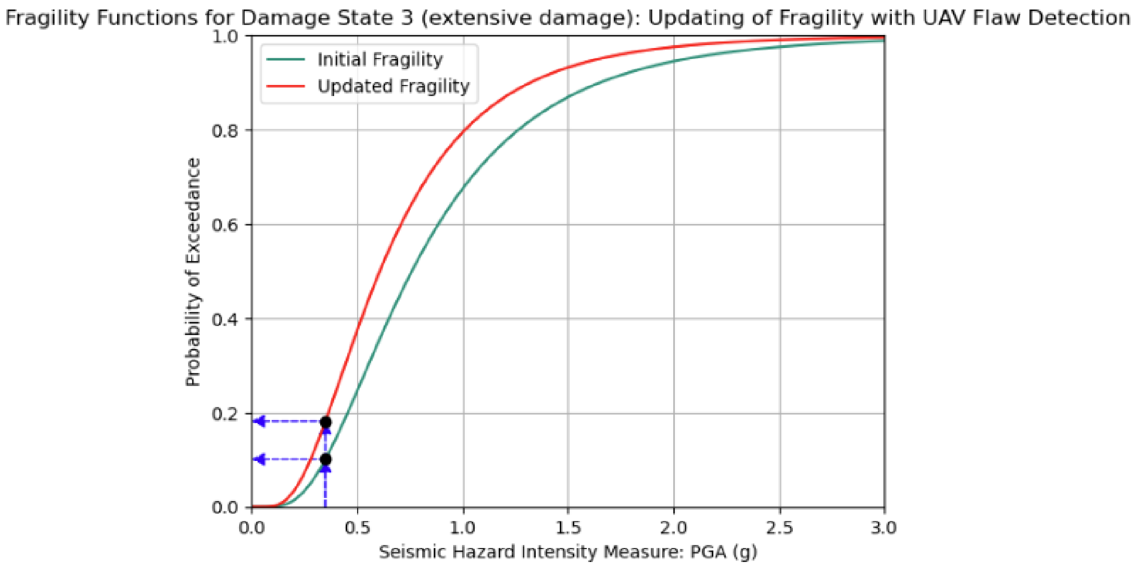

Figure 5: Conceptual illustration of a potential shift in the DS3 (extensive damage) fragility curve for seismic hazard. The shift to the left represents an increased probability of exceeding DS3 at lower intensity levels, reflecting the potential impact of the observed corrosion. This shift is illustrative and does not represent a quantified update to the fragility model. It serves to highlight the potential impact of the observed degradation on the asset's vulnerability and the need for further expert evaluation.

This example demonstrates how UAVs can provide valuable data for triggering further investigation and informing expert judgment in pre-event vulnerability assessments. The ability to detect and monitor potential structural flaws allows for a more dynamic and accurate representation of risk, ultimately leading to better-informed risk management decisions.

6 Conclusions

In conclusion, the YADES project offers a significant advancement in the field of cultural heritage risk management by providing a framework that is not only comprehensive in its initial assessment but also crucially adaptive over time. Grounded in the established risk assessment principles of analyzing Hazard, Exposure, and Vulnerability, it provides a structured methodology for understanding the baseline risks faced by diverse CH assets. However, its most defining contribution lies in the sophisticated integration of **dynamic updating mechanisms**. Recognizing that CH assets and their environments are constantly changing due to factors like disaster impacts, environmental degradation, and human interventions (repair, retrofitting), YADES implements explicit procedures for incorporating new data to ensure the continued accuracy and relevance of the risk assessment.

At the core of this dynamic approach is a robust method for **updating fragility curves**. By leveraging data from post-hazard event assessments (using satellite/UAV imagery and field surveys) or from routine inspections, structural monitoring, and maintenance records, the framework facilitates the refinement of asset-specific FE models. These updated models, reflecting either increased damage or enhanced structural integrity, are then used to rigorously recalculate fragility curves, providing a quantifiable measure of changes in vulnerability. This process, visually represented by the shifting of fragility curves (leftward for increased fragility post-damage, rightward for decreased fragility post-intervention), ensures that the assessment accurately reflects the asset's current condition. The ability to integrate data from a wide array of sources, including various sensor types (hazard, response, impact) and observational techniques (UAVs, field assessments), further strengthens the framework's capacity for timely updates. Ultimately, the YADES dynamic risk assessment framework moves beyond static evaluations, offering a continuously evolving understanding of risk. This enhanced accuracy and timeliness empower stakeholders with better-informed decision-making capabilities for prioritizing interventions, allocating resources effectively, and implementing more resilient strategies for the long-term protection and stewardship of irreplaceable CH.

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