# Conservation of Cultural Heritage Against Dynamic Loads

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# Outlines

- Introduction
- Research Gap
- Research objectives
- Methodology
- FE Model
- Seismic Input
- Linear Vs Non-Linear Dynamic Analysis
- Hazard Consistent stress demand maps
- Probability of cracking
- Mitigations strategies
- Viscoelastic Material
- Optimization of Viscoelastic parameters
- Limitations & Future Work
- Conclusion

# Introduction

•Cultural heritage monuments represent **irreplaceable historical, cultural, and scientific value**, requiring long-term protection against natural hazards.
•Many monumental stone structures were **constructed without seismic design considerations**, making them vulnerable to dynamic loads.
•The **Giza Plateau**, hosting the Pyramids and the Great Sphinx, is among the world's most iconic heritage sites.
•Historical and instrumental records confirm that **moderate-to-strong earthquakes** have affected Egypt, including events from **Dahshur, Aqaba, and the Eastern Mediterranean**.
•Even **moderate seismic motions** can induce **tensile stresses and cracking** in brittle limestone masonry.
•There is a critical need for **mechanics-based, high-fidelity numerical frameworks** to realistically assess seismic vulnerability of heritage monuments.
•**Probabilistic approaches** enable identification of **most vulnerable zones** rather than relying on single deterministic scenarios.

# Research Gap

Limited studies integrate:

- Full **3D soil–rock–structure interaction**
- **Multiple historical earthquakes**
- **Probabilistic damage metrics**

•Existing assessments rarely provide **spatial vulnerability maps** for large monumental complexes.

•This creates a gap in:

- **Preventive conservation**
- **Risk-informed decision making**
- **Targeted mitigation strategies**

# Research Objectives

To develop a **high-fidelity numerical framework** for seismic vulnerability assessment of monumental heritage.

To apply the framework to the **Giza Plateau**, focusing on:

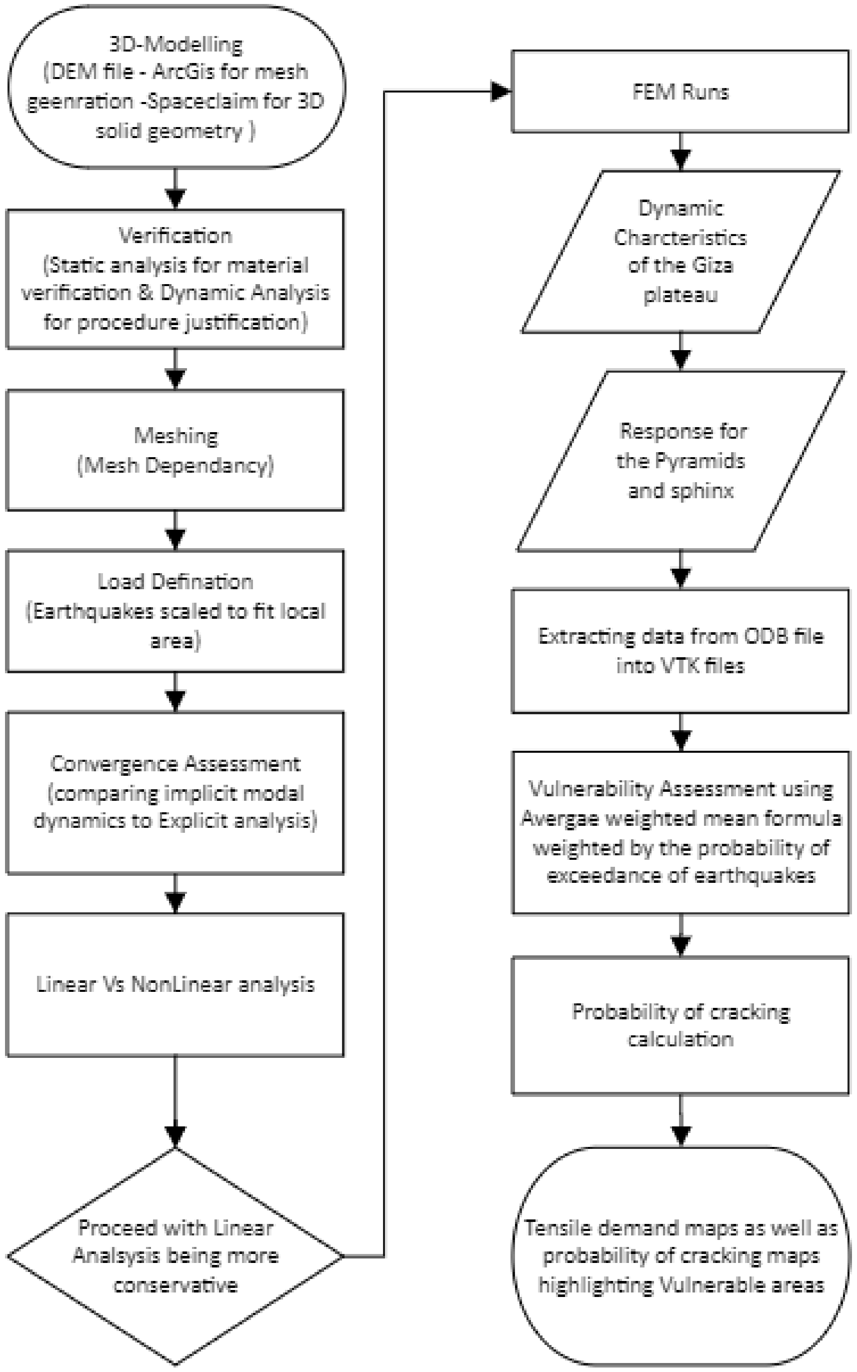
- The **Khufu and Khafre pyramids**
- The **Great Sphinx**

To identify **critical zones susceptible to cracking and damage** under seismic excitation.

To develop a mitigation strategy that help protection of monumental heritage under dynamic loads

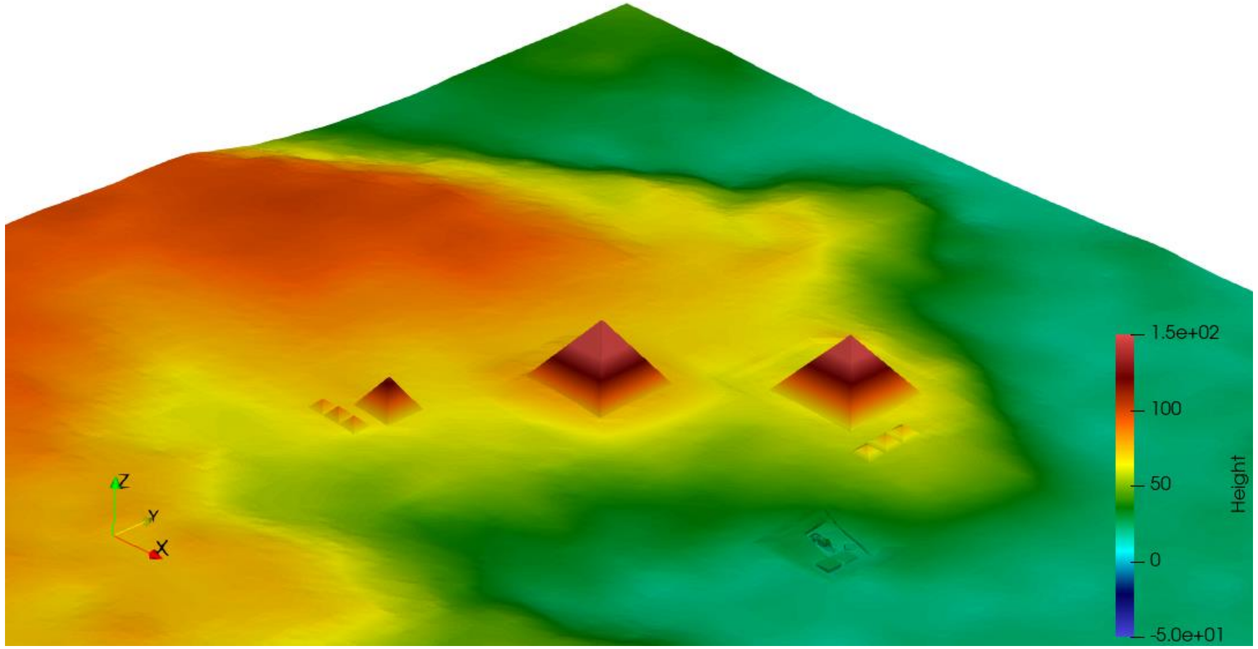
# Methodology

- A **numerical framework** was developed to evaluate seismic vulnerability of monumental heritage.
- The methodology integrates **site-specific seismic input**, **3D finite-element modeling**, and **damage-oriented response metrics**.
- Both **linear and nonlinear dynamic analyses** were conducted to quantify structural response and damage potential



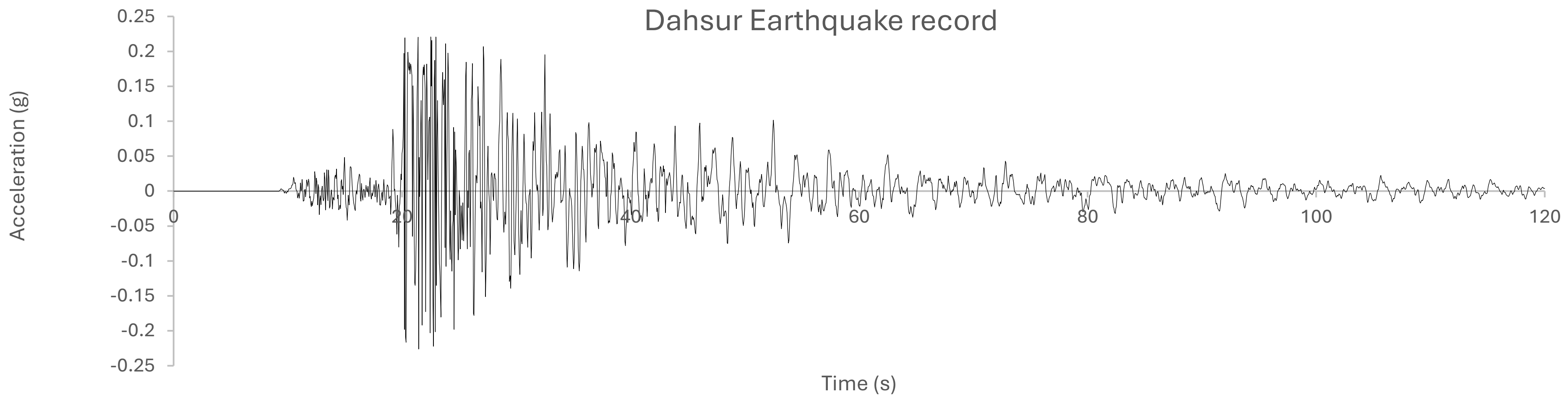
# FE Modelling

- High-fidelity **3D finite-element models** were developed for:
  - Khufu Pyramid
  - Khafre Pyramid
  - Great Sphinx
- Limestone was modelled as a **brittle geomaterial**, capturing:
  - Elastic response
  - Tensile stress sensitivity
  - Nonlinear behaviour relevant to cracking
- The surrounding soil and rock layers were explicitly modelled to account for **soil–rock–structure interaction**



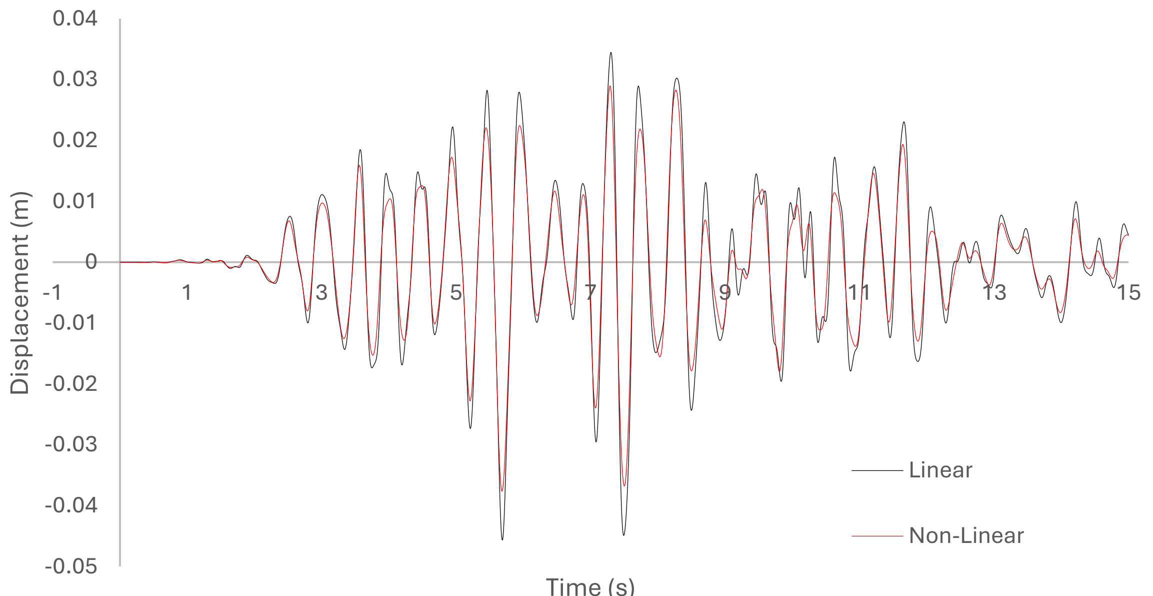
# Seismic Input

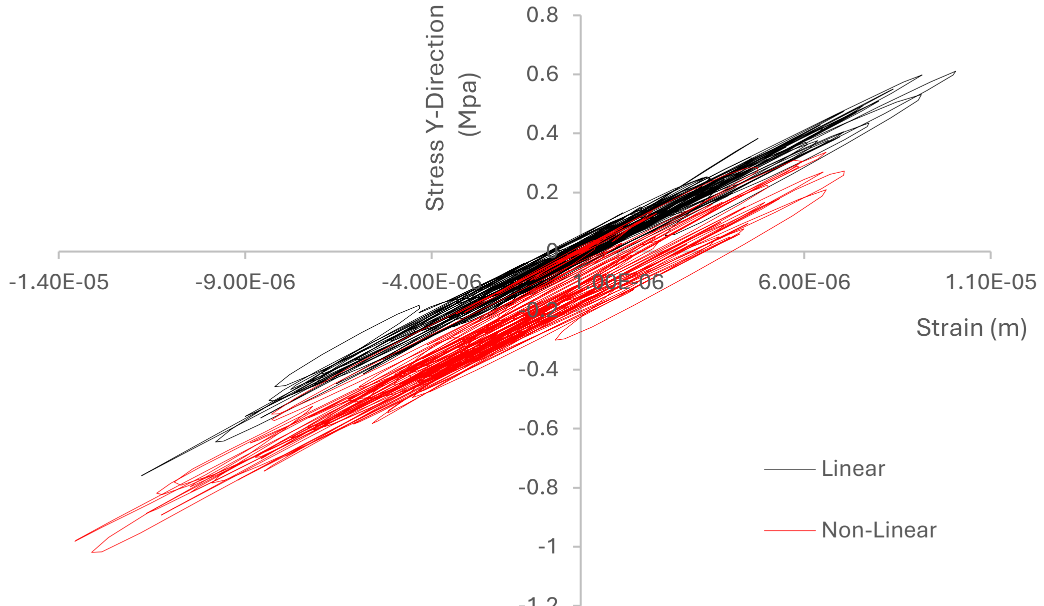
- A set of **historically significant earthquake records** relevant to Egypt and the Eastern Mediterranean was selected.
- Ground motions were:
  - Scaled to represent **regional seismic hazard levels**
  - Applied at the base of the 3D soil domain
- **Time-history dynamic analyses** were performed using:
  - Linear elastic formulation



# Linear Vs Non-Linear Dynamic Analysis

- Given that the study's primary objective is to evaluate vulnerability and crack initiation, which are effectively captured within the elastic range.
- Both analyses produced similar displacement time histories, with maximum amplitudes occurring between 5-9 seconds, indicating consistent global dynamic behavior.
- However, the nonlinear response showed 15% reduced displacement response as well as reduced peak stresses and energy dissipation effects due to material yielding
- Overall, while both analyses show similar stress localization trends, the nonlinear simulation demonstrates a more realistic stress attenuation behavior, confirming the energy dissipation and minor cracking. However, given that the magnitude and distribution patterns remain comparable, the linear analysis was considered efficient for the overall vulnerability assessment of the plateau.



# Vulnerability Assessment

- Seismic demand was evaluated using:
  - Principal tensile stresses
  - Stress concentration patterns
- **Critical cracking zones** were identified based on:
  - Tensile stress exceedance
  - Spatial persistence across events
- An **Average Weighted Mean (AWM)** metric was employed to:
  - Combine responses from multiple earthquakes
  - Reduce dependence on a single ground motion

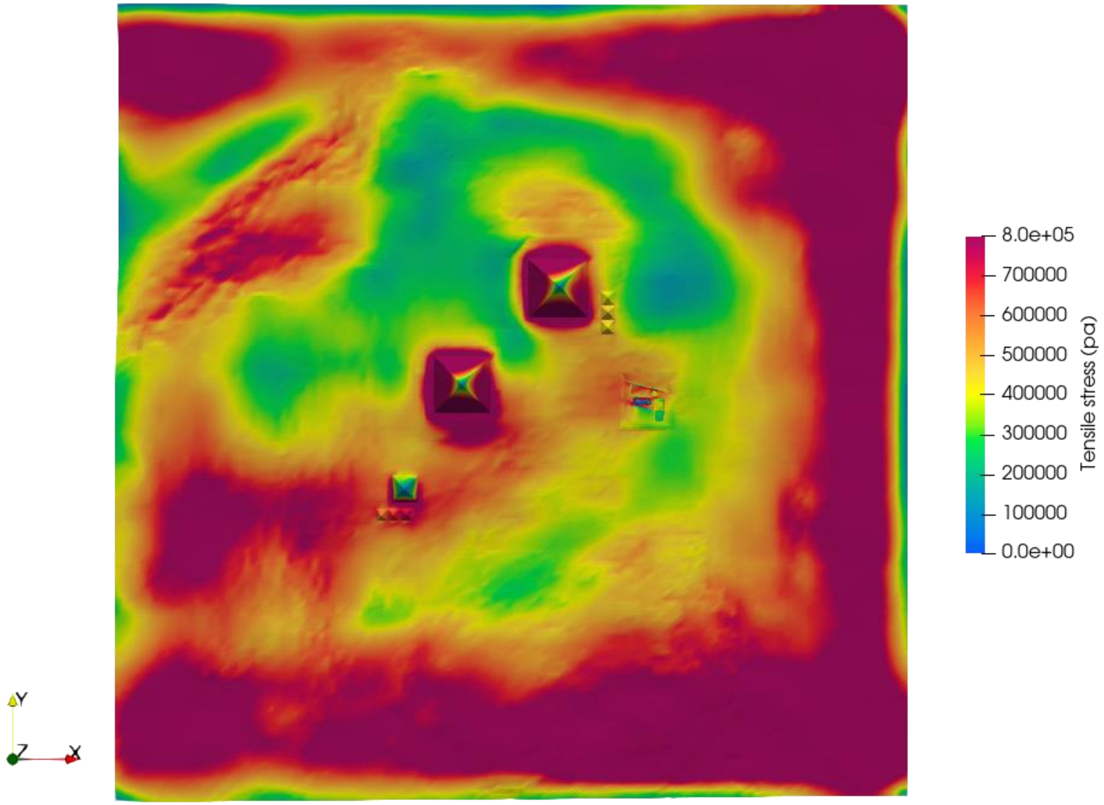
| Earthquakes | Magnitude | N(M) | Probability of Exceedance in 100 Years | Normalized weights for the probability of exceedance |
|---|---|---|---|---|
| Dahshur 1992 | 5.9 | 0.41 | 1.0 | 0.16 |
| Aqaba | 6.2 | 0.19 | 1.0 | 0.16 |
| Greece Kozani | 6.4 | 0.11 | 1.0 | 0.16 |
| Northridge | 6.7 | 0.05 | 1.0 | 0.16 |
| El-Centro | 7.1 | 0.02 | 0.86 | 0.14 |
| Kobe | 7.2 | 0.02 | 0.78 | 0.13 |
| Turkey Duzce | 7.5 | 0.01 | 0.51 | 0.09 |

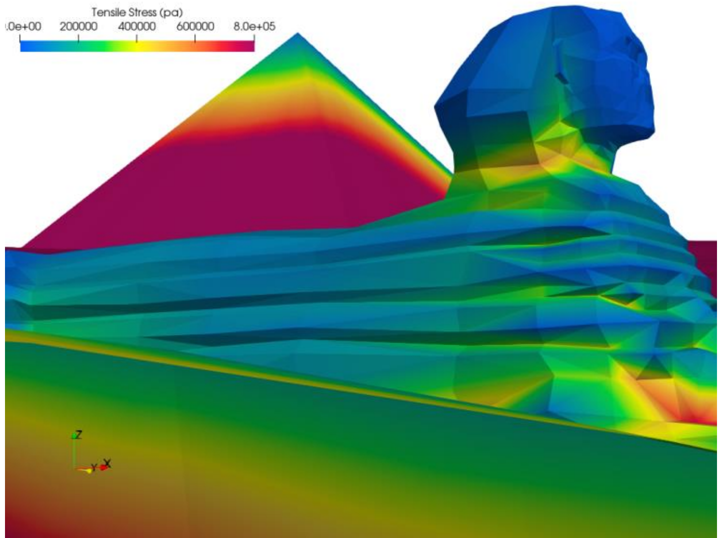
# Spatial Vulnerability Mapping

- Element-wise response data were post-processed to generate:
    - Vulnerability maps
    - Damage-prone zone distributions

- Results were used to identify:
    - Monument-scale vulnerability
    - Localized fragile components (e.g., Sphinx neck and chest)

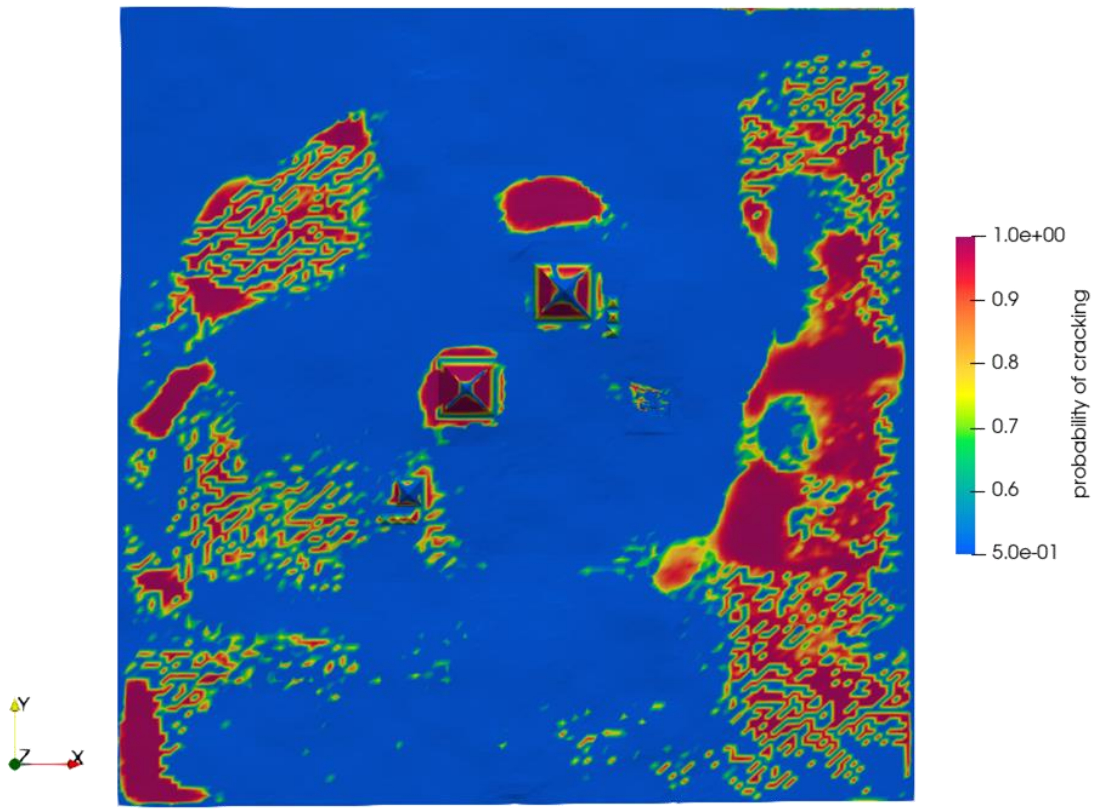
- Consistency of damage patterns across events was used as **internal validation** of the framework.

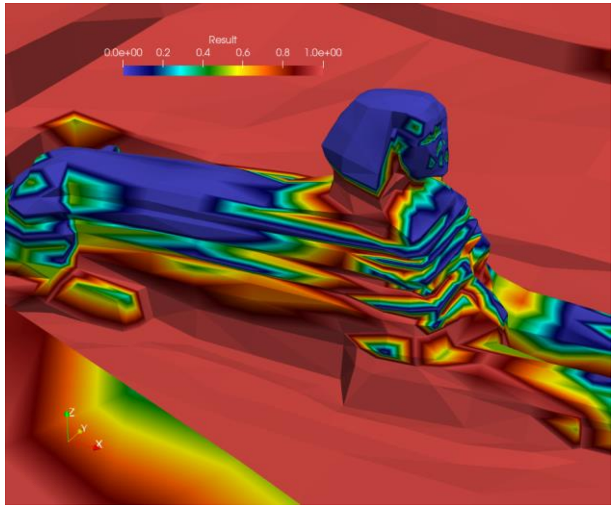


# Probability of cracking

- Limestone monuments exhibit **brittle behaviour**, with cracking initiated when **tensile stresses exceed material capacity.**
- Seismic excitation induces **nonuniform tensile stress distributions**, varying spatially and temporally.
- Crack initiation is treated as a **stress-controlled damage phenomenon** rather than explicit fracture propagation.
- Cracking probability is quantified using a **lognormal fragility function**, widely adopted in seismic risk assessment.
- Zones consistently exceeding tensile limits across events are classified as:
    - **High-probability cracking regions**
- Results enable identification of:
- Monument-scale vulnerable areas
- Localized critical components (e.g., Sphinx neck)



# Engineering Significance

**The probability-based approach supports:**

**Risk-informed conservation planning**

**Targeted strengthening and monitoring**

**Provides a practical alternative to:**

Explicit fracture modelling

Data-intensive damage calibration

**Suitable for heritage structures where:**

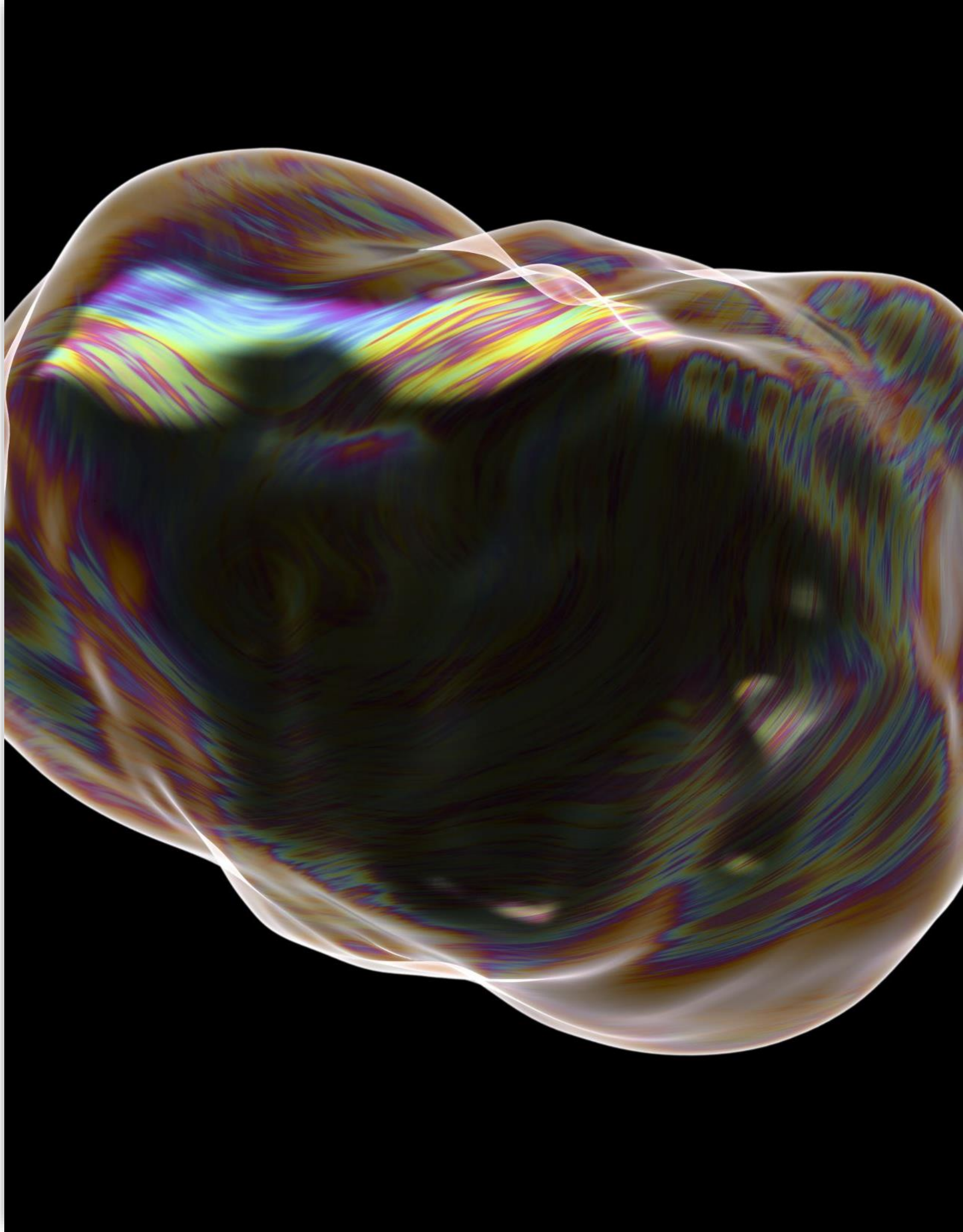
Experimental data are limited

Non-invasive assessment is required

# Mitigation strategy: Reversable Viscoelastic Intervention

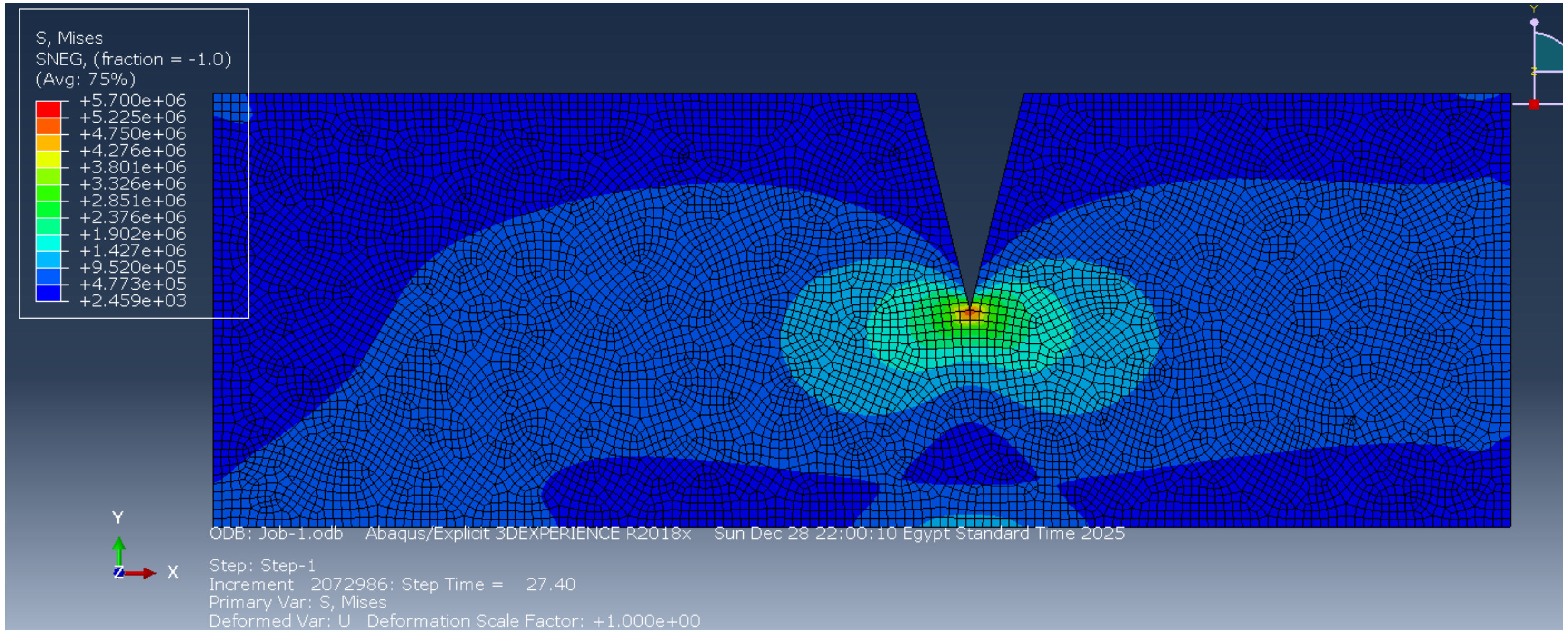
•Seismic-induced cracking in limestone is governed by **localized tensile stress concentration**, particularly at crack tips.
•A **local viscoelastic material** is proposed as a **passive mitigation strategy** to reduce stress amplification.
•The intervention targets **critical zones** identified from fragility-based cracking probability maps.

- The viscoelastic layer acts to:
  - **Dissipate seismic energy**
  - **Redistribute stresses**
- **Reduce peak principal tensile stresses** at crack tips



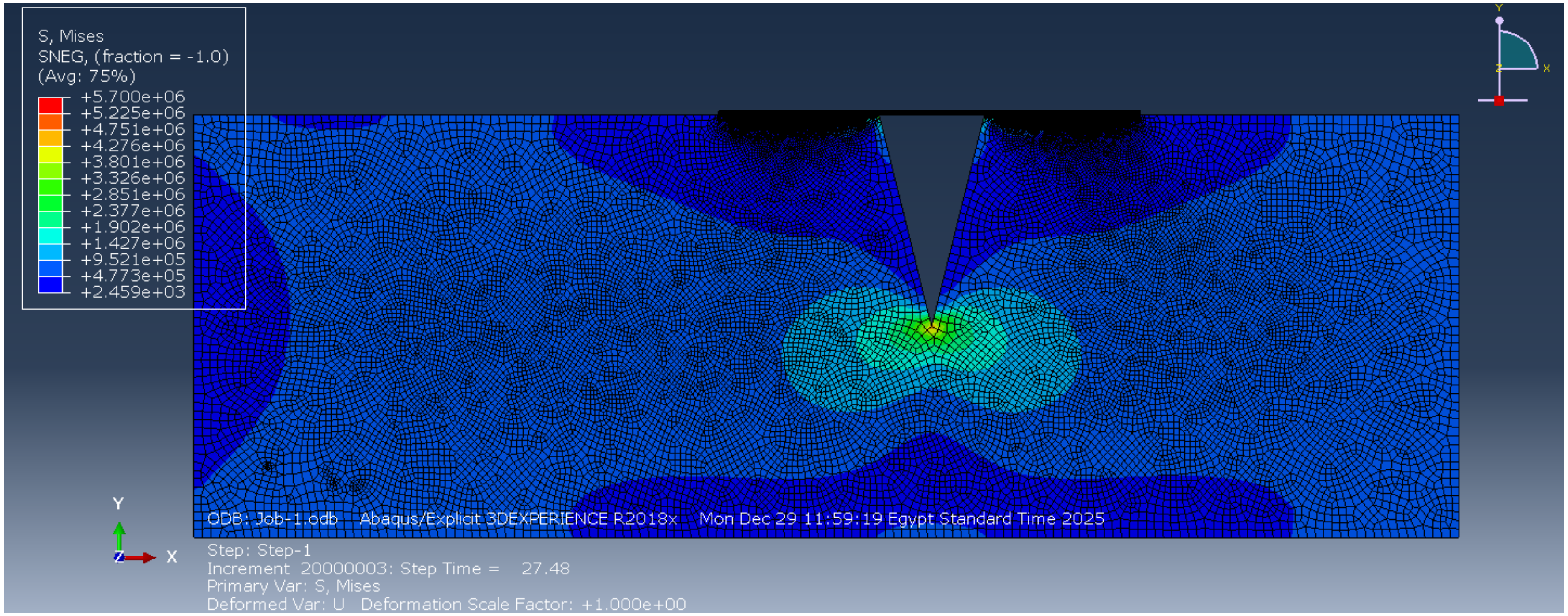
# Viscoelastic Numerical implementation

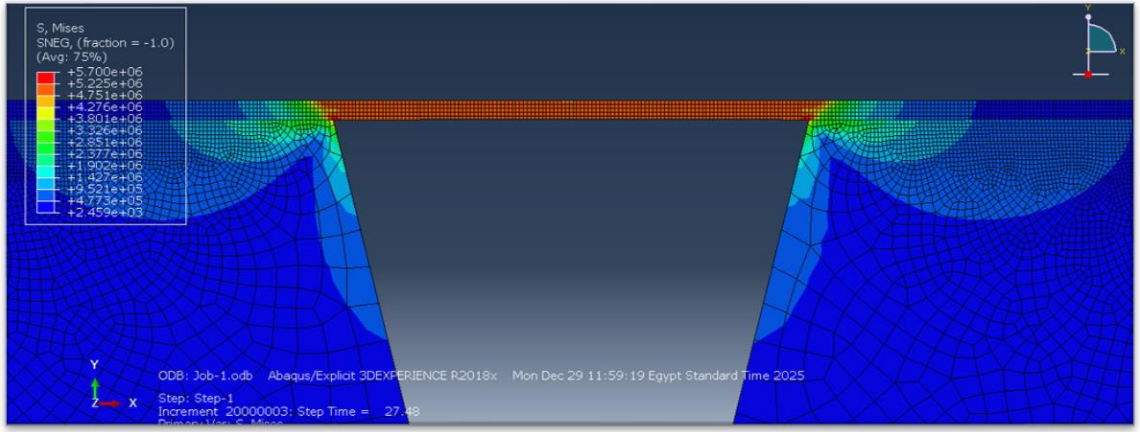
- Viscoelastic behaviour is modelled using: Linear viscoelastic constitutive law (Prony series).
- The material is locally assigned near:
  - Crack tips
  - High-probability cracking regions
- Under dynamic loading, the viscoelastic material exhibits:
  - Time-dependent deformation
  - Hysteretic energy dissipation



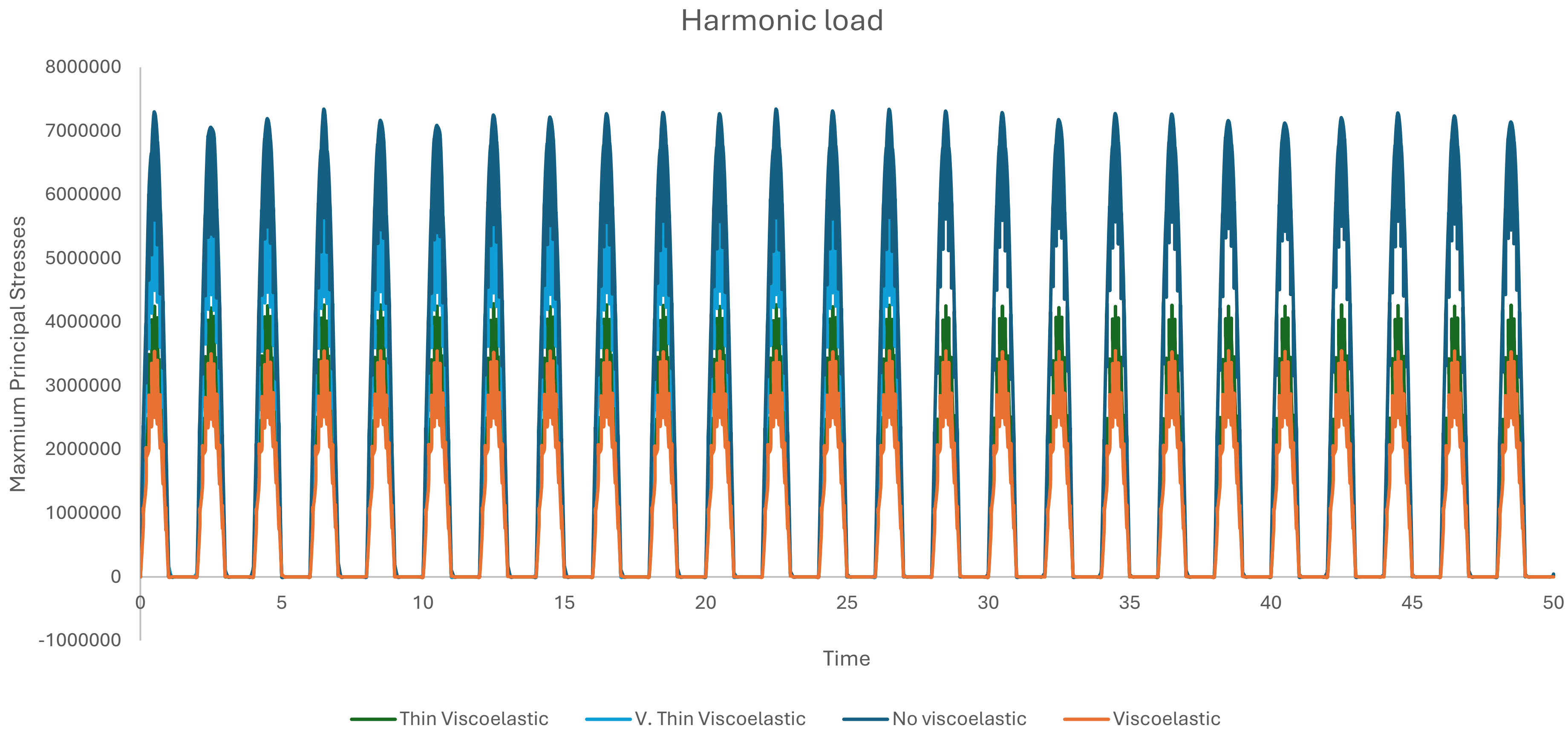
# Viscoelastic Material - Local Effect

- Under dynamic loading, the viscoelastic material exhibits:
  - Time-dependent deformation
  - Hysteretic energy dissipation
- Stress reduction mechanisms include:
  - Relaxation of tensile stress peaks
  - Delay in crack propagation
  - Reduction in stress intensity concentration

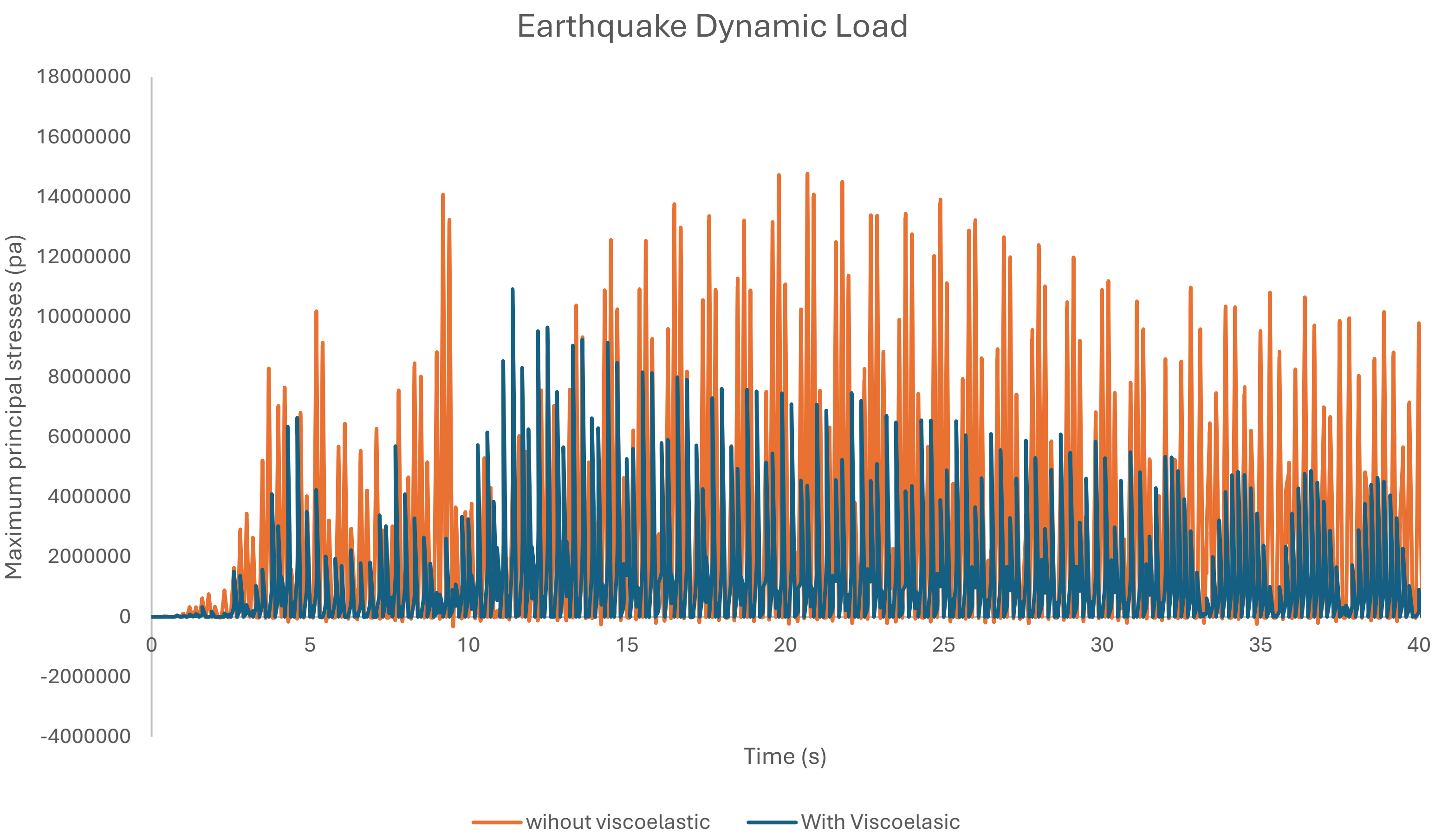


# Viscoelastic Effect under periodic load

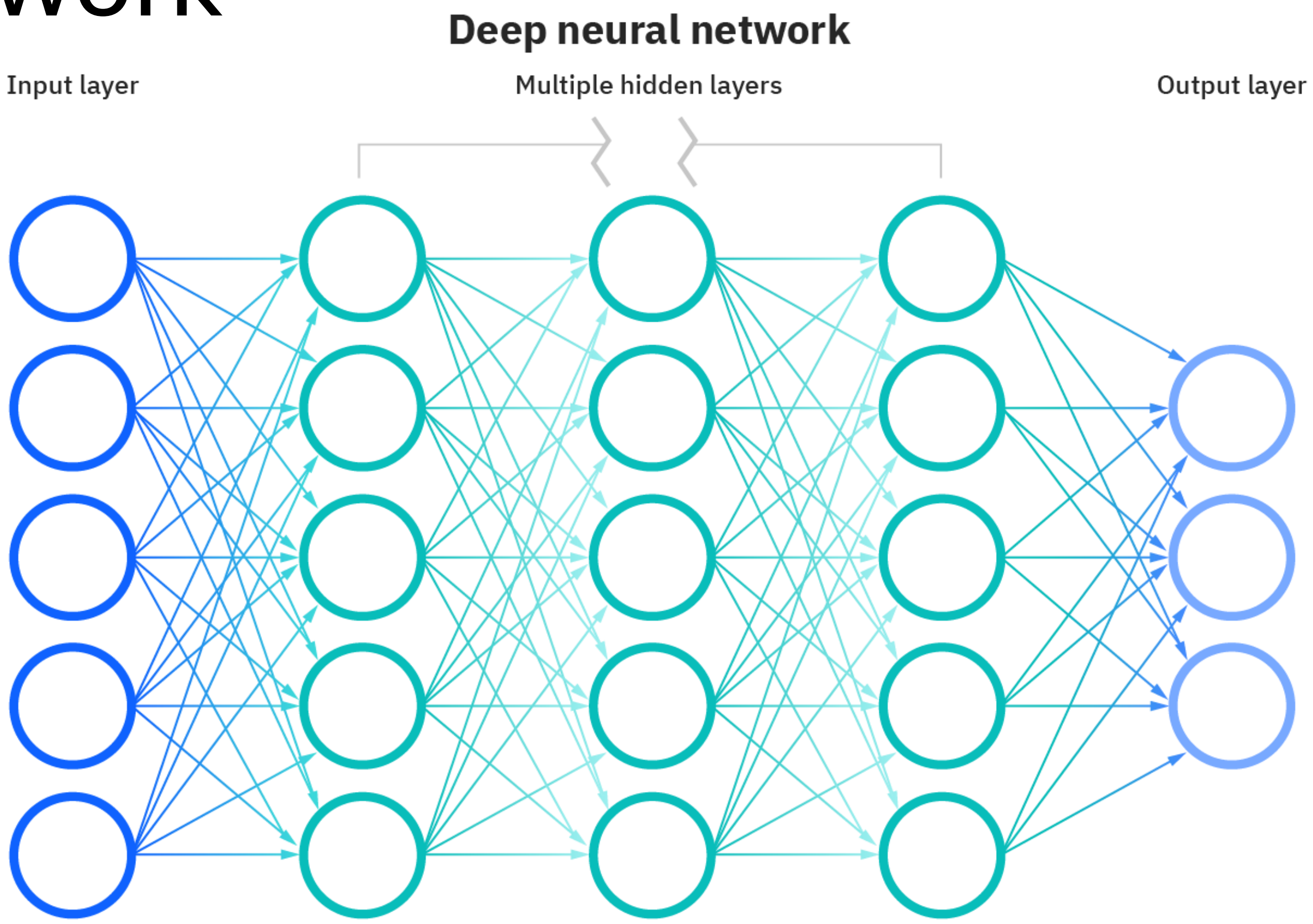


# Viscoelastic Effect under Earthquake load



# Viscoelastic parameters optimization Artificial Neural Network

- To optimize viscoelastic parameters, an **Artificial Neural Network** approach is proposed.
- ANNs allow efficient exploration of parameter space, linking viscoelastic properties to stress reduction performance, and supporting optimal design under limited experimental data.



# Limitations and Future work

- Crack behaviour is represented through **stress-based damage indicators** rather than explicit crack initiation and propagation modelling.
- Extend the current framework to a **fully nonlinear dynamic analysis.**
- The viscoelastic mitigation strategy is evaluated **numerically**, without full-scale experimental or field validation.

# Thank You