Computational Methods and tools : Project Report

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1 Deviation from Project Proposal

Initially we wanted to study the behavior of building when subjected to earthquakes using two different models, the SDOF(Single Degree Of Freedom) and the MDOF (Multiple Degrees Of Freedom). We have slightly deviated from our initial idea.

First we wanted to model the building's displacement using a SDOF model to ease into the subject. It is easier to use but is less realistic. We realized that we didn't have enough time to build this model and it's more realistic version, the MDOF model. Thus we decided to focus on the conception of the MDOF modeling to obtain at the end a result that we can discuss and that can be used to draw conclusion. We also have done the modeling on three different countries and not five, because we didn't find enough data to properly model for Chile. And Turkey was to similar to Greece so we only kept Greece.

2 Introduction

Earthquakes represent one of the most severe types of loading that building structures can experience. Their dynamic, intense, and unpredictable nature exposes the limits of structural systems and reveals progressive damage mechanisms that are difficult to assess without appropriate simulation tools.

The seismic response of these buildings strongly depends on their mechanical properties, height, ductility, and ability to dissipate energy through nonlinear behavior. At the scale of an urban cluster, these differences can lead to highly heterogeneous damage patterns.

The objective of this project is to develop a computational model capable of simulating the dynamic response of a small neighborhood composed of buildings representative of different seismic-resistant construction techniques. Through this study, we compare the seismic performance of buildings designed according to different national construction practices, with the aim of identifying which design approaches provide the highest resilience under severe seismic loading. In addition, the analysis examines, within each construction tradition, how variations in building configuration influence structural response.

The central research question addressed is: how do buildings with different structural designs respond to major earthquakes when considered collectively, and to what extent does progressive degradation affect their overall performance? This work adopts a modeling and comparative analysis perspective, with the goal of providing a coherent interpretation of seismic behavior at the neighborhood scale.

3 Approach used

Table 1: Variables used in the Newmark equations and related computations (ordered by appearance).

Symbol	Description	Symbol	Description
m_j	Mass of story j (kg)	M	Mass matrix (kg)
$a_g(t_i)$	Ground acceleration at time step i (m/s^2)	F_t	Seismic inertial force vector (N)
$u_j(t_i)$	Floor displacement of story j (m)	$\dot{u}_j(t_i)$	Floor velocity of story j (m/s)
$\ddot{u}_j(t_i)$	Floor acceleration of story j (m/s^2)	P_{eff}	Newmark effective load vector (N)
C	Damping matrix (N·s/m)	K_{cur}	Tangent stiffness matrix (N/m)
$k_{cur,j}$	Current stiffness of story j (N/m)	K_{eff}	Newmark effective stiffness (N/m)
a_0–a_5	Newmark constants	β, γ	Newmark parameters
λ	Generalized eigenvalues	ω_1, ω_2	Circular frequencies (rad/s)
ξ	Damping ratio	n	Number of stories
$\text{dr}_j(t_i)$	Inter-story drift of story j		

Seismic inertial force. The excitation due to ground acceleration at t i + 1 produces a body force vector

$$\mathbf{F}t = -M_{\mathbf{1}}\text{ag}(ti+1) \quad (\text{entrywise } F_{t,j} = -m_j\text{ag}(t_{i+1}). \tag{1}$$

Effective load (Newmark one-step).

$$\mathbf{P}_{\text{eff}} = \mathbf{F}_t + M\big(a_0\mathbf{u}_i + a_2\dot{\mathbf{u}}_i + a_3\ddot{\mathbf{u}}_i\big) + C\big(a_1\mathbf{u}_i + a_4\dot{\mathbf{u}}_i + a_5\ddot{\mathbf{u}}_i\big). \tag{2}$$

Tangent / effective stiffness assembly

Using the current per-story stiffnesses k_{cur} the tangent stiffness matrix K_{cur} is assembled (same shear assembly as above). The Newmark effective stiffness matrix at a timestep is

$$K_{\text{eff}} = K_{\text{cur}} + a_0 M + a_1 C. \tag{3}$$

Rayleigh damping. From the generalized eigenproblem $K_{\text{initial}}\phi = \lambda M\phi$, the circular frequencies are $\omega = \sqrt{\lambda}$. For two modes,

$$a_0^{\text{ray}} = \frac{2\xi\omega_1\omega_2}{\omega_1+\omega_2}, \quad a_1^{\text{ray}} = \frac{2\xi}{\omega_1+\omega_2}, \quad C = a_0^{\text{ray}} M + a_1^{\text{ray}} K_{\text{initial}},$$

and for a single mode, $C = 2\xi\omega_1 M$.

Derived quantities. The maximum drift and stiffness reduction are

$$\text{maxdr}_j = \max|d_j(t_i)|, \quad \text{Reduction}(\%) = \frac{k_j^{\text{elastic}} - k_j^{\text{final}}}{k_j^{\text{elastic}}} \times 100.$$

Inter-story drifts. Relative drifts are computed as $d_1 = u_1/h_1$ and $d_j = (u_j - u_{j-1})/h_j$ for $j = 2, \ldots, n$.

4 Results

To keep the report concise and results-focused, we merged these detailed graphs and raw outputs into a single, summarized visual graphs. This allows readers to immediately see the final performance indicators—such as maximum drift and overall damage state —without navigating multiple technical plots.

In appendix we can find the three graphs that trace the evolution of our values.

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AT2=/home/munongo/Desktop/myfiles/CMT/Project CMT/keep going/data/earthquake_data.AT2, dt=0.01, npts=4172, PGA_g=1.219

Country         Building            Stories MaxDisp (mm)   StiffRed (%) State
------------------------------------------------------------------------------------
Ancient Greece  GR_Building_1       2      24.3           43.2         Severe
Ancient Greece  GR_Building_2       3      68.7           35.0         Severe
Ancient Greece  GR_Building_3       1      5.6            14.3         Yielding
Ancient Greece  GR_Building_4       4      23.3           32.0         Severe
Ancient Japan   JP_Building_1       4      130.9          2.4          Yielding
Ancient Japan   JP_Building_2       2      32.3           0.4          Yielding
Ancient Japan   JP_Building_3       3      52.8           0.7          Yielding
Ancient Japan   JP_Building_4       2      2.6            0.0          Elastic
USA             US_Building_1       5      439.5          21.6         Moderate
USA             US_Building_2       4      253.0          17.7         Moderate
USA             US_Building_3       8      579.8          18.3         Moderate
USA             US_Building_4       2      118.0          10.7         Yielding
```

Figure 1: Enter Caption

The table presents the seismic performance of 12 buildings from three regions (Ancient Greece, Ancient Japan, and the USA) subjected to the same ground motion. Performance is measured by the maximum story drift (MaxMsg in mm) and stiffness reduction (StiffRed in %), with an assigned qualitative State.

Key Findings:

- **Maximum Drift:**
  - US buildings experienced the largest displacement(579.8 mm), with US_Building_3 (8 stories).
  - Japanese buildings showed moderate displacement (2.6 mm to 130.9 mm), except for JP_Building_4, which remained nearly at rest.
  - Greek buildings had lower displacement(5.9 mm to 68.7 mm) compared to US buildings, but similar to Japanese ones in some cases.
- **Stiffness Reduction:**
  - Japanese buildings (except JP_Building_4) suffered minimal stiffness loss (0.0–2.4%), indicating a primarily elastic or yielding response without significant degradation.

  - Greek buildings showed high stiffness reduction (14.3–43.2%), suggesting substantial inelastic damage.
  - US buildings had moderate stiffness loss (10.7–21.6%).

- **Damage States:**
  - **Ancient Greece:** 3 out of 4 buildings in a *Severe* state; one in *Yielding*.
  - **Ancient Japan:** 3 in *Yielding*, 1 in *Elastic*.
  - **USA:** 3 in *Moderate*, 1 in *Yielding*.

The results demonstrate a strong internal consistency, with a logical and explainable relationship between observed drifts, stiffness loss, and assigned damage states. This coherence, evident both within each building group and across the different regional typologies, validates the robustness of our numerical model. The simulated structural response remains physically plausible and accurately reflects the expected mechanical behavior for each of the studied construction systems. Therefore, the proposed model yields satisfactory.

5 Discussion

The results reveal clear regional differences in structural vulnerability and seismic design philosophy:

- **Ancient Greek buildings** experienced high stiffness degradation despite relatively lower story displacements. This suggests brittle structural behavior—likely due to masonry or low-ductility materials—where stiffness is lost rapidly upon yielding, leading to *Severe* states even under modest displacements.

- **Ancient Japanese buildings** exhibited minimal stiffness reduction, even with significant displacements (e.g., JP_Building_1: 130.9 mm drift, only 2.4% stiffness loss). This indicates a highly ductile and resilient design, likely incorporating flexible wooden frames capable of large deformations without major stiffness degradation. JP_Building_4 remained *Elastic*, showing possible over-design or a low-height advantage.

- **US buildings** showed the largest absolute displacements but were classified mainly as *Moderate* damage. This reflects modern ductile design principles, where controlled inelastic deformation is accepted to dissipate energy. Stiffness loss is moderate, implying retained post-yield integrity.

Engineering Implications:

- The Greek examples highlight the risk of stiffness-based damage in non-ductile systems.

- The Japanese models demonstrate the effectiveness of traditional flexible, energy-absorbing designs.

- US structures illustrate the success of modern seismic design in limiting damage state despite large displacements, prioritizing life safety over stiffness retention.

Limitations: The results depend on the single ground motion used; different frequency content could alter the outcomes, We took the ground acceleration only in one direction and not three. ((Material modeling assumptions (not provided) also influence stiffness degradation trends.))

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6 Conclusion

This comparative analysis of the seismic performance of structures subjected to high-intensity ground motion reveals fundamental information on the importance of material rigidity, building height, and the number of storys.

The divergent performance of the three regional typologies underscores that displacement alone is an insufficient indicator of seismic damage. While US buildings exhibited the largest displacements, their controlled, ductile response limited structural degradation to a moderate level. In contrast, Ancient Greek buildings suffered severe damage at relatively lower drifts due to rapid stiffness loss—a hallmark of brittle material failure. Ancient Japanese structures demonstrated that significant deformation capacity can coexist with minimal stiffness degradation, a principle of resilience highly relevant to modern seismic design.

These findings emphasize that stiffness retention and damage progression are critical metrics for assessing seismic vulnerability, particularly for historical and non-ductile systems.

Ultimately, the study confirms that performance-based seismic design succeeds in prioritizing life safety, as seen in the US examples, but also highlights the need for multi-criteria assessment frameworks that account for both deformation and degradation.

7 Authorship statement

Luc-Faustin Kazembe Munongo:

-Done all the Github part

-Found how to model stiffness degradation

-Finding how to use/create MDOF model

-Managed to redirect graphs into separated documents for each country

-Partially created all the codes to plot for inter story drifts.

Mathis Olivier Horst:

-Finding all the sources to get values for each type of building

-Wrote the report

-Created the functions to get k and m values for storys

-Partially created all the codes to plot for inter story drifts.

8 Annexe

Equation 2:

Newmark coefficients. The constants used in the time-stepping scheme are

$$a_0 = \frac{1}{\beta\,\Delta t^2}, \qquad a_1 = \frac{\gamma}{\beta\,\Delta t}, \qquad a_2 = \frac{1}{\beta\,\Delta t}, \qquad a_3 = \frac{1}{2\beta} - 1, \qquad a_4 = \frac{\gamma}{\beta} - 1, \qquad a_5 = \Delta t\left(\frac{\gamma}{2\beta} - 1\right)$$

where $\Delta t = dt$ and Newmark parameters $(\beta, \gamma) = (1/4, 1/2)$.

Mise à jour des vitesses et accélérations (Newmark)

$$\dot{u}_{i+1} = a_1(u_{i+1} - u_i) - a_4\dot{u}_i - a5\ddot{u}_i$$

$$\ddot{u}_{i+1} = a_0(u_{i+1} - u_i) - a_2\dot{u}_i - a3\ddot{u}_i$$

$$M_j = m_j\big(a_0 u_j(t_i) + a_2\dot{u}_j(t_i) + a_3\ddot{u}_j(t_i)\big),$$
$$C_j = \sum_{k=1}^{n} C_{jk}\big(a_1 u_k(t_i) + a_4\dot{u}_k(t_i) + a_5\ddot{u}_k(t_i)\big).$$

Graph analysis: Figure 2 Damage Evolution Diagram: Shows how structural damage progresses over time across all five stories of the US building, illustrating stiffness degradation and yielding behavior. It highlights the story that suffers the most from a loss of rigidity.

Figure 3 Displacement Time Histories: Displays the displacement response of each story throughout the earthquake duration, with amplitudes increasing toward the top floor.

Figure 4 Numerical Results Summary: Provides the key performance metrics extracted from the analysis, including maximum drifts, plastic drifts, stiffness reduction, and damage states per story.

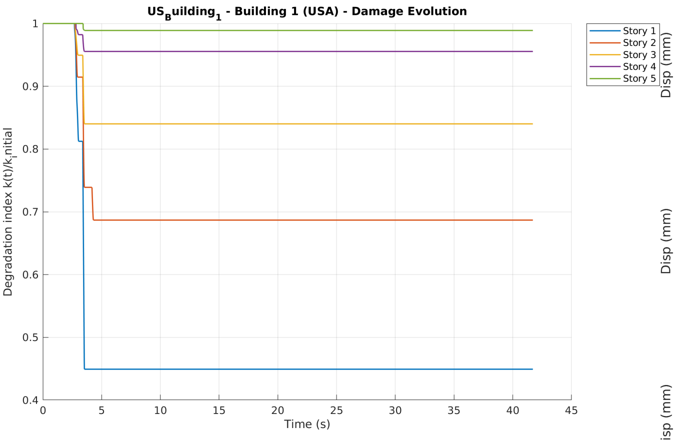

Figure 2: Evolution of the degradation index for US_Building_1

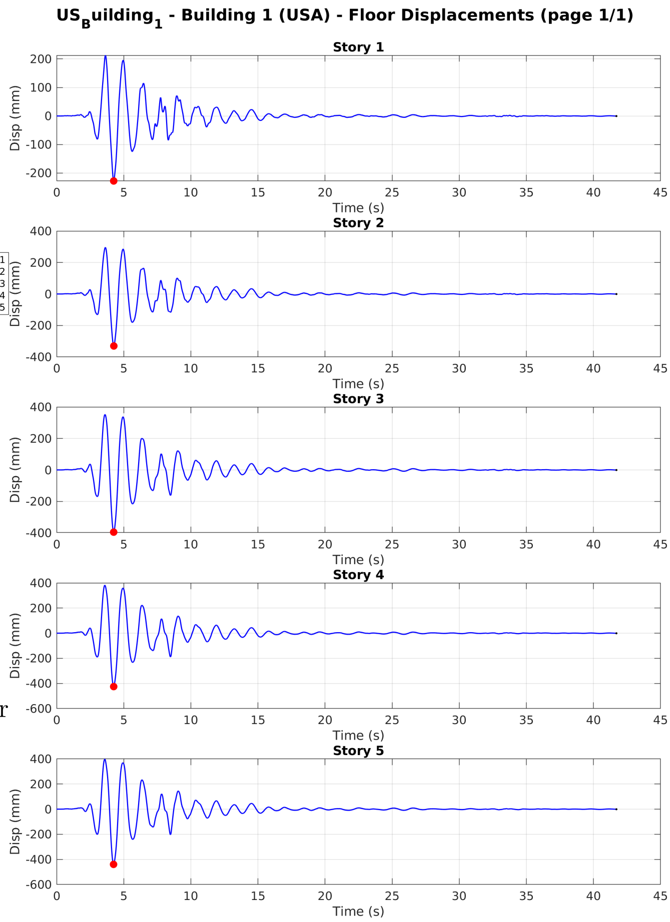

Figure 3: Damage distribution by floor

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EARTHQUAKE RECORD:
File: /home/munongo/Downloads/projet_cmt-main/data/earthquake_data.AT2
PGA: 1.219 g
Duration: 41.7 s
Time step: 0.0100 s | Number of steps: 4172

DISPLACEMENT RESULTS:
Floor    Max Disp (mm)    Residual Disp (mm) Drift Ratio (%)
------------------------------------------------------------
1        227.8            -0.4             5.695
2        330.4            -0.6             2.741
3        395.3            -0.7             1.866
4        425.0            -0.7             0.955
5        439.5            -0.8             0.472

FINAL RESULTS:
Story    Max Drift(%) Plastic Drift(%) Stiffness(%)    Damage State         Yielded?
1        5.695        5.295            44.9            Moderate             YES
2        2.741        2.341            68.7            Yielding             YES
3        1.866        1.466            84.0            Yielding             YES
4        0.955        0.555            95.5            Yielding             YES
5        0.472        0.072            98.9            Yielding             YES

OVERALL BUILDING CONDITION:
MODERATE DAMAGE - Noticeable stiffness reduction

NONLINEAR ANALYSIS STATISTICS:
Yielded stories: 5/5 (100%)
Average stiffness reduction: 21.6%
Maximum plastic drift: 5.295%
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Figure 4: Comparison of inter-floor displacements