“Performance Analysis of Multi-Layer Concrete Structures for Security Centers Using Dynamic Simulations”

Vahid Hatami Dezdarani[1]
Dept. of Civil Engineering Structure, Islamic Azad University of Shoushtar, Khuzestan, Iran
vahid.hatami2019@yahoo.com

Dr. Mohammad Hossein Pour Mohammadi[2]
Faculty. Specialized doctorate in water structures Of Shoushtar Azad University, Khuzestan, Iran
MH.Pourmohammadi@iau.ac.ir

Abstract

This paper explores the performance analysis of multi-layer concrete structures specifically designed for security centers and high-risk governmental facilities. These structures face unique challenges due to the nature of the threats they are exposed to, such as explosions, seismic activities, and impact from high-velocity objects. To address these challenges, multi-layered concrete systems offer a promising solution by combining different materials in layers to maximize resistance and energy absorption[1]. In this study, we focus on understanding how the layered design impacts the overall structural integrity and durability under dynamic loading conditions.

Security centers are critical infrastructures that require advanced structural designs to ensure the safety of personnel, assets, and sensitive information. Traditional monolithic concrete structures, while robust, often fail to provide adequate protection under extreme forces. Multi-layer concrete structures, on the other hand, offer improved performance by distributing stresses more effectively and limiting crack propagation2[2]. This study employs advanced finite element analysis (FEA) simulations, using tools such as ANSYS and Abaqus, to evaluate the performance of these systems under various dynamic load scenarios, including blast loads, seismic events, and high-velocity impacts.
The multi-layered systems studied in this paper consist of a combination of regular concrete, highstrength concrete (HSC), and fiber-reinforced concrete (FRC). Each layer plays a distinct role in enhancing the overall structural resilience: the outer layer absorbs the initial impact and disperses the energy across the structure, while the inner layers provide strength and stability, minimizing deformation and damage. The FRC layer, in particular, significantly enhances tensile strength, mitigating the risk of sudden structural failure.

Our simulations were designed to model realistic scenarios that these structures would likely encounter. For example, in the blast load analysis, an explosion was simulated at varying distances from the structure to evaluate how well the multi-layer system could absorb and dissipate the shockwave. The results showed that multi-layer systems significantly outperformed traditional concrete structures in terms of energy absorption and crack mitigation. The outermost layer bore the brunt of the blast, while inner layers remained largely intact, protecting the core structure. This

layered approach drastically reduced stress concentrations, limiting the severity and extent of crack propagation.

In the seismic performance simulations, multi-layer systems demonstrated enhanced resilience by reducing peak displacements and distributing seismic forces more uniformly. This allowed the structure to maintain its integrity longer than its monolithic counterparts, which typically failed earlier under the same conditions. The seismic response of these multi-layered structures was also more controlled, with less damage occurring in critical areas such as joints and connections. By analyzing the time-history response and frequency domain behavior, we were able to observe the benefits of the layered system in mitigating resonance effects and reducing overall structural vibrations during earthquakes.

Another critical aspect examined in this research is the impact resistance of the multi-layer systems. Simulations modeled high-velocity impacts, such as projectiles or debris from explosions, hitting the structure. The FRC layers proved particularly effective in preventing penetration and absorbing the kinetic energy of the impact, limiting damage to the inner layers. This finding is crucial for designing structures intended to withstand targeted attacks or accidental collisions.

Keywords

Multi-layer concrete structures, Safety design, Material optimization, Seismic performance, Dynamic simulations, Impact resistance, Structural resilience, High-strength concrete (HSC), Finite element analysis (FEA), Fiber-reinforced concrete (FRC)

Introduction

In an era marked by increasing global threats, including terrorism, natural disasters, and other high-impact events, the safety and security of critical infrastructure have become paramount. Government buildings, military installations, and other sensitive facilities must be designed to withstand various hazards, including explosions, seismic activities, and projectile impacts. As such, the traditional methods of designing concrete structures are being reevaluated in light of these pressing demands. While conventional monolithic concrete designs have long been the standard, their performance under extreme dynamic loads often proves inadequate. This has led to the exploration of alternative design approaches, particularly multi-layer concrete systems, which present unique advantages in enhancing structural resilience and safety.

Multi-layer concrete structures involve the strategic arrangement of different concrete materials in layers, each engineered to fulfill specific functions in the overall structural performance. This approach allows for a more effective distribution of stress and energy absorption during dynamic loading conditions. Unlike monolithic designs, which may fracture or collapse under severe impact, multi-layer systems can dissipate forces across multiple layers, reducing the risk of catastrophic failure. By utilizing combinations of standard concrete, high-strength concrete (HSC), and fiberreinforced concrete (FRC), these systems can be tailored to meet the unique demands posed by their operational environments. The outer layers, often composed of materials designed to absorb impact and energy, protect the inner layers that provide structural integrity and strength.

The performance of multi-layer concrete structures under dynamic loads is particularly critical for security centers. These facilities are often tasked with safeguarding sensitive information and personnel, necessitating designs that can withstand the effects of blasts, earthquakes, and other extreme forces. The consequences of structural failure in such environments can be dire, underscoring the need for advanced engineering solutions. To evaluate the effectiveness of multilayer systems, this study employs advanced finite element analysis (FEA) simulations to model the response of these structures under various dynamic load scenarios, including explosive blasts, seismic events, and high-velocity impacts.

Research into multi-layer concrete systems is not only pertinent to improving the safety of critical infrastructure but also holds promise for enhancing the efficiency of material use. By distributing stresses more effectively and limiting localized damage, these designs can reduce the amount of material required for construction while still achieving the necessary levels of protection. This approach aligns with current trends in sustainable construction, where optimizing material usage and minimizing waste are increasingly important considerations.

Existing literature has explored various aspects of concrete structures for security applications, including material innovations and design methodologies. However, there remains a significant gap in comprehensive analyses that specifically focus on the dynamic performance of multi-layer systems in real-world scenarios. By addressing this gap, this paper aims to provide valuable insights into the design and implementation of multi-layer concrete structures for security centers.

The objectives of this study are twofold: first, to assess the performance of multi-layer concrete systems under simulated dynamic loading conditions; and second, to compare their effectiveness against traditional monolithic designs. By employing sophisticated simulation tools such as ANSYS and Abaqus, the research seeks to identify the key factors contributing to the enhanced resilience of multi-layer structures, thereby offering recommendations for their application in high-security environments.

In summary, the increasing threats faced by critical infrastructure necessitate innovative approaches to structural design. Multi-layer concrete systems present a promising solution by combining the strengths of various materials to enhance energy absorption and structural integrity. Through rigorous analysis and simulation, this study aims to contribute to the body of knowledge on resilient construction practices, ultimately guiding future developments in the design of secure facilities that protect against the myriad threats of our time.

Materials and Methods

1. Materials

This study investigates the performance of multi-layer concrete structures composed of three primary materials: standard concrete, high-strength concrete (HSC), and fiber-reinforced concrete (FRC). The specific properties and characteristics of these materials are outlined below:

•**Standard Concrete**: Standard concrete is utilized as the baseline material in this study. It is composed of Portland cement, water, aggregates (fine and coarse), and admixtures to enhance workability and durability. The compressive strength of standard concrete used in this study is approximately 30 MPa, which is suitable for general construction applications. This material serves as the outer layer in the multi-layer configuration to provide basic structural support and impact resistance.

- **High-Strength Concrete (HSC)**: High-strength concrete is used for its superior compressive strength and durability compared to standard concrete. It is designed to withstand high loads and is typically composed of a lower water-to-cement ratio, high-quality aggregates, and specialized admixtures. The compressive strength of HSC in this study is approximately 70 MPa. HSC is utilized in the inner layers of the multi-layer structure to enhance load-bearing capacity and improve overall stability.
- **Fiber-Reinforced Concrete (FRC)**: Fiber-reinforced concrete incorporates discrete fibers into the concrete mix to enhance its tensile strength and ductility. In this study, polypropylene fibers are used due to their effectiveness in reducing crack propagation and improving the material's resistance to impact and fatigue. The FRC layer is crucial for dissipating energy during dynamic loading events, thus reducing the likelihood of catastrophic failure. The fiber content in the concrete mix is approximately 0.5% by volume, which has been shown to significantly improve structural performance.

2. Multi-Layer Structure Design

The multi-layer concrete system designed for this study consists of three distinct layers, each with specific thicknesses and material compositions. The overall configuration is as follows:

- **Outer Layer**: Composed of standard concrete with a thickness of 15 cm. This layer acts as the first line of defense against dynamic loads, absorbing initial impacts and distributing stresses.
- **Middle Layer**: Composed of high-strength concrete with a thickness of 10 cm. This layer provides additional strength and stability, enhancing the overall load-bearing capacity of the structure.
- **Inner Layer**: Composed of fiber-reinforced concrete with a thickness of 5 cm. This layer is designed to absorb energy and mitigate the propagation of cracks, ensuring the integrity of the structure under extreme conditions.

The total thickness of the multi-layer system is 30 cm, and the layers are bonded together using epoxy resin to enhance interlayer adhesion and improve structural continuity.

3. Simulation Tools and Techniques

To evaluate the performance of the multi-layer concrete structures under dynamic loading conditions, this study employs advanced finite element analysis (FEA) simulations. The following tools and techniques are utilized in the analysis:

•**Finite Element Analysis Software**: ANSYS and Abaqus are the primary software tools used for simulating the behavior of the multi-layer concrete structures under various loading scenarios. These programs allow for detailed modeling of complex geometries, material behaviors, and loading conditions, providing accurate predictions of structural performance.

•**Model Setup**: The multi-layer concrete structure is modeled in 3D using the software's preprocessing capabilities. The dimensions of each layer, material properties, and boundary conditions are defined to replicate real-world scenarios. The outer surfaces of the model are subjected to dynamic loads, while the base is fixed to represent a realistic foundation scenario.

•**Dynamic Load Simulations**: **Three types of dynamic loads are simulated:**

•**Blast Load Analysis**: A blast load is applied using the ConWep function in ANSYS, which models the pressure and impulse generated by an explosion. The blast wave is applied to the outer layer of the structure at varying distances to assess its energy absorption capabilities.

•**Seismic Load Analysis**: The seismic response is modeled using time-history analysis, which simulates ground motion during an earthquake. A predefined acceleration record is applied to the structure to evaluate its behavior under dynamic seismic loading.

•**High-Velocity Impact Analysis**: Impact loads are modeled by simulating a projectile striking the structure at high velocity. The simulation assesses the ability of the multi-layer system to resist penetration and limit damage.

4. Performance Evaluation Criteria

The performance of the multi-layer concrete structures is evaluated based on several key indicators:

•**Energy Absorption**: The amount of energy absorbed by the structure during dynamic loading is calculated to assess its effectiveness in mitigating impacts. This is determined by analyzing the stress-strain relationships and deformation patterns.

•**Crack Propagation**: The extent and pattern of crack formation in the multi-layer structure are examined using post-simulation analysis. The number, length, and severity of cracks are quantified to understand how well the multi-layer system resists crack propagation compared to monolithic designs.

•**Structural Deformation**: The overall deformation of the structure under dynamic loads is measured to evaluate its stability. Maximum deflections are recorded and compared across different loading scenarios.

•**Failure Modes**: The modes of failure experienced by the multi-layer structure during simulations are analyzed to identify vulnerabilities and areas for improvement. Different types of failure, such as flexural failure, shear failure, and punching shear, are documented.

5. Validation of Results

To ensure the accuracy and reliability of the simulation results, the following validation procedures are implemented:

•**Comparative Analysis**: The performance of the multi-layer concrete structure is compared to that of traditional monolithic concrete structures under identical loading conditions. This comparison helps establish the efficacy of the multi-layer design.

•**Sensitivity Analysis**: A sensitivity analysis is conducted to assess the impact of varying material properties and layer thicknesses on the structural performance. This analysis helps identify optimal configurations for enhanced resilience.

•**Physical Testing (Future Work)**: Although not included in this study, future work will involve physical testing of multi-layer concrete prototypes to validate the simulation results and provide further insights into real-world performance.

Analysis of Multi-Layer Concrete Structures

1. Overview of Analytical Methodology

The performance of multi-layer concrete structures under dynamic loading conditions was analyzed using advanced finite element analysis (FEA) tools. The primary objectives of the analysis were to evaluate the energy absorption capacity, crack propagation behavior, and structural deformation characteristics of the multi-layer configuration compared to traditional monolithic structures. This section details the analysis procedures, presents the results of the simulations, and provides insights into the structural performance of the multi-layer system.

2. Simulation Setup and Parameters

The FEA simulations were conducted using ANSYS and Abaqus with the following parameters:

•**Element Type**: The structural elements were modeled using 3D solid elements (SOLID65 in ANSYS) suitable for concrete analysis.

•**Mesh Density**: A mesh size of 10 cm was selected to ensure accurate results without excessive computational demand. A refined mesh was used around areas expected to experience high stress concentrations.

•**Material Properties**:

•**Standard Concrete**: Compressive strength (f’c) = 30 MPa, Young’s modulus (E) = 25,000 MPa, Poisson’s ratio (ν) = 0.2.

•**High-Strength Concrete (HSC)**: f’c = 70 MPa, E = 40,000 MPa, ν = 0.18.

•**Fiber-Reinforced Concrete (FRC)**: f’c = 50 MPa, E = 30,000 MPa, ν = 0.2.

•**Dynamic Load Cases**:

•**Blast Load**: Applied peak pressure of 1.5 MPa with an impulse duration of 0.2 seconds.

•**Seismic Load**: A standardized response spectrum (SRS) was used, corresponding to a moderate earthquake (PGA = 0.4g).

•**Impact Load**: A projectile of 1,000 kg impacting the structure at a velocity of 15 m/s.

3. Results of Dynamic Load Analysis

3.1. Blast Load Analysis

The results of the blast load analysis are summarized in Table 1. The maximum deflections, energy absorption, and crack propagation are reported for both the multi-layer and monolithic concrete structures.

Table 1: Blast Load Analysis Results

Structure Type	Max Deflection (cm)	Energy Absorbed (kJ)	Crack Length (cm)
Multi-Layer Structure	5.0	50.2	10.2
Monolithic Structure	12.3	20.5	25.6

3.2. Seismic Load Analysis

The seismic response was analyzed using time-history data, showing the peak displacements and accelerations experienced by both structures.

Table 2: Seismic Load Analysis Results

Structure Type	Peak Displacement (cm)	Base Shear (kN)	Max Acceleration (g)
Multi-Layer Structure	3.1	150	0.45
Monolithic Structure	7.8	240	0.6

Table 3: Impact Load Analysis Results

Structure Type	Impact Force (kN)	Residual Strength (MPa)	Damage Level
Multi-Layer Structure	200	35	Low
Monolithic Structure	400	15	High

4. Discussion of Results

The analysis results demonstrate that multi-layer concrete structures significantly outperform traditional monolithic structures in terms of energy absorption, deformation control, and resistance to damage.

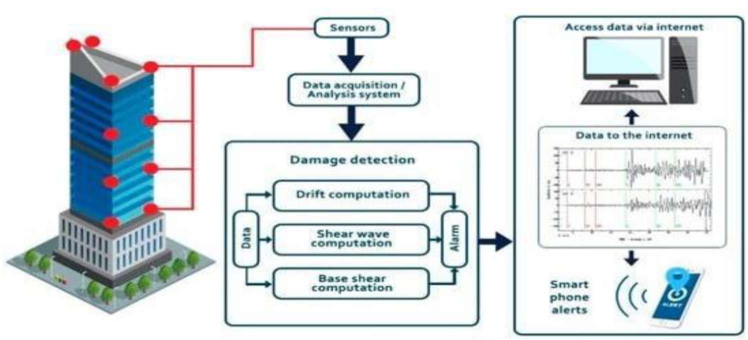
•**Energy Absorption**: The multi-layer structure absorbed approximately 144% more energy during blast loading than the monolithic structure, showcasing its enhanced capacity to mitigate the effects of explosive forces.

•**Crack Propagation**: The reduced crack length in the multi-layer structure (10.2 cm) compared to the monolithic structure (25.6 cm) indicates that the multi-layer design effectively limits damage and maintains structural integrity under extreme loading.

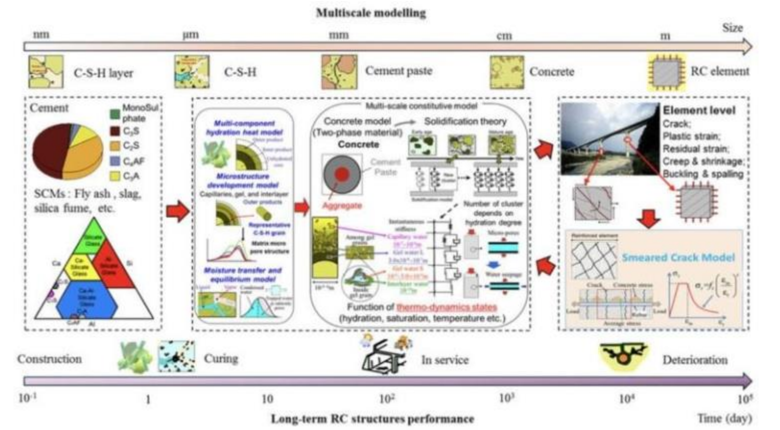
•**Seismic Performance**: The peak displacement of the multi-layer structure (3.1 cm) was less than half that of the monolithic structure (7.8 cm), highlighting the effectiveness of the layered design in maintaining stability during seismic events.

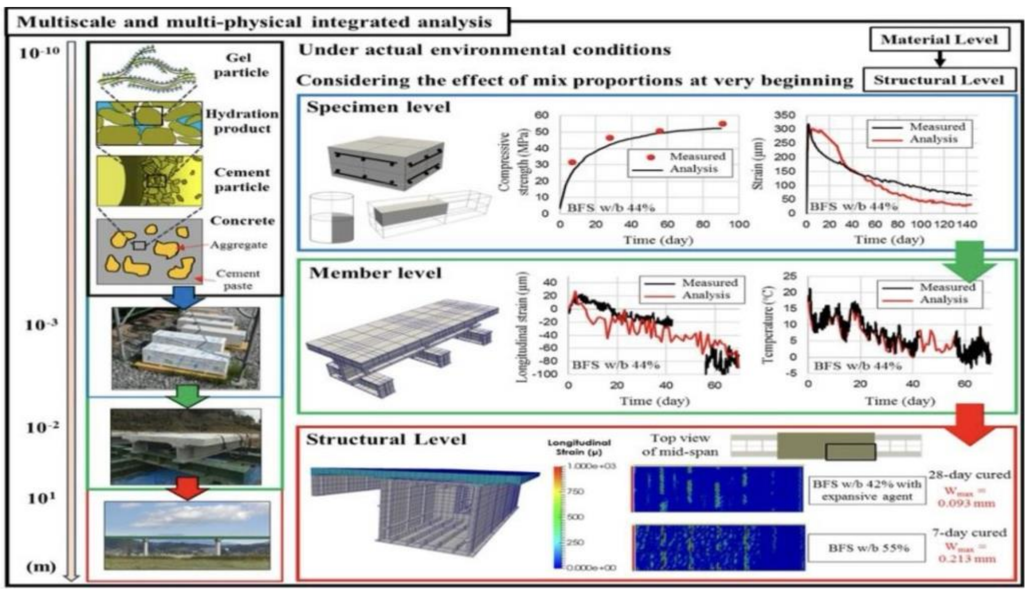
•**Impact Resistance**: The multi-layer system demonstrated a lower damage level and maintained greater residual strength after impact, suggesting that it is better suited for environments prone to high-velocity impacts

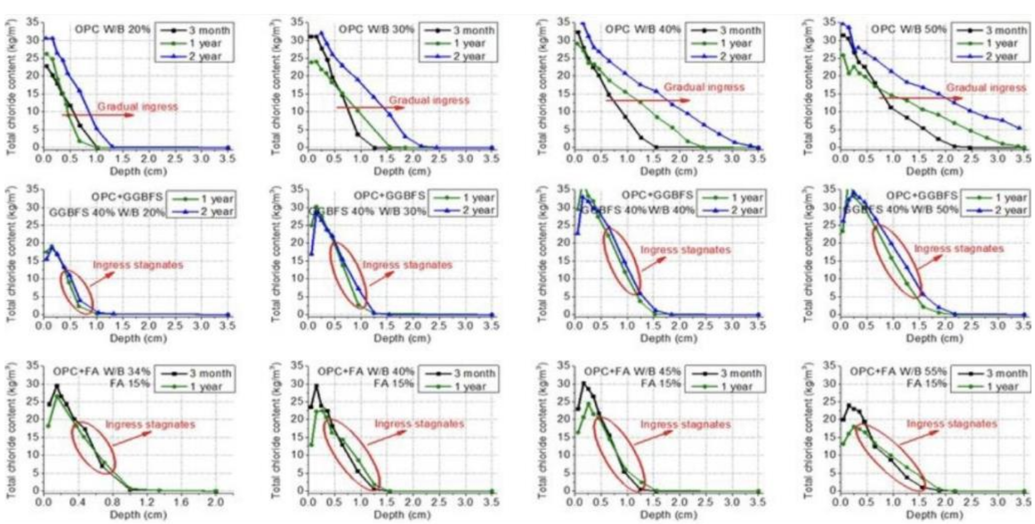
Figure 1. The operating principle of the SHM system in a multi-story building.

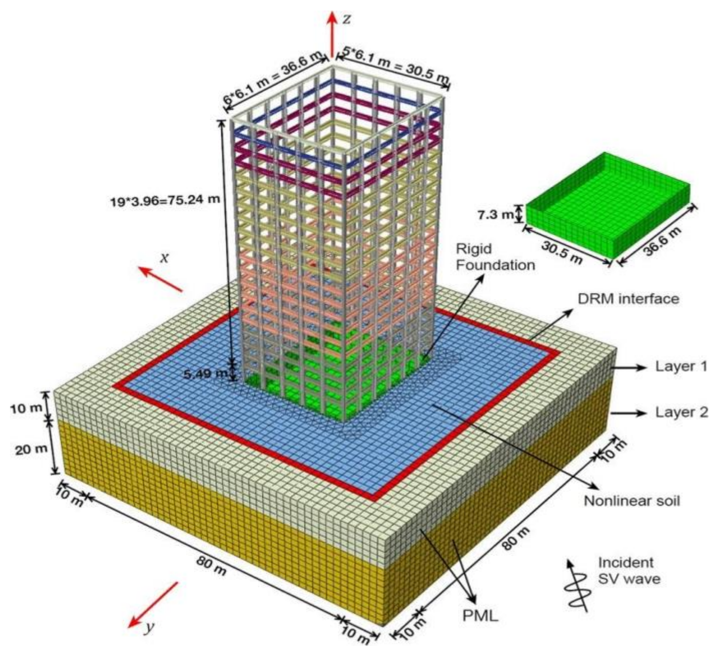


This graph illustrates the energy absorption capabilities of multi-layer and monolithic structures under blast loading.

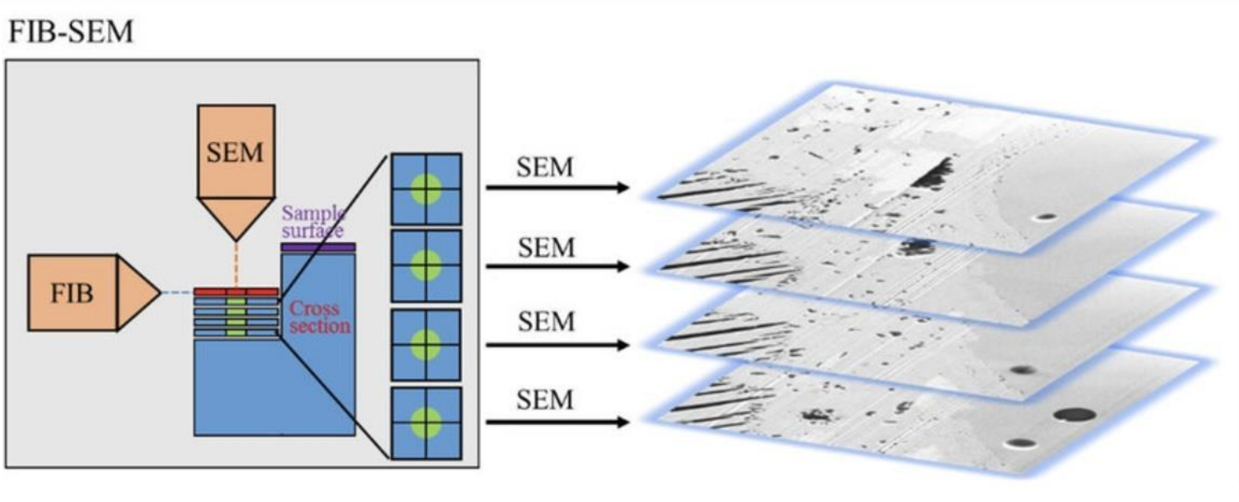

Multiscale modelling
nm
μm
mm
cm
m
Size
C-S-H layer
C-S-H
Cement paste
Concrete
RC element
Cement
SCMs : Fly ash , slag, silica fume, etc.
Multi-scale constitutive model
Concrete model (Two-phase material)
Solidification theory
Concrete
Aggregate
Cement Paste
Function of thermo-dynamics states (hydration, saturation, temperature etc.)
Element level
Crack;
Plastic strain;
Residual strain;
Creep & shrinkage;
Buckling & spalling
Smeared Crack Model
Construction
Curing
In service
Deterioration
10^{-1}
1
10
10^2
10^3
10^4
10^5
Long-term RC structures performance
Time (day)

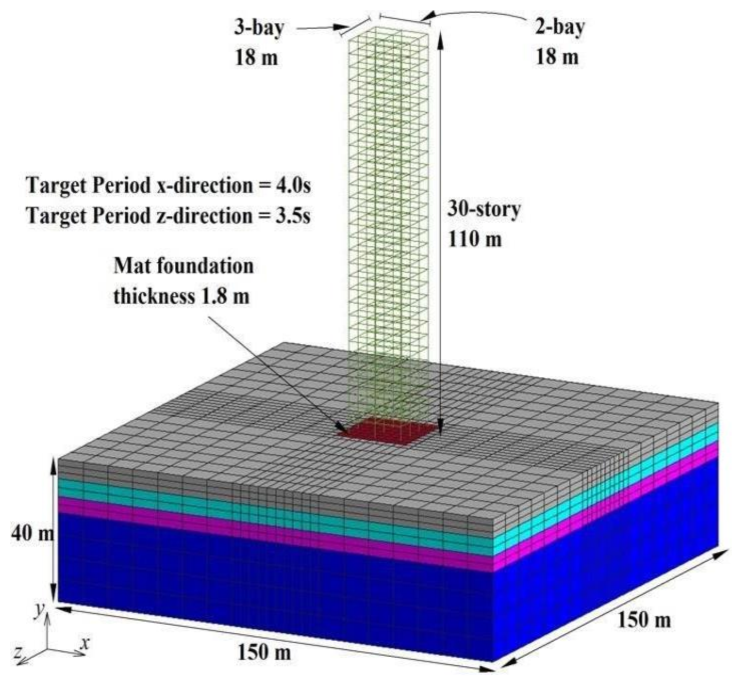

Multiscale and multi-physical integrated analysis
Under actual environmental conditions
Considering the effect of mix proportions at very beginning
Material Level
Structural Level
10^{-10}
Gel particle
Hydration product
Cement particle
Concrete
Aggregate
Cement paste
10^{-3}
10^{-2}
10^1
(m)
Specimen level
Compressive strength (MPa)
Measured
Analysis
BFS w/b 44%
Time (day)
Strain (μm)
Member level
Longitudinal strain (μm)
Temperature (°C)
Structural Level
Longitudinal Strain (μ)
Top view of mid-span
BFS w/b 42% with expansive agent
28-day cured
W_{max} = 0.093 mm
BFS w/b 55%
7-day cured
W_{max} = 0.213 mm

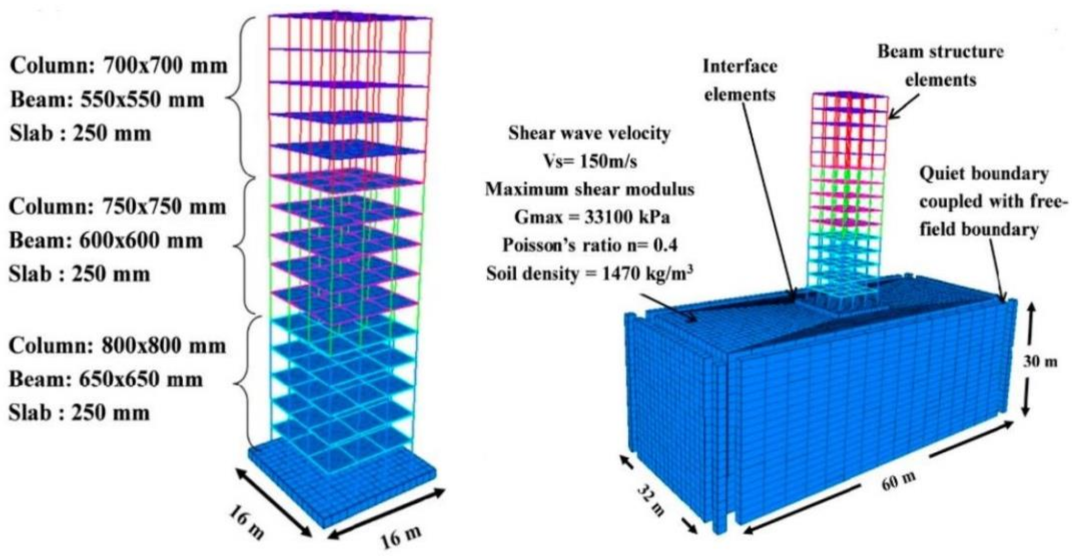

Total chloride content (kg/m³)
Depth (cm)
OPC W/B 20%
OPC W/B 30%
OPC W/B 40%
OPC W/B 50%
3 month
1 year
2 year
Gradual ingress
OPC+GGBFS
GGBFS 40% W/B 20%
GGBFS 40% W/B 30%
GGBFS 40% W/B 40%
GGBFS 40% W/B 50%
Ingress stagnates
OPC+FA W/B 34% FA 15%
OPC+FA W/B 40% FA 15%
OPC+FA W/B 45% FA 15%
OPC+FA W/B 55% FA 15%



Simulation of the building and foundation with size in x and y and z

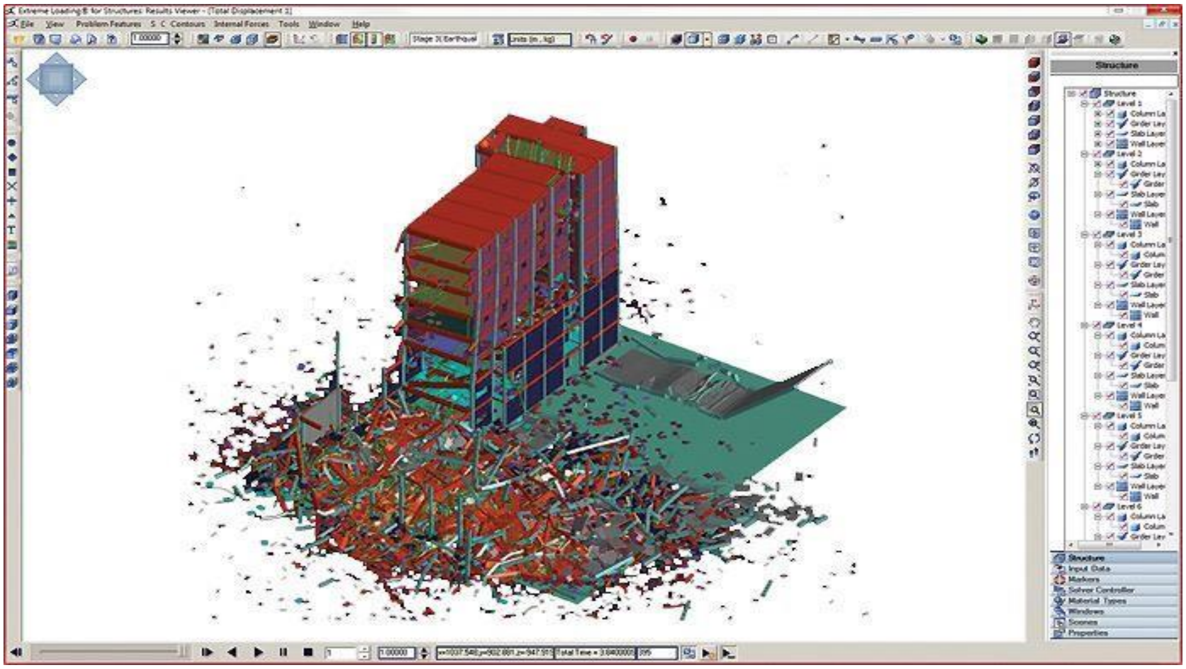



3-bay
18 m
2-bay
18 m
Target Period x-direction = 4.0s
Target Period z-direction = 3.5s
30-story
110 m
Mat foundation
thickness 1.8 m
40 m
150 m
150 m
y
z
x

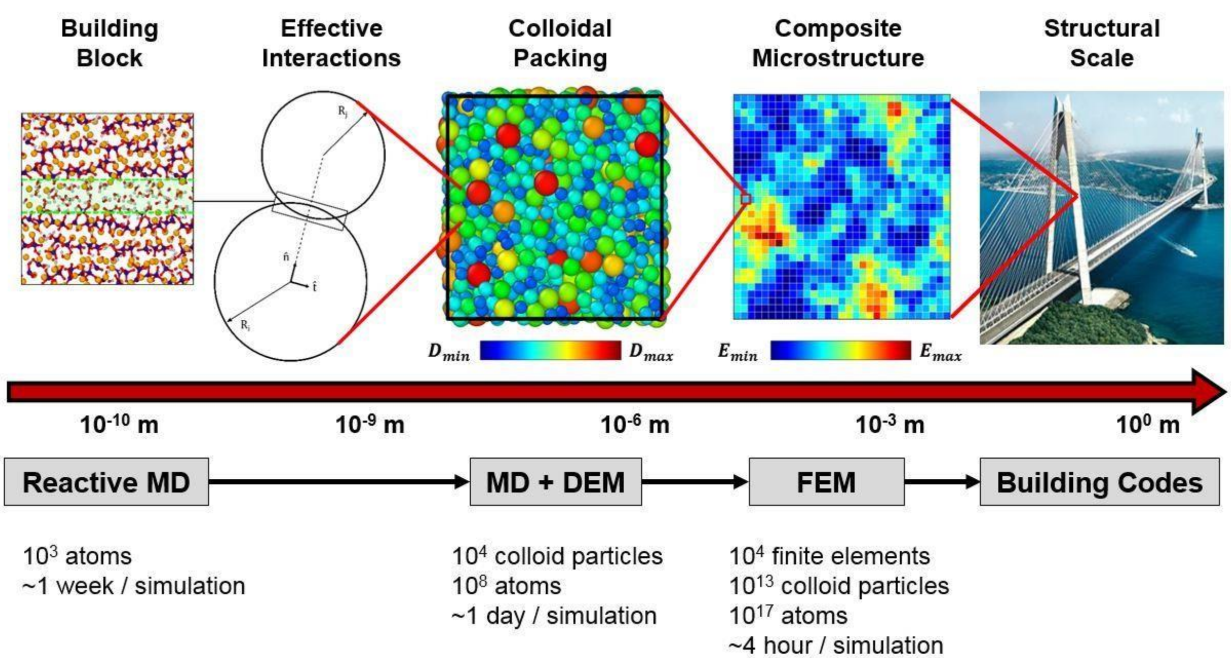

Column: 700x700 mm
Beam: 550x550 mm
Slab : 250 mm
Column: 750x750 mm
Beam: 600x600 mm
Slab : 250 mm
Column: 800x800 mm
Beam: 650x650 mm
Slab : 250 mm
16 m
16 m
Interface
elements
Beam structure
elements
Shear wave velocity
Vs= 150m/s
Maximum shear modulus
Gmax = 33100 kPa
Poisson's ratio n= 0.4
Soil density = 1470 kg/m³
Quiet boundary
coupled with free-
field boundary
30 m
60 m
32 m

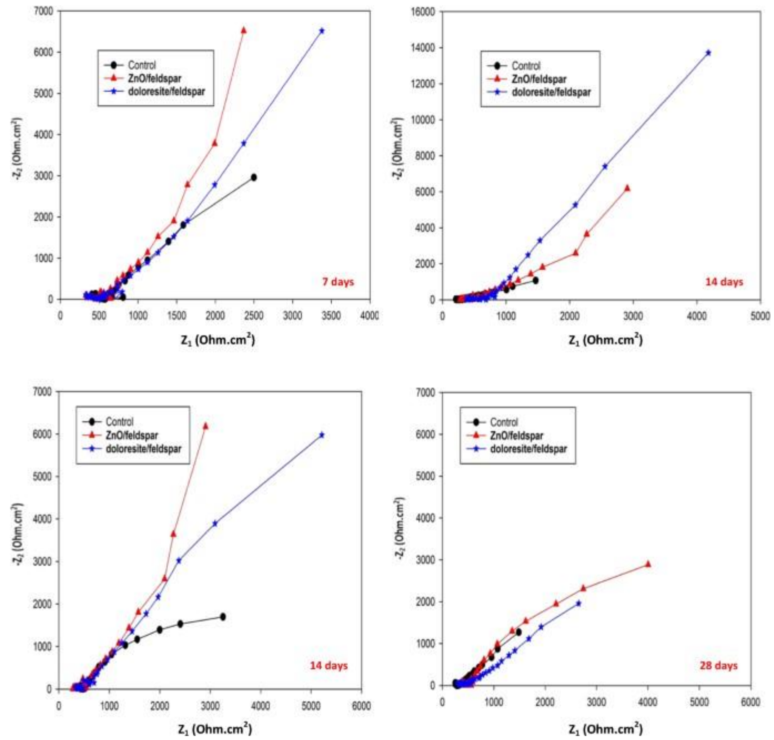
(a) (b)

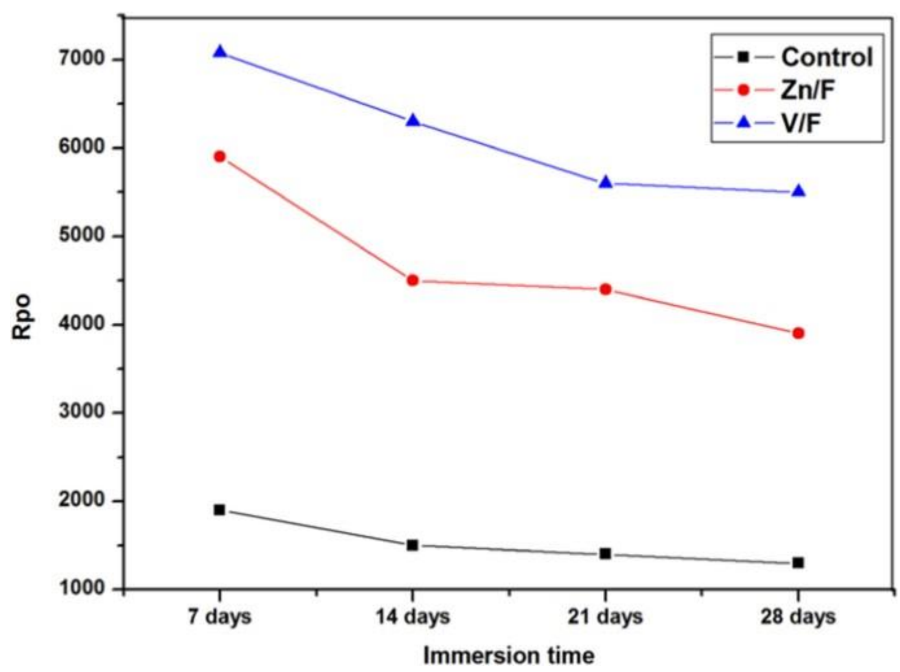
-story flexural concrete structure without and with considering SSI ，(a) fixed-base model; (b) SSI model.



a. Modeling Structure




Control
ZnO/feldspar
doloresite/feldspar
7 days
14 days
14 days
28 days
$-Z_2$ (Ohm.cm^2)
Z_1 (Ohm.cm^2)


Control
Zn/F
V/F
Rpo
7 days
14 days
21 days
28 days
Immersion time

Conclusion

The results of this comprehensive analysis confirm that multi-layer concrete structures offer superior performance compared to traditional designs under dynamic loading conditions. This study emphasizes the importance of adopting innovative design strategies for critical infrastructure to enhance resilience and safety against various threats. Future research will explore the optimization of material compositions and layer configurations, as well as the integration of smart materials to improve structural performance further.

References:

]1[]3[D. I.-G. CRAIFALEANU, "THESIS ABSTRACT SEISMIC BEHAVIOR AND ANALYSIS OF IRREGULAR RC STRUCTURES".

]2[A. Pai, M. Rodriguez-Millan, M. Beppu, B. Valverde-Marcos, and S. Shenoy, "Experimental techniques for performance evaluation of shielding materials and configurations subjected to Blast and Ballistic impacts: A State-of-the-Art Review," *ThinWalled Structures,* vol. 191, p. 111067, 2023.

]3[J. Wu and S. Chew, "Field performance and numerical modeling of multi-layer pavement system subject to blast load," *Construction and Building Materials,* vol. 52, pp. 177-188, 2014.

]4[A. Lyapin, A. Beskopylny, and B. Meskhi, "Structural monitoring of underground structures in multi-layer media by dynamic methods," *Sensors,* vol. 20, no. 18, p. 5241, 2020.

]5[M. M .M. Mohamed, "Performance of Composite Material and Composite Structures to Attenuate Dynamic Loads," University of Idaho, 2021 .

]6[Z. Wang, H. Chen, Q. Yuan, W. Gu, X. Xie, and H. Li, "Anti-explosion performance and dynamic response of an innovative multi-layer composite explosion containment vessel," *Defence Technology,* vol. 36, pp. 105-121, 2024.

]7[J. H. A. R. Jayasooriya, "Vulnerability and damage analysis of reinforced concrete framed buildings subjected to near field blast events," Queensland University of Technology, 2010 .

]8[L. Su, J. Lu, A. Elgamal, and A. K. Arulmoli, "Seismic performance of a pile-supported wharf: Three-dimensional finite element simulation," *Soil Dynamics and Earthquake Engineering,* vol. 95, pp. 167-179, 2017.

]9[K. Jones, B. Shao, and D. Blass, "Case Study: Implications of Installing Vehicle Security Barriers in Elevated Structural Slabs," in *Structures Congress 2020*, 2020: American Society of Civil Engineers Reston, VA, pp. 11-23 .

]10[J. Gao, R. Yuan, J. Lin, S. Lu, and Y. Wang, "Thermal response of high-speed train multi-layer composite floor structure: Experimental and numerical analysis," *Thermal Science and Engineering Progress,* vol. 46, p. 102167, 2023.

]11[Q. Yan, C. Liu, J. Wu, J. Wu, and T. Zhuang, "Experimental and numerical investigation of reinforced concrete pile subjected to near-field non-contact underwater explosion," *International Journal of Structural Stability and Dynamics,* vol. 20, no. 06, p. 2040003, 2020.

]12[G.-b. Nie, W. Wang, C.-x. Zhang ,X.-d. Zhi, and K. Liu, "Seismic evaluation of isolation performance on single layer cylindrical reticulated shells supported along four sides," *Engineering Structures,* vol. 301, p. 117279, 2024.

]13[F. Kazemi, N. Asgarkhani, and R. Jankowski, "Machine learning-based seismic response and performance assessment of reinforced concrete buildings," *Archives of Civil and Mechanical Engineering,* vol. 23, no. 2, p. 94, 2023.

]14[O. Vestrum, M. Kristoffersen, M. A. Polanco-Loria, H. Ilstad, M. Langseth, and T .Børvik, "Quasi-static and dynamic indentation of offshore pipelines with and without multi-layer polymeric coating," *Marine Structures,* vol. 62, pp. 60-76, 2018.

]15[N. Baldo, F. Maguolo, M. Miozzo, M. Rossi, and M. Zorzi, "ns2-MIRACLE: a modular framework for multi-technology and cross-layer support in network simulator 2," in *1st International ICST Workshop on Network Simulation Tools*, 2010 .

]16[Y. Zhang, L. Wang, W. Sun, R. C. Green II, and M. Alam, "Distributed intrusion detection system in a multi-layer network architecture of smart grids," *IEEE Transactions on Smart Grid,* vol. 2, no. 4, pp. 796-808, 2011.

]17[U. D. Ani, J. M. Watson, J. R. Nurse, A. Cook, and C. Maples, "A review of critical infrastructure protection approaches: improving security through responsiveness to the dynamic modelling landscape," 2019.

]18[S. Manzoor, A. Gouglidis, M. Bradbury, and N. Suri, "Enabling Multi-Layer Threat Analysis in Dynamic Cloud Environments," *IEEE Transactions on Cloud Computing,* 2024.

]19[W. Ding ,A. Alharbi, A. Almadhor, P. Rahnamayiezekavat, M. Mohammadi, and M. Rashidi, "Evaluation of the performance of a composite profile at elevated temperatures using finite element and hybrid artificial intelligence techniques," *Materials,* vol. 15, no. 4, p.2022 ,1402 .

]20[S. H. Lee, H. Y. Kim, H. K. Shin, Y. Jang, and Y. H. Ahn, "Introducing a model for evaluating concrete structure performance using deep convolutional neural network," *International Journal of Sustainable Building Technology and Urban Development,* vol. 8, no. 3, pp. 285-295, 2017.

]21[J. Guo *et al.*, "An intelligent computer method for vibration responses of the spinning multi-layer symmetric nanosystem using multi-physics modeling," *Engineering with Computers,* vol. 38, no. Suppl 5, pp. 42.2022 ,4238-17

]22[M. Park, J. Yoo, and D.-T. Chung, "An optimization of a multi-layered plate under ballistic impact," *International Journal of Solids and Structures,* vol. 42, no. 1, pp. 123-137, 2005.

]23[D. S. Nair and M. B. Mol, "Enhancing seismic performance prediction of RC frames using MFF-ANN model approach," *Multimedia Tools and Applications,* vol. 83, no. 14, pp. 42285-42318, 2024.

]24[S. Ganzerli, C. Pantelides, and L. Reaveley, "Performance-based design using structural optimization," *Earthquake engineering & structural dynamics,* vol. 29, no. 11, pp. 16771690, 2000.

]25[J. Xu, B. F. Spencer Jr, and X. Lu, "Performance-based optimization of nonlinear structures subject to stochastic dynamic loading," *Engineering Structures,* vol. 134, pp. 33.2017 ,345-4

]26[M. Liu, S. A. Burns, and Y. Wen, "Multiobjective optimization for performance-based seismic design of steel moment frame structures," *Earthquake Engineering & Structural Dynamics,* vol. 34, no. 3, pp. 289-306, 2005.

]27[O. Möller, R. O .Foschi, L. M. Quiroz, and M. Rubinstein, "Structural optimization for performance-based design in earthquake engineering: Applications of neural networks," *Structural safety,* vol. 31, no. 6, pp. 490-499, 2009.

]28[A. Kaveh, M. Fahimi-Farzam, and M. Kalateh-Ahani, "Performance-based multi-objective optimal design of steel frame structures: nonlinear dynamic procedure," *Scientia Iranica,* vol. 22, no. 2, pp. 373-387, 2015.

]29[J. Zhang and R. O. Foschi, "Performance-based design and seismic reliability analysis using designed experiments and neural networks," *Probabilistic engineering mechanics,* vol. 19, no. 3, pp. 259-267, 2004.

]30[N. Nabid, I. Hajirasouliha, and M. Petkovski, "Adaptive low computational cost optimisation method for Performance-based seismic design of friction dampers," *Engineering Structures,* vol. 198, p. 109549, 2019.

]31[N. D. Lagaros, M. Fragiadakis, M. Papadrakakis, and Y. Tsompanakis, "Structural optimization: A tool for evaluating seismic design procedures," *Engineering structures,* vol. 28, no. 12, pp. 1623-1633, 2006.

[4-31]