2026.05.07
Korean Nuclear Society 2026 Spring Meeting

Evaluation of Floor Response Spectra at Unmeasured Degrees of Freedom in Nuclear Power Plant Auxiliary Buildings via Seismic Response Reconstruction

지진 응답 재구성을 통한 원자력 발전소 보조 건물의 미계측 자유도 층응답스펙트럼 평가

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KAIST SCIS

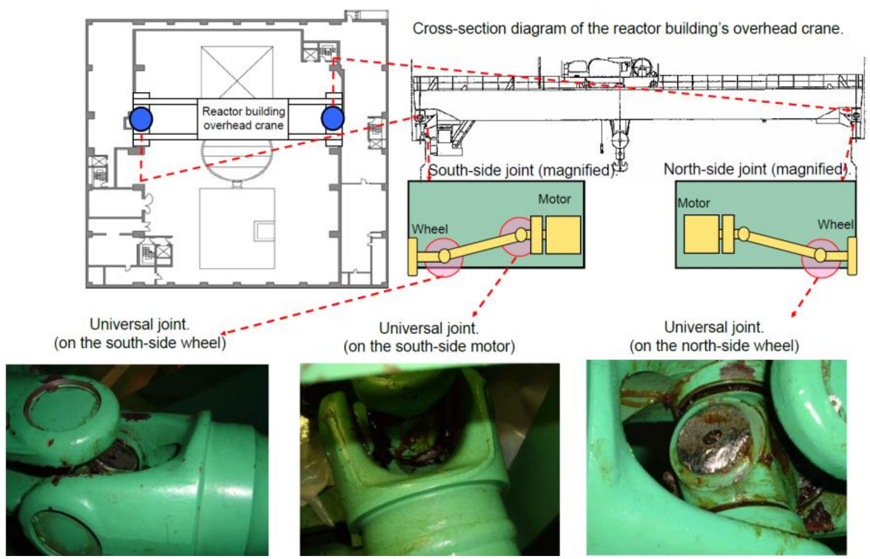
Contents

I. Introduction

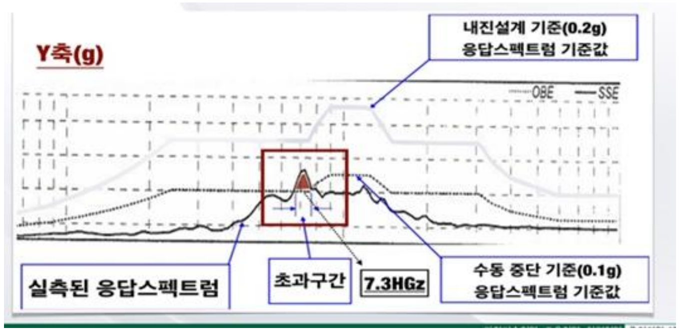
I Introduction

■ Research Background (1/2)

- **Operational disruptions in critical infrastructure**
  - Lead to cascading socio-economic losses
- **The paradigm shift in seismic resilience**
  - Collapse prevention ⟶ **Functional continuity**



< Crane joint damage at nuclear power plant after 2007 Niigata EQ [1] >



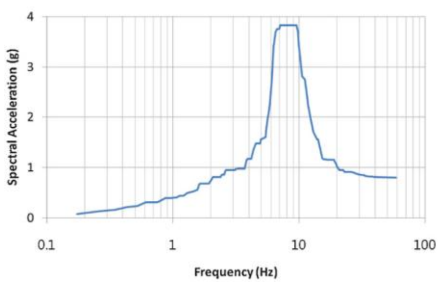
< 계측 응답 스펙트럼의 운전기준(OBE) 초과 사례 [2] >
(2016 경주 지진)

→ ***Seismic assessment must address individual critical locations, not just the overall structure***

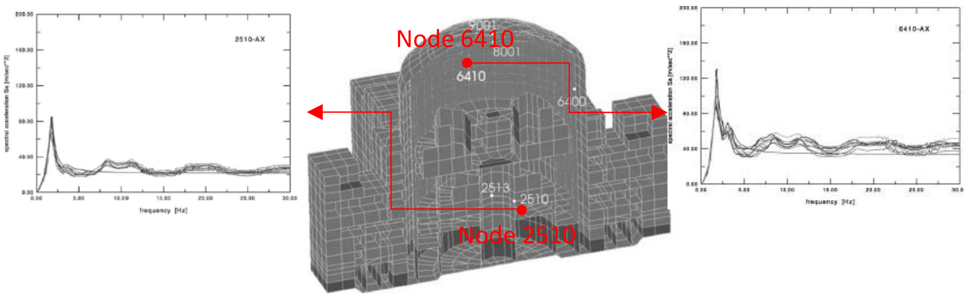
↳ (e.g., battery rack, switchgear, EDG, SGBD tank, electrical cabinet)

■ Research Background (2/2)

- **Equipment damage/malfunction is driven by floor acceleration**
  - Floor response spectra (FRS) at installation sites: Essential for functional continuity assessment & rapid inspection prioritization



< Case study: FRS application by major equipment location [3] >



< Case study: FRS estimation by major equipment location >
Adapted from [4]

→ Accurate FRS identification at critical locations must be preceded, but…

- Sensing constraints [5, 6]
- Seismic non-stationarity [7]
- Structural complexity

→ Necessity for reliable FRS reconstruction at critical locations under <u>diverse seismic scenarios</u> and <u>local behaviors</u> with <u>limited sensors</u>

II. Proposed Reconstruction Framework

Ⅱ Proposed Reconstruction Framework

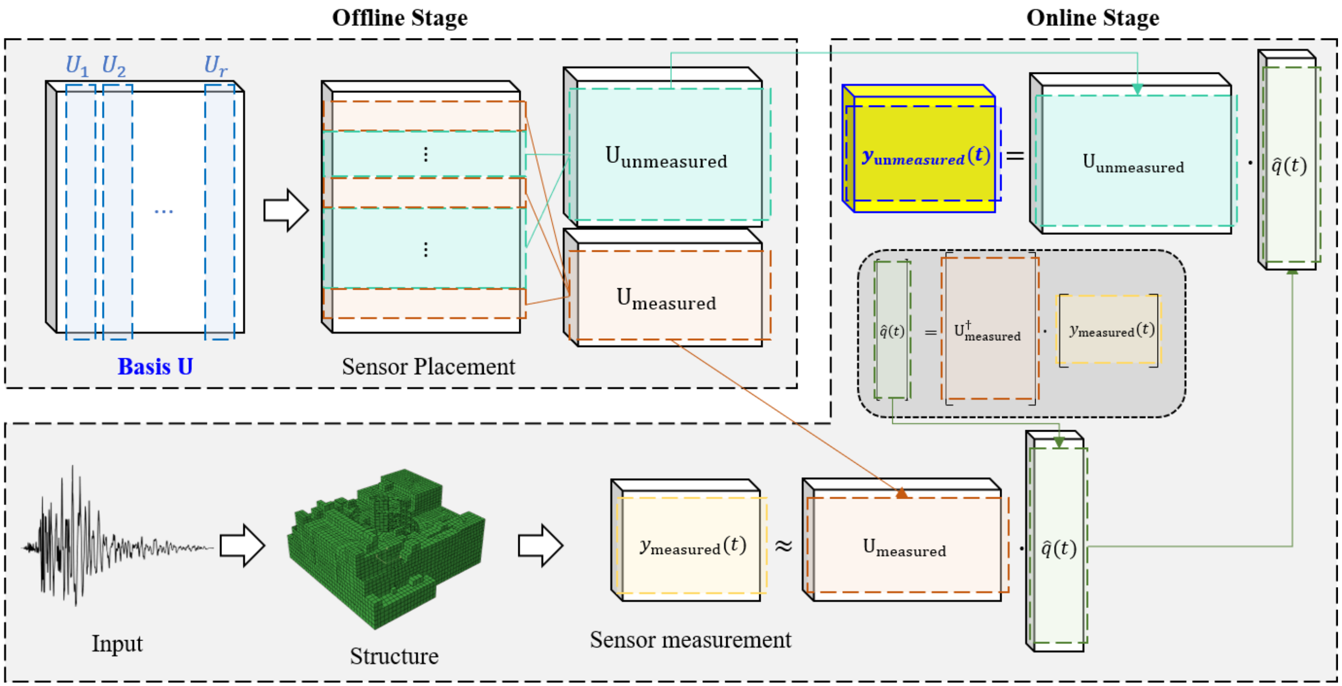
■ Time-domain Seismic Response Reconstruction

- **Conventional method: modal expansion**
  - Expresses time-domain responses as a linear combination of bases
  - Calculates coefficients from sensor data to expand to unmeasured locations
- **Performance determinants**

1) Basis representability → $\hat{y}(t) = \underbrace{\mathrm{U}}_{\text{basis}} \underbrace{(\mathrm{U}^\top W \mathrm{U})^{-1}\mathrm{U}^\top W\ y(t)}_{\text{modal coordinate}}$

2) Modal coordinate identification stability

$y(t) \in \mathbb{R}^{n\times T}$: actual response
$\hat{y}(t) \in \mathbb{R}^{n\times T}$: subspace-projected response
$\mathrm{U} \in \mathbb{R}^{n\times r}$: basis
$W \in \mathbb{R}^{n\times n}$: weighting matrix

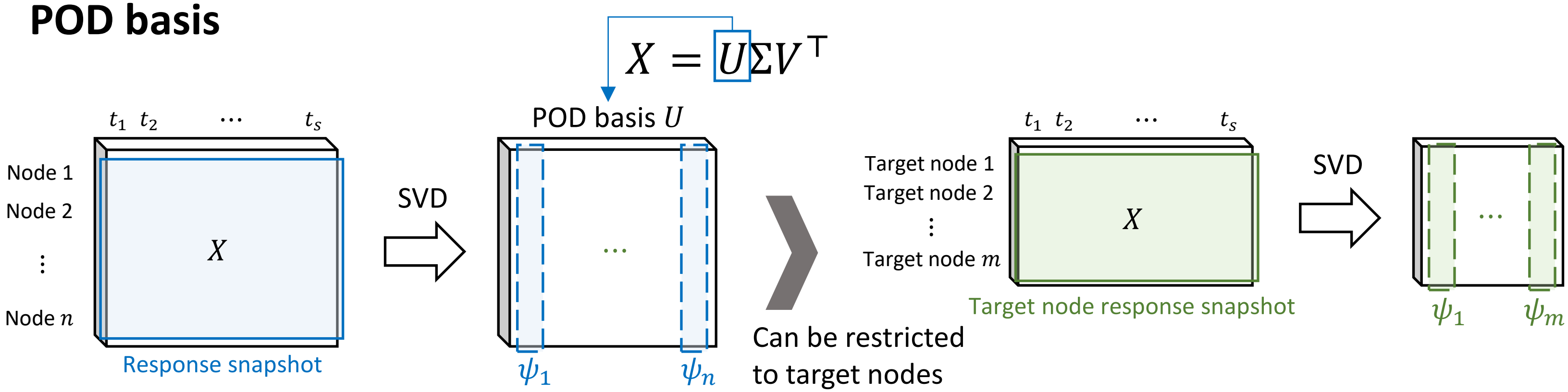


< Flowchart of modal expansion procedure >

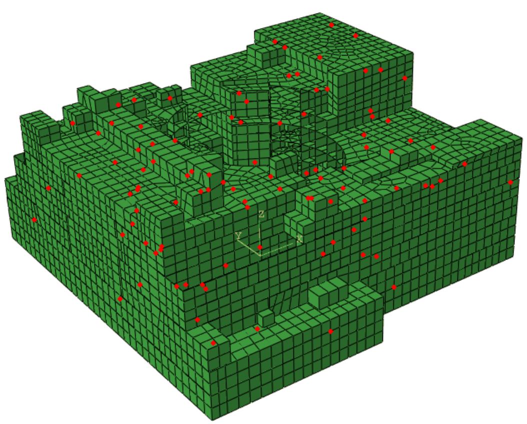
II Proposed Reconstruction Framework

■ Proper Orthogonal Decomposition (POD) (1/3)

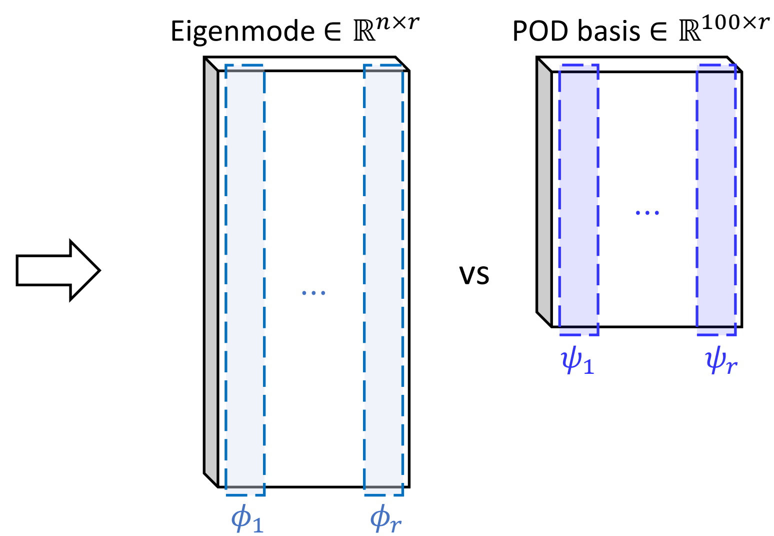
- **POD basis**



– Advance: target-oriented basis



< n DOFs structure with 100 target nodes >



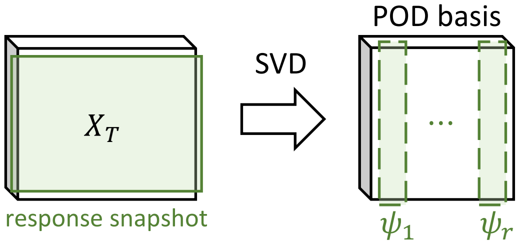
→ ***Enables the use of a basis restricted to target node responses***

Proper Reconstruction Framework

■ Proper Orthogonal Decomposition (POD) (2/3)

- **POD basis**
  - Limitations
    1. Limited robustness to unseen data [8] → Earthquake robustness

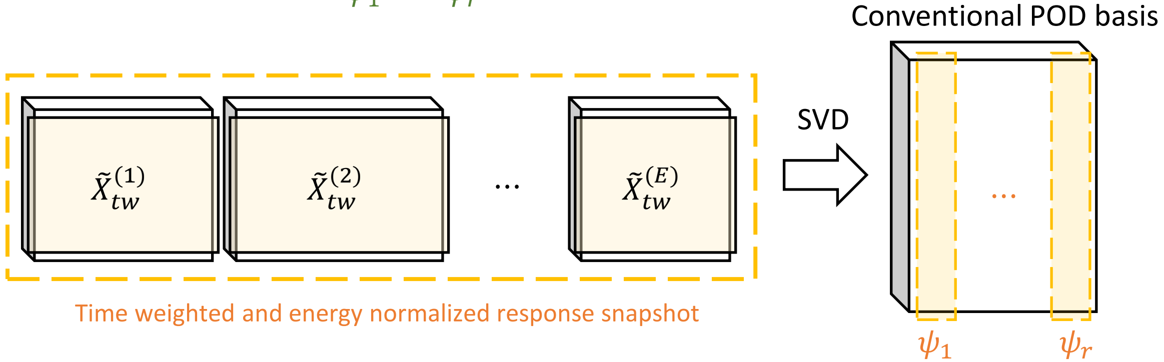
▪ POD basis



Optimized for X_T

No guaranty for the unknown response X_V

▪ Conventional POD basis [9]



Equalizes the influence of all earthquake scenarios

→ Scenarios with similar spectra tend to dominate the basis construction

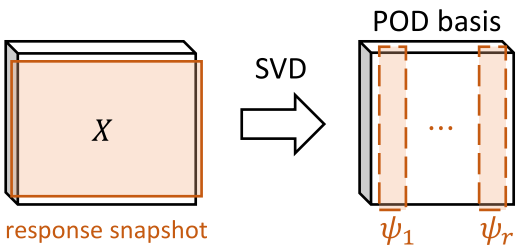
⇩

Fails to guarantee uniform robustness across all scenarios.

II Proposed Reconstruction Framework

■ Proper Orthogonal Decomposition (POD) (3/3)

- **POD basis approach**
  - Limitations
    2. <u>No per-node worst-case guaranty</u> → Node robustness



$$R(U) = \begin{bmatrix} r_1(U) \\ r_2(U) \\ \vdots \\ r_m(U) \end{bmatrix}$$

$$\text{POD basis} \in \underset{U^\top U = I_r}{\arg\min} \ \frac{1}{s} \left\| X_T - UU^\top X_T \right\|_F^2$$

$$\min_{U^\top U = I_r} \ \max_{1 \le i \le m} \ \frac{1}{s} \left\| r_i(U) \right\|_2^2$$

Fails to guarantee uniform robustness across all target nodes.

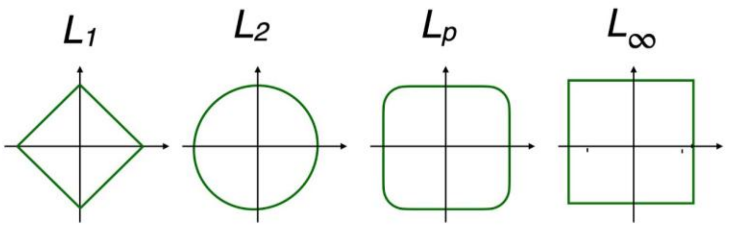
Proposed Reconstruction Framework

■ Proposed Method: IRLS-Weighted POD

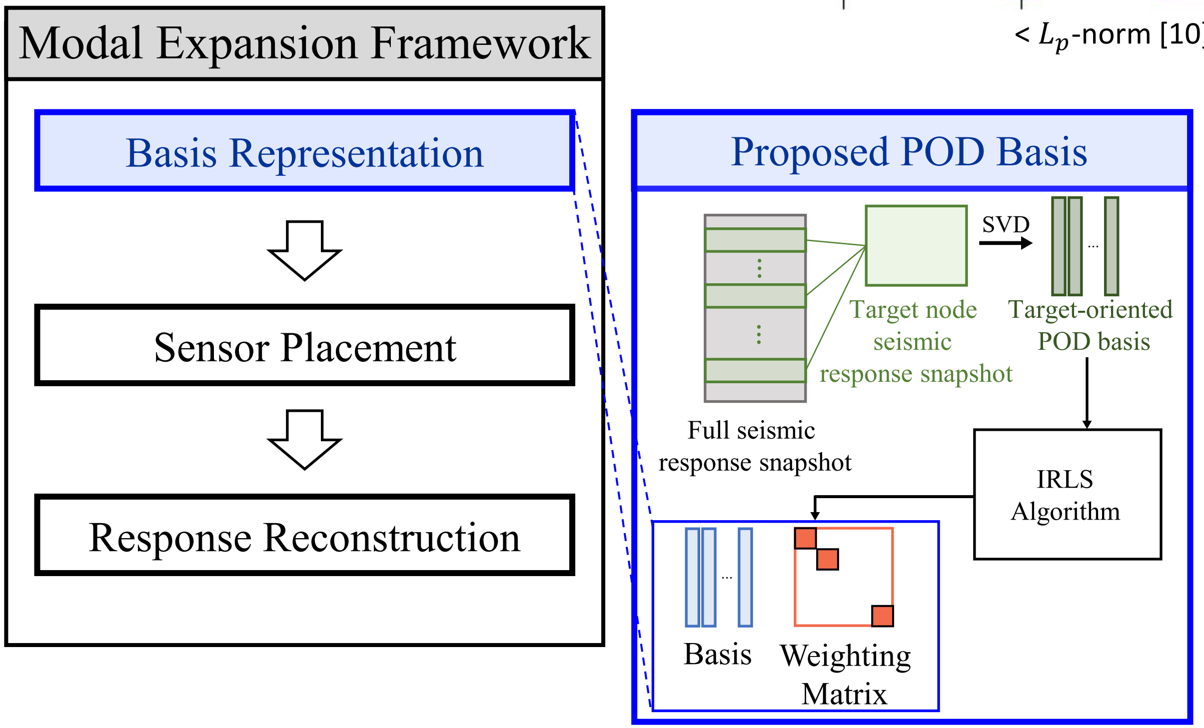
- **Iteratively Reweighted Least Squares (IRLS) Algorithm**

Weighted least squares problem

→ *p-norm minimization problem*



< L_p-norm [10] >



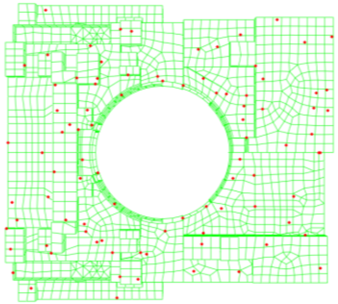
< Framework of proposed response reconstruction method >

III. Performance Validation

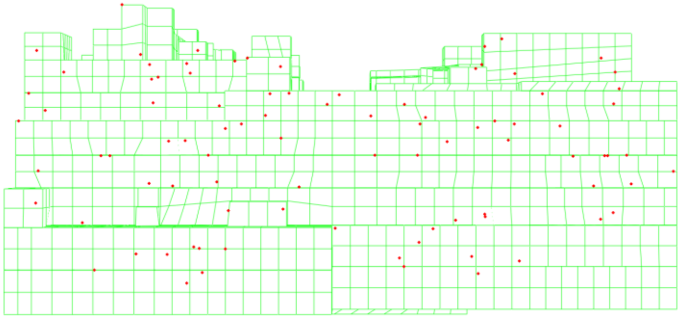
Performance Validation

■ Validation Configuration (1/2)

- **Target node selection method**
  - Maximize **modal diversity** for a **conservative assessment** of robustness.
- **NPP auxiliary building model with 90 target nodes**



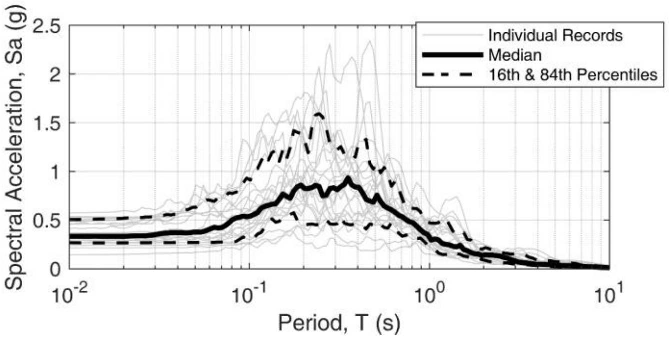
(a) Top view



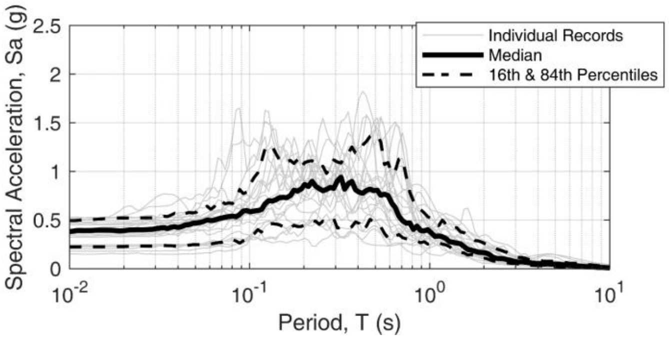
(b) Side view

< Nuclear power plant auxiliary building FE model with 90 target nodes >

- **Input ground motions: FEMA P-695 far-field earthquakes [11]**



(a) Training cases



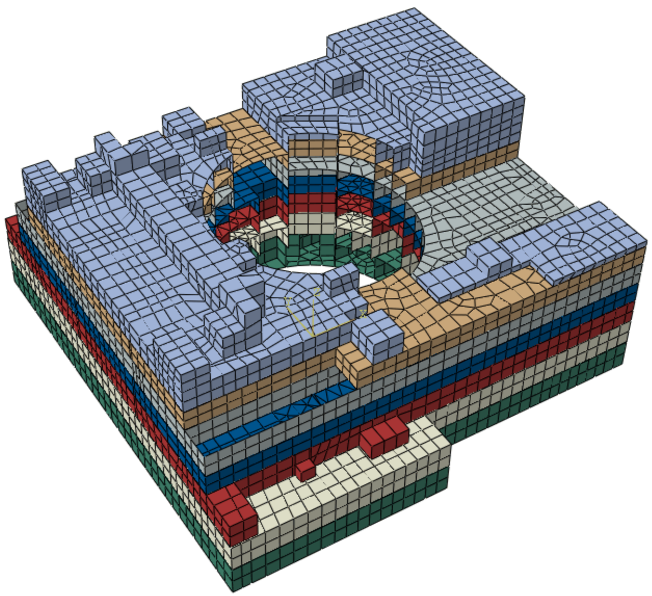
(b) Test cases

< Response spectra of the FEMA P-695 far-field ground motion set >

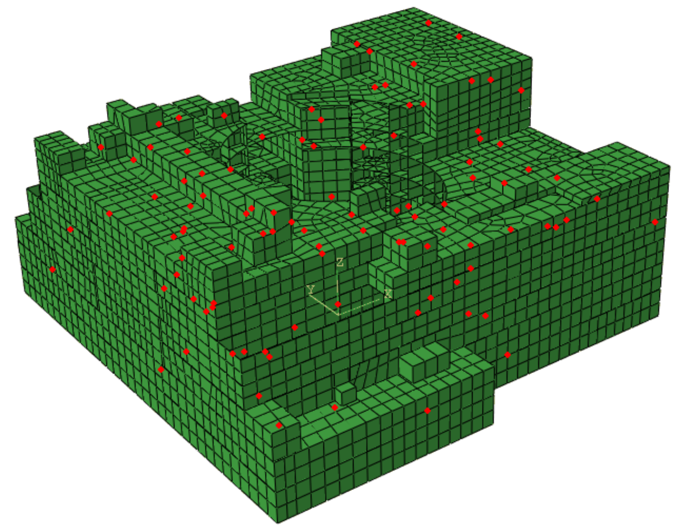
Performance Validation

■ Validation Configuration (2/2)

- **Auxiliary building shell FE model of nuclear power plant structure**
  - 66852 DOFs



(a) 7 floors



(b) 90 target nodes

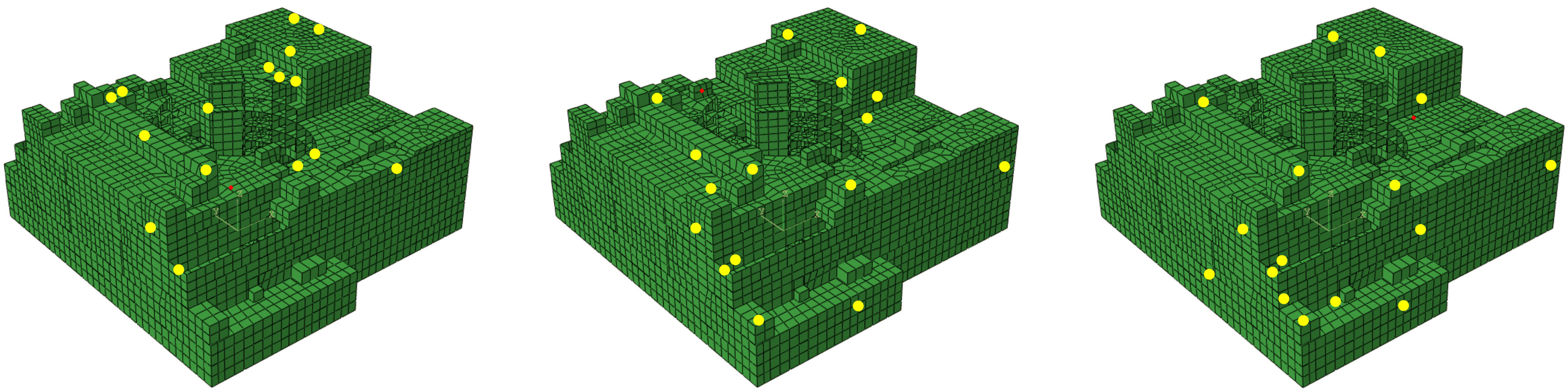
< FE model >

< Material properties >

Material	Young's Modulus E (lb/in^2)	Poisson's ratio ν	Mass density ρ (lb/in^2)
Concrete	4.031×10^6	0.17	2.25×10^{-4}
Reinforcement	2.90×10^7	0.30	7.346×10^{-4}
Stee	2.9008×10^7	0.30	7.346×10^{-4}

III Performance Validation

■ Sensor Placement



(a) Eigenmode (b) Conventional POD basis (c) Proposed POD basis

< Optimal placement [12] of 16 sensors using 13 basis vectors >

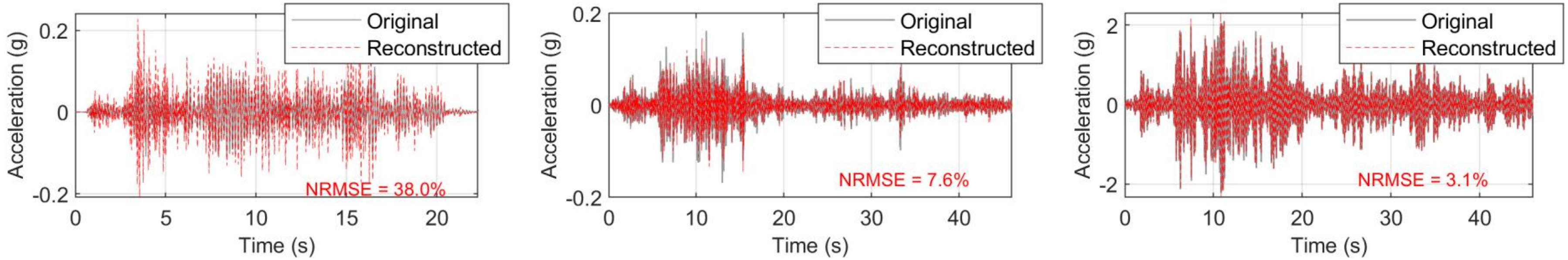
< Number of sensors per floor >

Floor	Number of sensors		
	Eigenmode	Conventional POD basis	Proposed POD basis
1^{st}	1	1	4
2^{nd}	0	2	3
3^{rd}	0	1	1
4^{th}	1	3	3
5^{th}	3	2	1
6^{th}	2	0	0
7^{th}	9	7	4

Performance Validation

■ Validation I: Time-domain

- **Modal expansion reconstruction on test input responses**



(a) Eigenmode (b) Conventional POD basis (c) Proposed POD basis

< Time-series comparison for the maximum NRMSE case of each basis method (16 sensors, 13 basis vectors) >

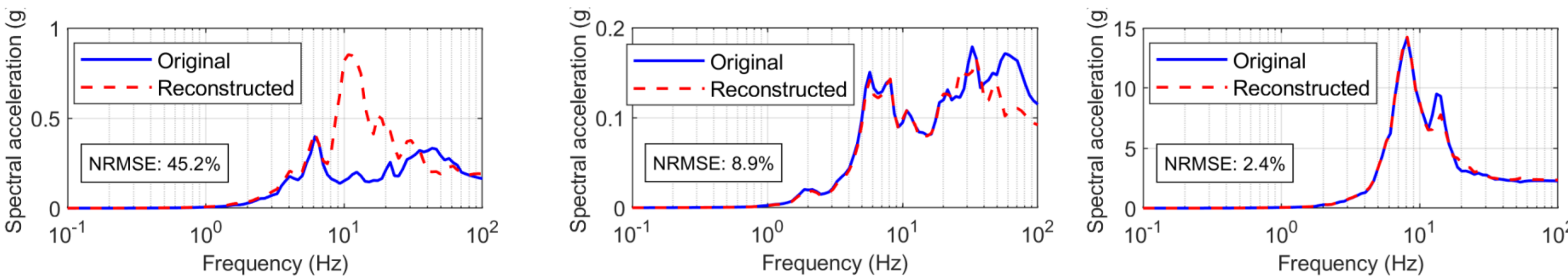
< Statistical summary >

	NRMSE (%)		
	Eigenmode	Conventional POD basis	Proposed POD basis
Max.	38.012	7.585	3.059
Min.	0.0001560	0.00009681	0.045
Mean	3.529	0.509	0.674

Performance Validation

■ Validation II: Floor Response Spectra

- **Modal expansion reconstruction on test input responses**



(a) Eigenmode (b) Conventional POD basis (c) Proposed POD basis

< Floor response spectra comparison for the maximum NRMSE case of each basis method (16 sensors, 13 basis vectors) >

< Statistical summary >

	NRMSE (%)		
	Eigenmode	Conventional POD basis	Proposed POD basis
Max.	45.238	8.919	2.420
Min.	0.0003033	0.00007870	0.024
Mean	3.900	0.474	0.443

IV. Conclusions

Conclusions

■ Conclusions

- **Robust FRS estimation: verification of the reconstruction framework**
  - Robustly reconstructs **unmeasured time-domain** seismic responses based on measured data
  - Successfully reproduces the **overall trends of the exact floor response spectra**
- **Algorithm limitations: focus on time-domain optimization**
  - Objective function focuses on minimizing the **worst-case NRMSE in the time domain**
  - Does not explicitly optimize **frequency-domain characteristics**

■ Future Works

- **Quantitative correlation analysis: time vs. frequency domain**
  - Requires a quantitative analysis of the correlation between **time-domain reconstruction errors** and **frequency-domain spectral accuracy**

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Thank you

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