Resilience Analysis of Smart Steel Moment Resisting Frame under Seismic-LPG Tank Explosion

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INTRODUCTION & MOTIVATION

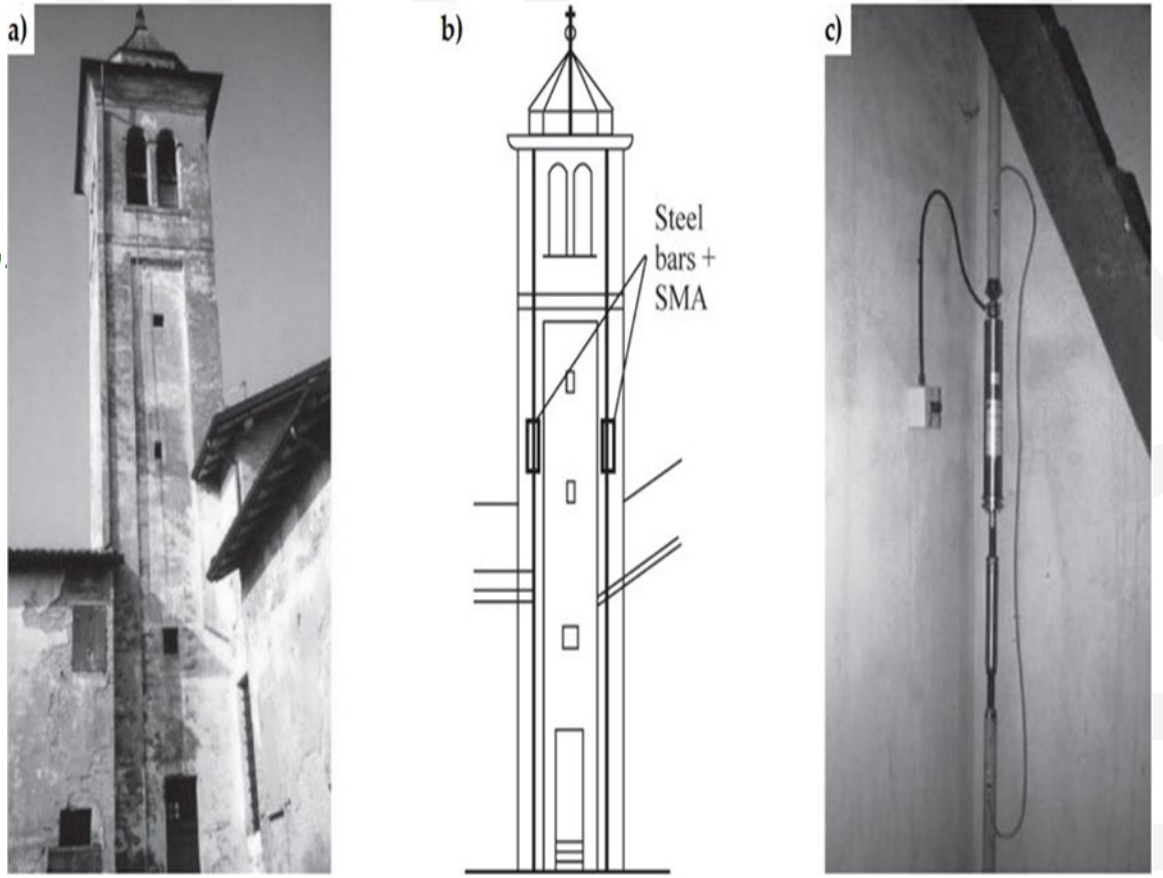
- Petrochemical steel facilities are vulnerable because of **explosive materials like LPG (Liquefied Petroleum Gas)**
- **BLEVE (Boiling Liquid Expanding Vapor Explosion)** can happen if LPG tanks are damaged.
- Real disasters:
  - ***Tohoku Earthquake, Japan (2011)*** *→ mechanical damage to LPG tanks triggered a BLEVE.*
- These show why we must consider **earthquake + explosion sequence loading**.

(Tsunami-triggered oil spill fires that spread over Kesennuma Bay, Miyagi Prefecture, Japan, after the 2011 Tohoku earthquake)

(Nishino et. al 2019)

INTRODUCTION & MOTIVATION

- Conventional strengthening approaches -> effective measure in preventing collapse -> significant residual deformations.
- Structures may survive, but they can't function after the event.
- **Superelastic NiTi SMA** was introduced as a solution:

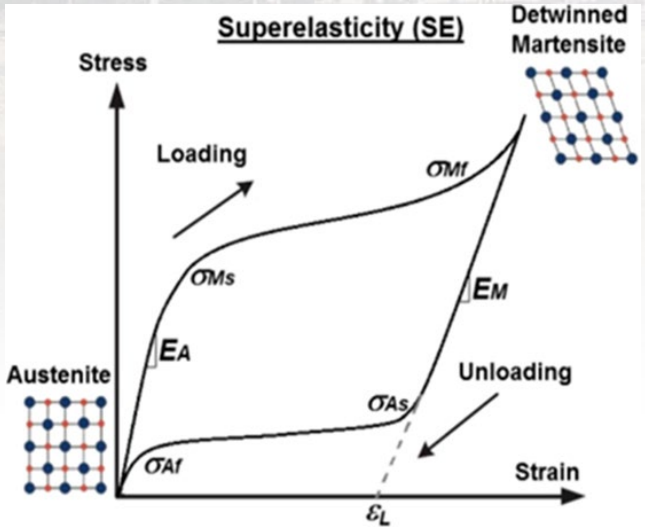


(Bell tower of the S. Giorgio Church)

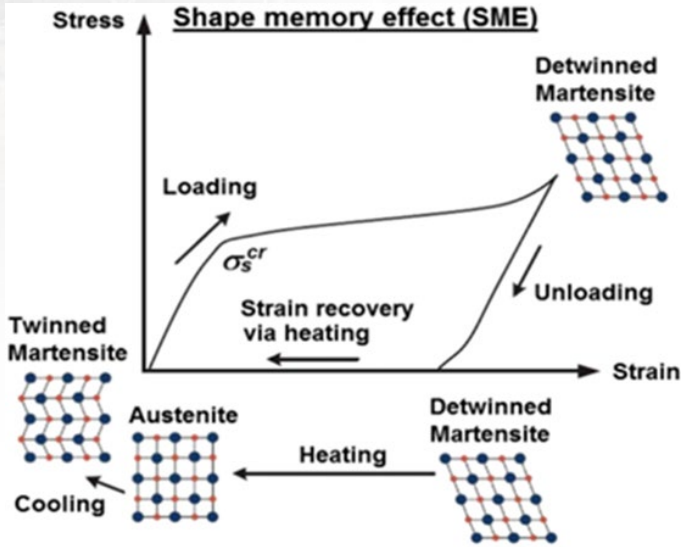
(Indirli et al. 2001)

EMERGING MATERIALS: NITI SMA

- Superelastic Effect
  - Enables large reversible deformations.
  - Capacity to withstand sudden and severe forces without permanent damage.
  - Minimizes residual deformation after extreme events (e.g., blast).



- Shape Memory Effect (SME)
  - Deforms in martensitic phase.
  - When heated, transforms back to austenite.
  - Recovers its original shape after deformation.

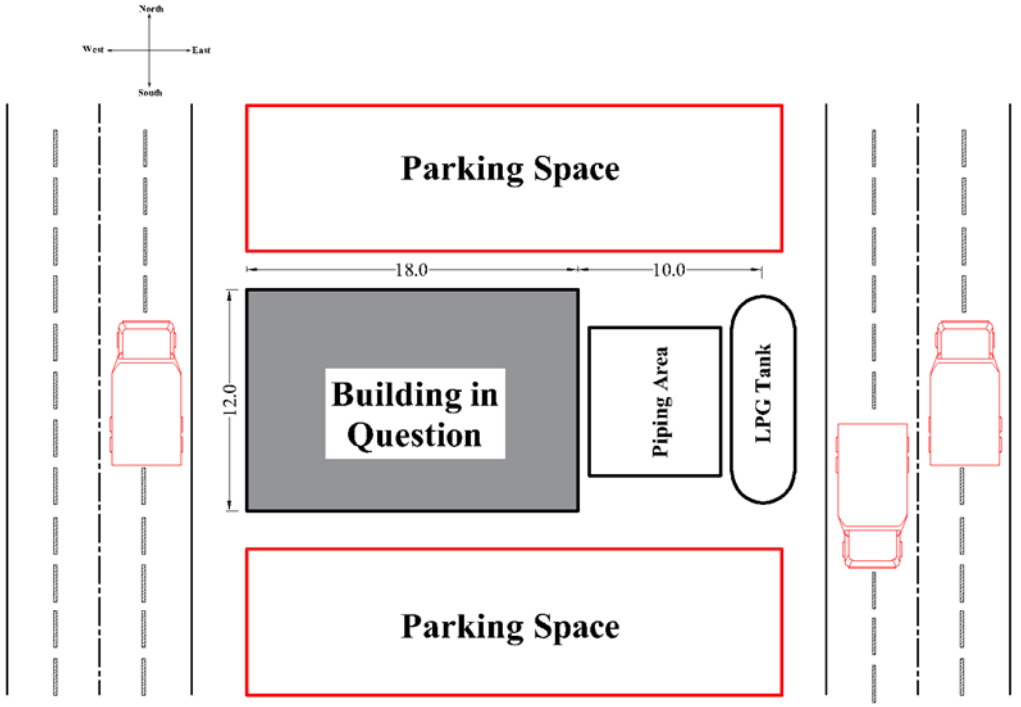


Case Study: Resilience Analysis of Smart MRF under Multi-Hazard LPG Tank Blast-Seismic Triggered Scenario

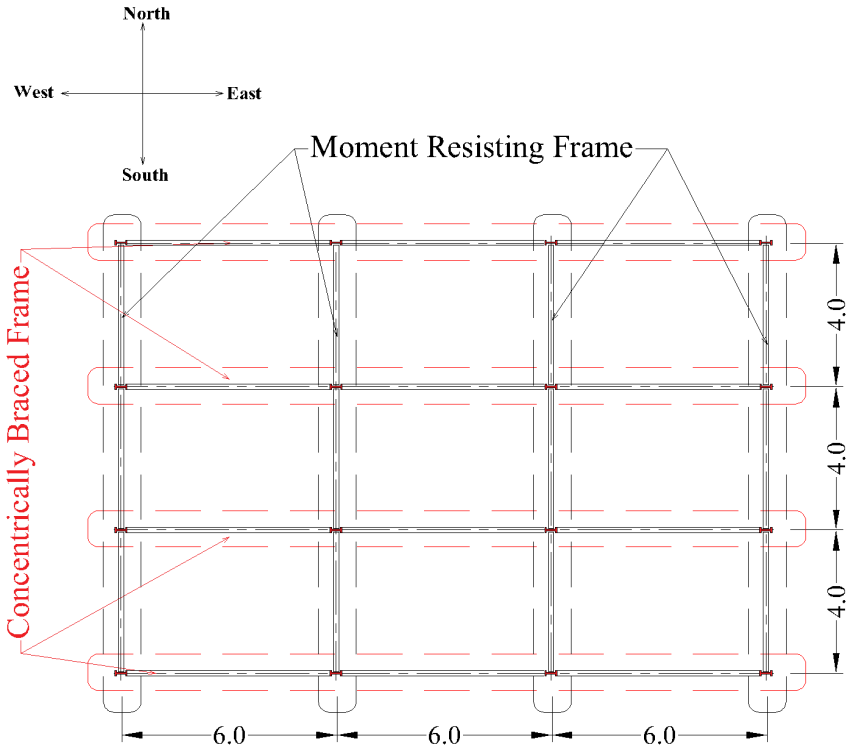
- Aim: Analyse the resilience of 5- to 10-story smart MRFs with NiTi SMA connections using a multi-hazard blast-seismic algorithm.
- Scenario: LPG tank (BLEVE) explosion triggered by earthquake-induced damage.

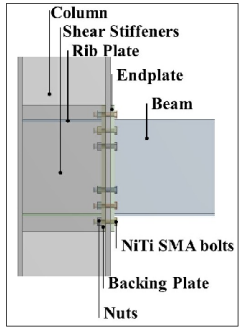
➢ We treat a BLEVE as an equivalent TNT charge. This converts "LPG rupture" into a blast time-history we can apply to the frame.

➢ From that TNT equivalence, we generate a reflected overpressure time-history at the façade using Kingery airblast curves.

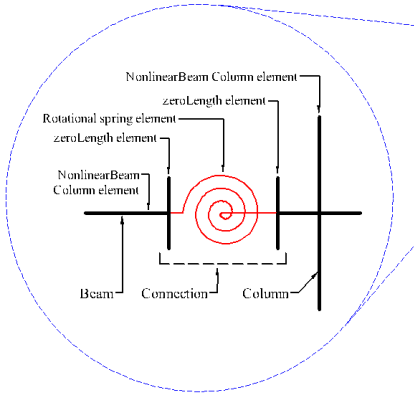


CASE STUDY BUILDING : 10-STORY PETROCHEMICAL MRF

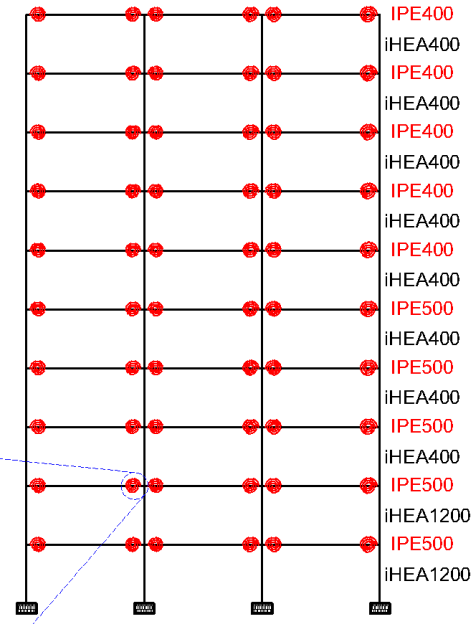




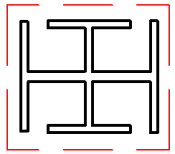
Smart Connection [24]



Self-Centering Connection Scheme



IPE: Beams iHEA: Columns



iHEA Column Profile

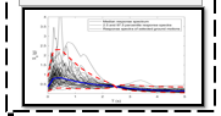
PROBABILISTIC RESILIENCE FRAMEWORK

Multi-hazard Loading

Seismic Loading Parameters

Seismic Time History Profile

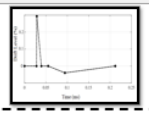
40 ground motion records have been used and scaled based on the pre-conditioned selection

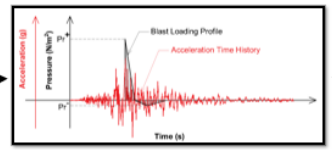


BLEVE

LPG-TNT Quantification (C, L, Tc, Tb, To, WTNT, …)

LPG-Based Blast Loading Profile





Building Modeling Information

Numerical Building Modeling (local-system modeling, and global system modeling)

Material and Geometry Nonlinearity

Required Information

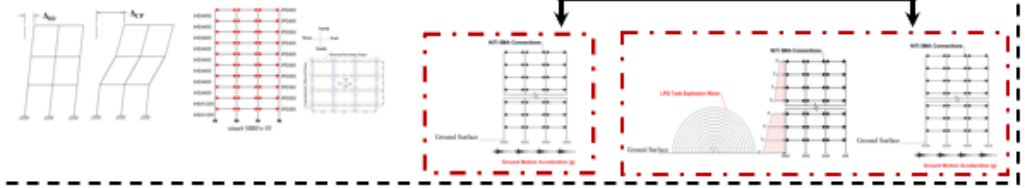
- Levels of Performance
- Level of Loading (Blast and Seismicity)
- General Building Description

Benchmark Model

Non-linear Time History Analysis

Modal Analysis → Gravity Analysis → Time History Analysis → LPG vessel damage

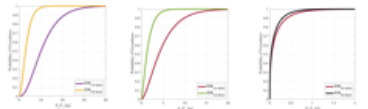
No | Yes



Multi-Hazard Probabilistic Analysis

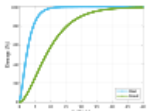
Fragility Analysis

$$P_{fr}(ISDR)_{ij} = P(ISDR_d \geq ISDR_d | I_k, W_{i_1,..,i_n})$$



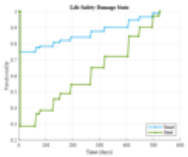
Vulnerability Analysis

$$\sum_{ds=1}^{n} P[ds = DS] XMDF_{ds}$$



Resilience Analysis

$$R = \int_{t_{OE}}^{t_{OE}+T_{RE}} \frac{Q(t)}{T_{RE}}$$



Recovery Analysis

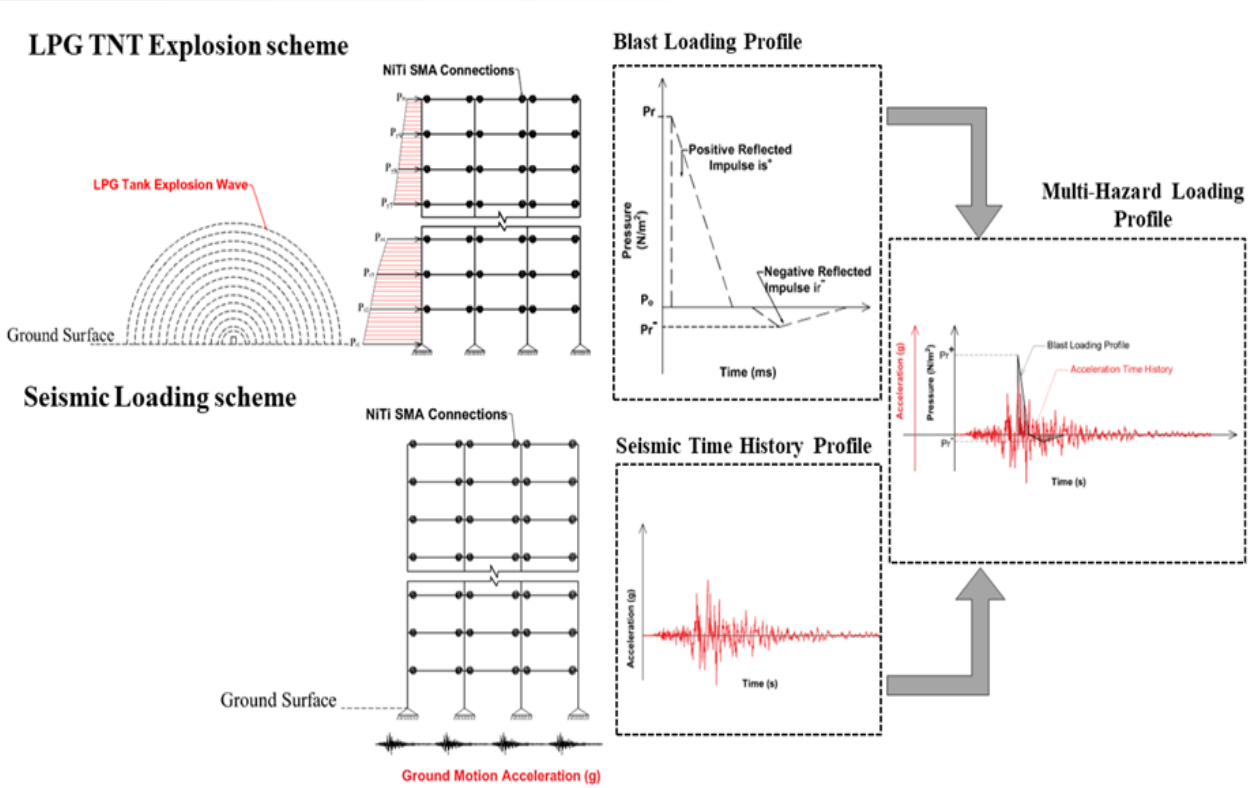
$$f_{rec} = a\left(\frac{t-t_{OE}}{T_{RE}}\right) + b \quad \text{linear}$$

$$f_{rec} = a\, exp\left(-b\frac{t-t_{OE}}{T_{RE}}\right) \quad \text{exponential}$$

$$f_{rec} = \frac{a}{2}\left\{1 + \cos\left[\frac{\pi b(t-t_{OE})}{T_{RE}}\right]\right\} \quad \text{trigonometric}$$

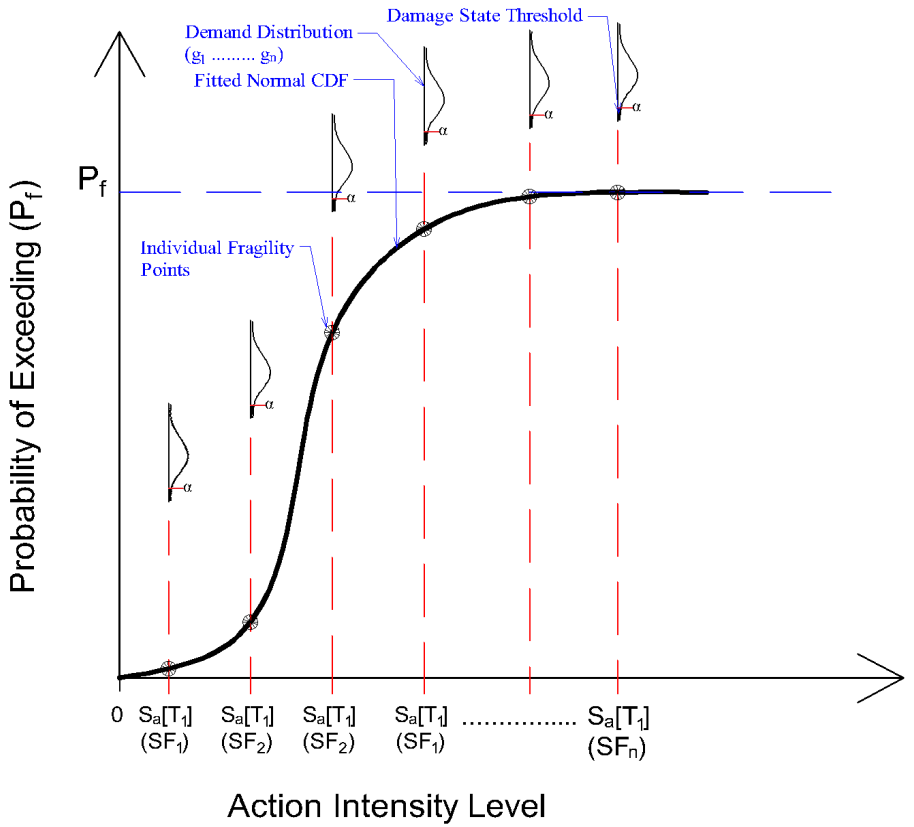
EARTHQUAKE RECORDS USED

- 40 recorded ground motions from the PEER database..
- During each nonlinear time-history, we monitor PGA vs. the tank's capacity threshold.
- If the threshold is exceeded, the BLEV blast is triggered and its overpressure record is appended at that time; if not, the building sees earthquake only.
- We apply the combined profile as: ground acceleration at the base + reflected overpressure on the front façade (simultaneously, per the trigge time).



FRAGILITY ANALYSIS

- Multi-Strip Analysis (MSA) used to derive fragility functions.
- Residual Inter-Story Drift Ratio (RISDR) as performance parameter.
- Normal distribution of demand → fragility points.
- Fragility curves capture: Probability of exceeding damage thresholds.Seismic + BLEVE uncertainties.



VULNERABILITY ANALYSIS

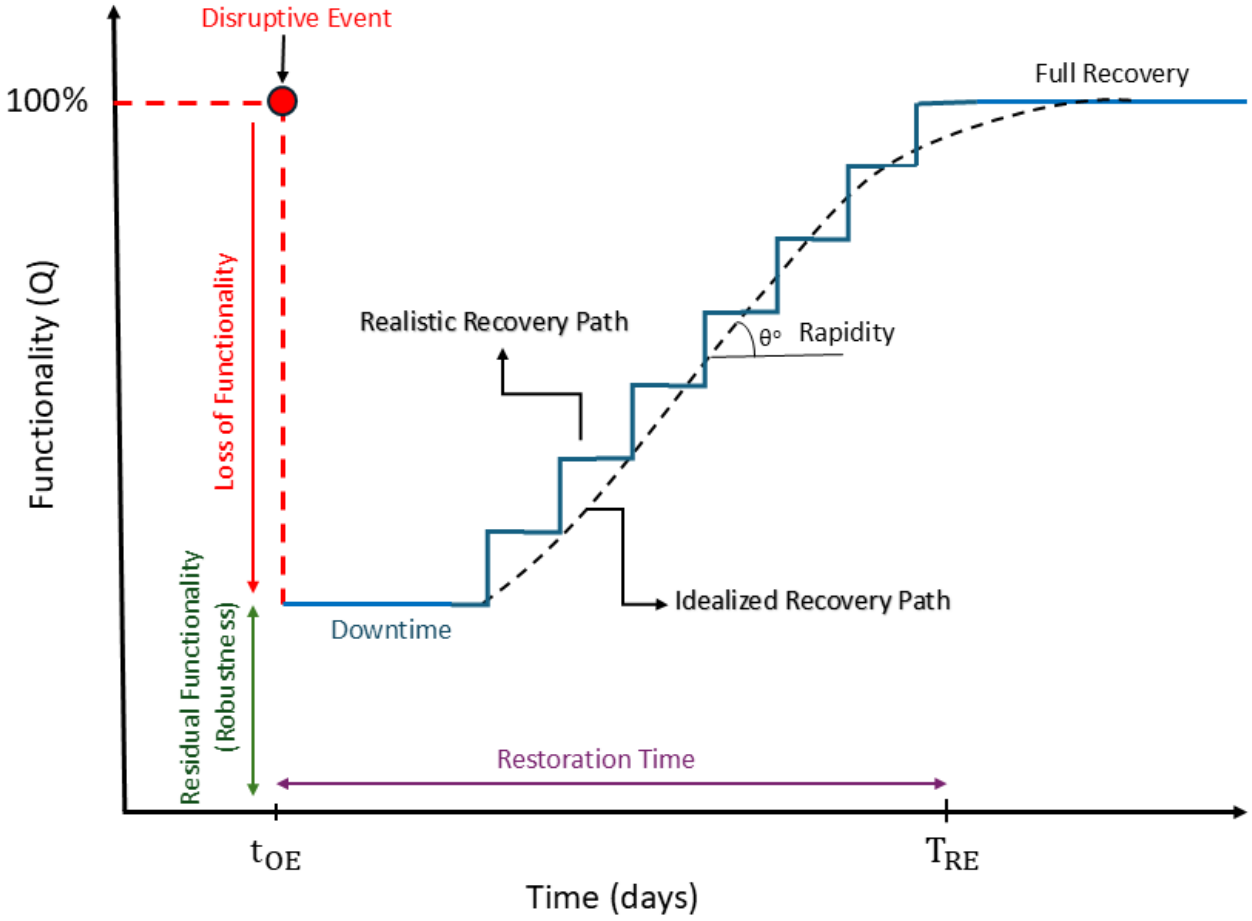
- % Damage Vs. % hazard intensity
- $Vulnerability = \sum_{ds=1}^{n} P[ds = DS] XMDF_{ds}$

Range of damage factors [62,63].

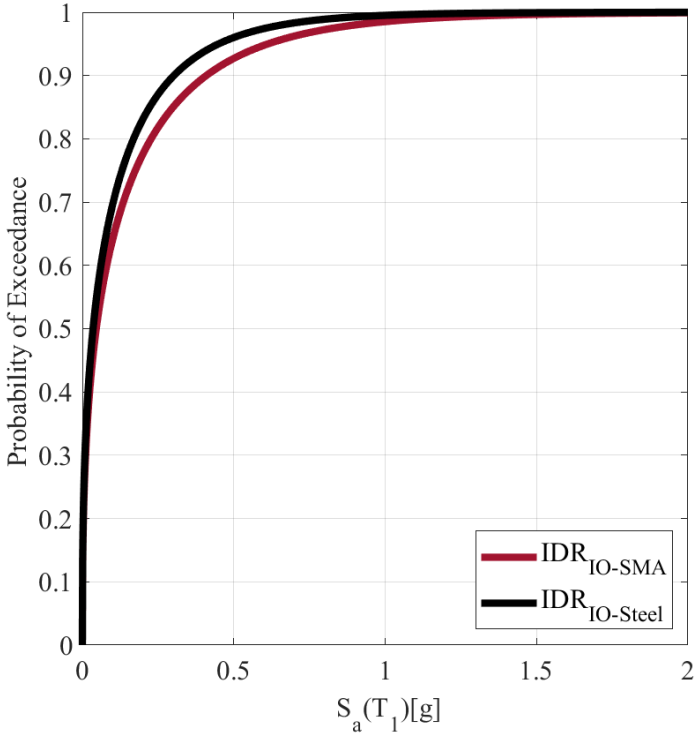
Damage state	Damage factor range (%)	Mean damage factor (%)
None	0	0
IO	>0–4	2
LS	4–96	50
CP	100	100

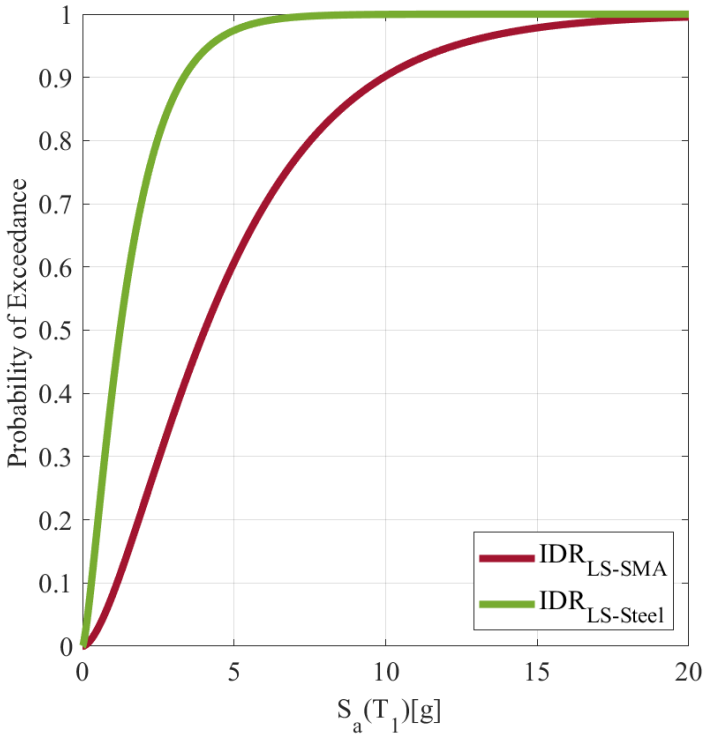
(FEMA – 356)

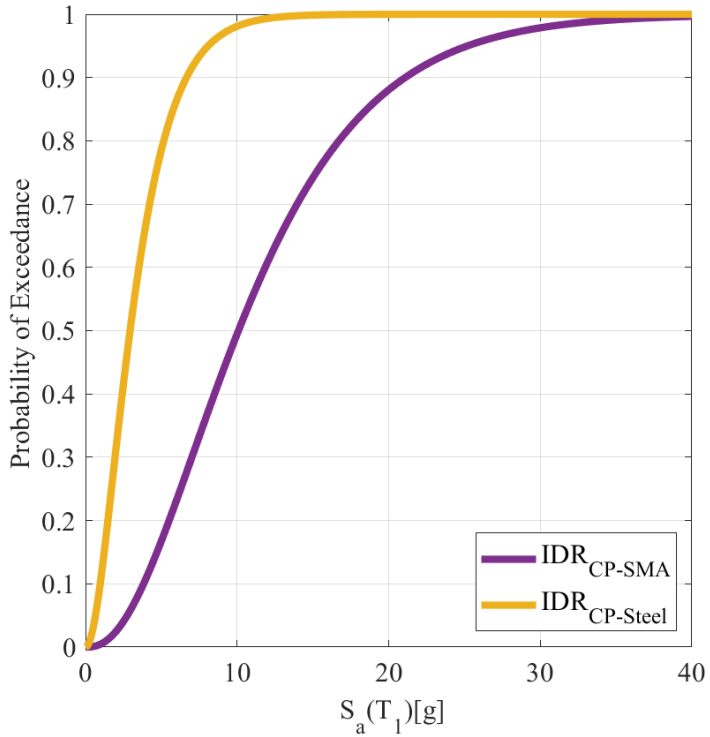
RESILIENCE ANALYSIS



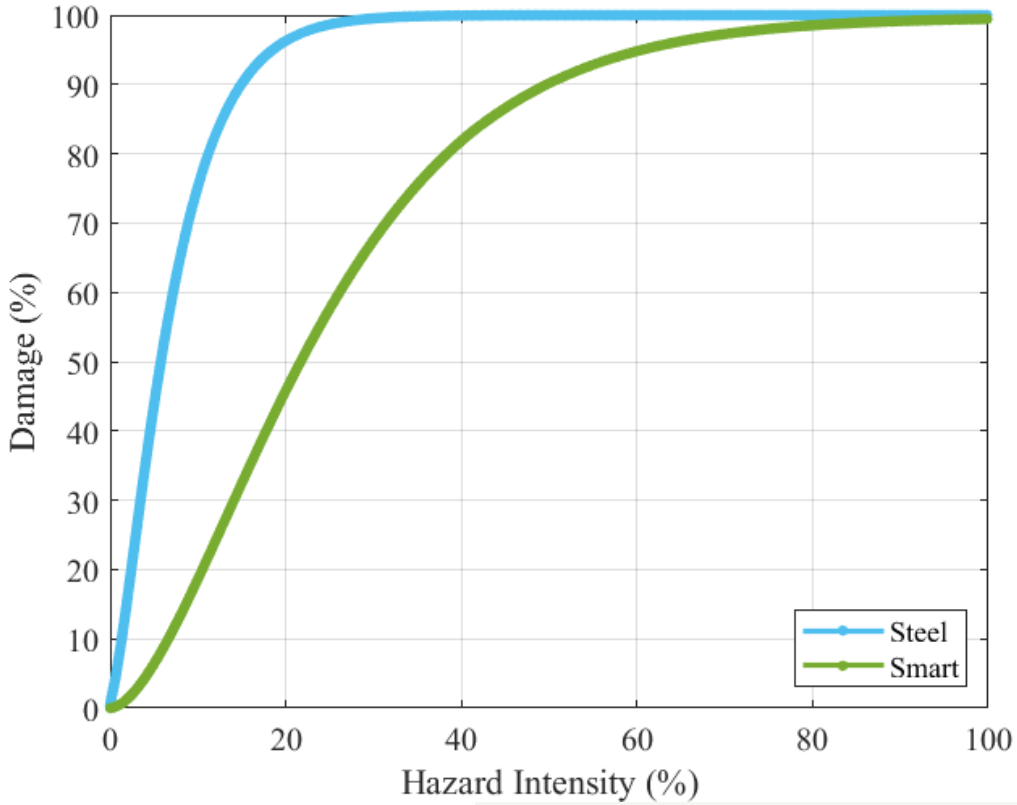
FRAGILITY ANALYSIS RESULTS



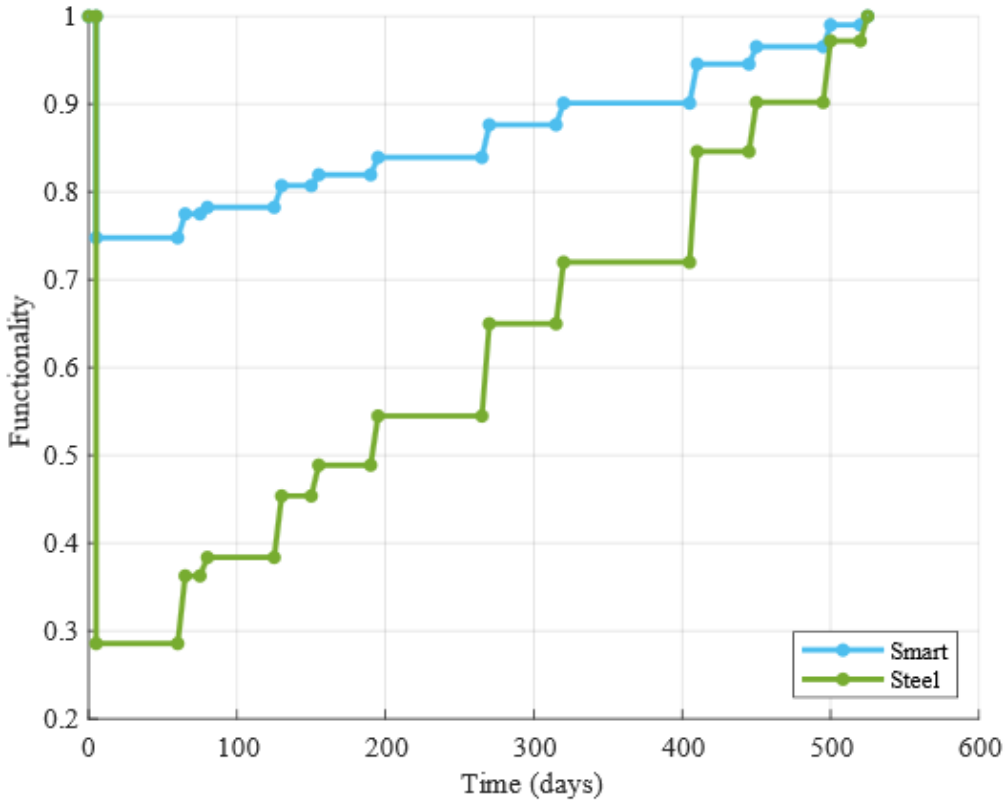


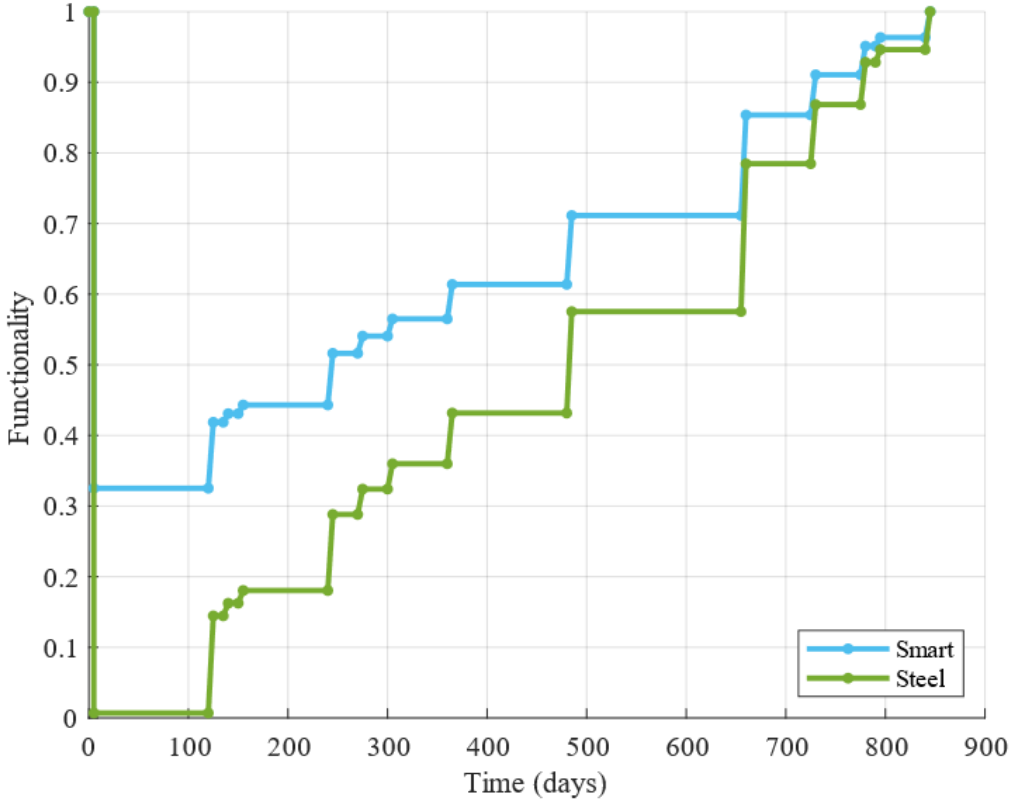


Vulnerability Results



RESILIENCE RESULTS





10. KEY CONCLUSIONS

- Developed a time history seismic-blast loading profile based on LPG vessel collapse; algorithm efficiently evaluated resilience.
- Vulnerability analysis:
- Steel MRFs = greater vulnerability and rapid deterioration.
- Smart MRFs = slower damage progression with distinct curve patterns.
- Resilience assessment: Smart MRFs maintained higher operational capacity under multi-hazard loading.
- NiTi SMA connections + key design procedures enhanced system performance of petrochemical steel structures.
- Singlehazard cases (seismic & blast): Smart MRFs showed controlled damage progress and improved performance.
- Adopted design procedures ensured uniform stiffness & strength distribution, supporting global collapse mechanisms and improved resilience.