COMPARATIVE LOSS ASSESSMENT OF A STEEL HOSPITAL USING MULTI-RESOLUTION NUMERICAL MODELS

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**Basic Definitions**

**Fragility**
- The conditional probability of exceeding a certain damage limit state (incremental dynamic analysis or other methods).

**Functionality & Recovery**
- Fragility functions, 
  \[ F(x) = \Phi\left[\ln\left(\frac{x}{m_R}\right)/\beta_R\right] \]
  - Fragility functions, function of the fragility of the lifeline to offer the service of available staffed beds and waiting time.
  - The capacity to recover quickly from the earthquake or the ability to afford certain levels of functionality for a critical building (area underneath the functionality curve).

**Losses**
- Direct economic losses, Direct social Losses, Indirect economic losses, Non-structural losses, function of the fragility of the lifeline to offer the service of available staffed beds and waiting time.

**Resilience**
- The capacity to recover quickly from the earthquake or the ability to afford certain levels of functionality for a critical building (area underneath the functionality curve).
- Defined as the ability of the lifeline to offer the service of available staffed beds and waiting time.

The driving engine for quantifying resilience is fragility functions, which is commonly determined using FE analysis.

*What type of FE model shall be used!*
**Modeling Resolution**

Different finite element modeling resolutions used in analysis:

- **Basic model**
- **Enhanced model**
- **Soil-structure interaction**
- **Stick model with lumped masses**
- **2-D model**
- **3-D model**

The effect of modeling resolution on the fragilities and the corresponding resilience is lacking
**Building Description**

- A buckling-restrained brace (BRB) hospital building
- Designed by *NEHRP* for Memphis, TN, USA
- *Six* stories and basement floor, *six* bays in N-S and *five* bays in the E-W direction
- Rests on *silty-clay* soil using an *isolated* footings and retaining wall for the basement floor
**APPROACH**

**Developed Models**

- **B-2D-NS**
  - Basic 2-D model *without* soil-structure interaction
  - *Simple* models for materials and connections

- **E-2D-NS**
  - *Simple to enhanced finite element model*

- **E-3D-NS**
  - Enhanced 3-D model *without* soil-structure interaction
  - *Comprehensive* model for materials and connections

- **E-3D-WS**
  - Enhanced 3-D model *with* soil-structure interaction
  - *Comprehensive* model for materials and connections
**Model Components**

- Bucking restrained brace core model
- Rigid connection model - ANSYS finite element
- Semi-rigid Connection model - ANSYS finite element
- Pinned Connection model
- Soil model - Beam on non-linear Winkler model
- Steel material model
- Basic model
- Enhanced model

**Results**

- Elongation %
  - Normalized axial force
  - Load
  - Displacement
- Load
- Displacement
- Yielding zone steel core
- X
- Z
- Φ

**Background**

- Model Components

**Objectives**

- APPROACH

**Conclusions**

- APPROACH
**Fragility**
- 44 ground motion records (FEMA-P695) used
- Damage limit state (HAZUS MH-MR5) utilized
- Incremental dynamic analysis developed for different model
- Lognormal parameters ($\mu$, $\sigma$) estimated

**Losses**
- Direct economic losses
  \[
  L_{SDE}(I) = \{R_S \cdot \sum_{j=1}^{n} C_{s,j} \cdot P_{S,R}(I)\} + \sum_{k=1}^{N_{NS}} [w_k \cdot R_{NS} \cdot \sum_{j=1}^{n} C_{NS,j} \cdot P_{NS,R}(I) / N_{NS}] + R_C \cdot \sum_{j=1}^{n} [C_{C,j} \cdot P_{C,R}(I)] \cdot \prod_{i=1}^{T_i} \frac{(1 + \delta_i)}{(1 + r_i)}
  \]
- Direct social losses
  \[
  L_{DS}(I) = \left[\sum_{i=1}^{4} (\alpha_i \cdot N_{i,\text{in}}) + \sum_{i=1}^{4} (\alpha_i \cdot N_{\text{out}})\right] / N_{\text{tot}}
  \]
- Indirect economic losses
  \[
  L_{IE}(x) = \sum_{t=0}^{TR} ((1 - Q_V(t)) \cdot C) + \sum_{t=0}^{TR} ((1 - R_f) \cdot I_{\text{tot}} \cdot (1 - Q_V))
  \]
- Indirect social losses
  \[
  L_{IS}(x) = \frac{N_{\text{inj}}}{N_{\text{tot}}}
  \]
Direct Economic Losses

- Direct economic losses: \( f(\text{structural losses, non-structural components losses, content losses, replacement cost, Depreciation and interest ratios etc.}) \)

\[
L_{S,DE}(I) = (R_S \cdot \sum_{j=1}^{n} [C_{S,j} \cdot P_{S,R}(I)]) + \sum_{k=1}^{N_{NS}} [w_k \cdot R_{NS} \cdot \sum_{j=1}^{n} [C_{NS,j} \cdot P_{NS,R}(I)]/N_{NS}] + R_C \cdot \sum_{j=1}^{n} [C_{C,j} \cdot P_{C,R}(I)] \prod_{i=1}^{T_i} \frac{1 + \delta_i}{(1 + r_i)}
\]

- \( I \) is the earthquake intensity
- \( j \) is the damage state level
- \( R_S, R_{NS}, R_C \) are the replacement cost for the structural, non-structural and content; respectively.
- \( C_{S,j}, C_{NS,j}, C_{C,j} \) are the repair cost ratio of structural, non-structural and content; respectively.
- \( P_{S,R}, P_{NS,R}, P_{C,R} \) are the damage fragility functions for the structural, non-structural and content; respectively.
- \( w_k \) is a weighting factor for each non-structural component
- \( N_{NS} \) is the non-structural component total number
- \( \delta_i \) is the annual depreciation rate
- \( r_i \) is the annual discount rate}

**Structural component losses**

**Non-structural component losses**

**Content losses**
**Direct Social Losses**

- Direct social losses: \( f(\text{building occupant, severity level, building fragility etc.}) \)

\[
L_{DS}(I) = \left[ \sum_{i=1}^{4} (\alpha_i \cdot N_{i,in}) + \sum_{i=1}^{4} (\alpha_i \cdot N_{i,out}) \right] / N_{tot}
\]

- \( I \) is the earthquake intensity
- \( i \) is the severity level
- \( \alpha_i \) is a weighting factor
- \( N_{i,in} \) is number of the indoor causalities
- \( N_{i,out} \) is number of the outdoor causalities
- \( N_{tot} \) is total number of the hospital building occupants

\[
N_{i,in} = N_{in} \cdot P_{i,in} \quad N_{i,out} = N_{out} \cdot P_{i,out}
\]

- \( P_{i,in} \) is the probability of the indoor causalities
- \( P_{i,out} \) is the probability of the outdoor causalities
**Indirect Economic Losses**

- Indirect economic losses: \( f(\text{business interruption, income losses, functionality}) \)

\[
L_{IE}(I) = \sum_{t=0}^{TR}(1 - Q_V(t)) \times C + \sum_{t=0}^{TR}(1 - R_f) \times I_{tot} \times (1 - Q_V)
\]

- \( I \) is the earthquake intensity
- \( TR \) is the total recovery time
- \( Q_V \) is the quantitative functionality
- \( C \) is the daily revenue of the hospital
- \( R_f \) is the recapture factor
- \( I_{tot} \) is total income of the hospital

**Indirect Social Losses**

- Indirect social losses: \( f(\text{number of patient suffering due to loss of functionality}) \)

\[
L_{IS}(t) = \frac{N_{inj}}{N_{tot}}
\]

- \( N_{inj} \) is the number of the patient who could get the hospitalization service
- \( N_{tot} \) is total number of the patient treated by the hospital
**Functionality (quantity-\(Q_v\))**

- **Fault tree** introduced to estimate the hospital **quantitative functionality**
- **Quantitative functionality** of hospital measured in terms of number of **staffed beds**

Based on work Mitrani-Reiser et. al. with modifications
**INCREMENTAL DYNAMIC ANALYSIS**

- **IDA** rigorously checked
- Observed **difference** between the IDAs for all models
- The dark black curve represents the **mean IDA** for each model
The model \textit{(B-2D-NS)} is not representative of performance.

The 2-D models are \textit{not-conservative}.

SSI is more relevant at \textit{higher earthquake intensities}.

The 3-D model with SSI \textit{(E-3D-WS)} shows \textit{more failure} at lower earthquake intensities compared with other models.

The building response differs based on \textit{earthquake direction}. 

\textbf{IDA for different modeling resolution level}

\begin{itemize}
  \item The model \textit{(B-2D-NS)} is not representative of performance.
  \item The 2-D models are \textit{not-conservative}.
  \item SSI is more relevant at \textit{higher earthquake intensities}.
  \item The 3-D model with SSI \textit{(E-3D-WS)} shows \textit{more failure} at lower earthquake intensities compared with other models.
  \item The building response differs based on \textit{earthquake direction}.
\end{itemize}
Fragility Functions

- The 2-D models result in less probability of failure.
- The SSI effect is similar for both the 2-D and 3-D models.
- The 3-D model with SSI (E-3D-WS) results in the highest damage for both the structural and non-structural components.
- The difference is significant for the drift-sensitive components compared to the acceleration-sensitive ones.
The 2-D models resulted in the least losses. The SSI effect is not significant for both directions, but it is a function of the earthquake direction. The 3-D models show major effect on the loss estimation. The 3-D model with soil-structure interaction (E-3D-WS) results in the highest losses. The majority of losses resulted from the non-structural components.
Are they Required?
ADVANCED SIMULATIONS

Are they Required?

Step Time=0 sec
Temperature=20°C

Step Time=10 min
Temperature=704°C

Step Time=20 min
Temperature=773.5°C

Step Time=30 min
Temperature=843°C

Step Time=40 min
Temperature=860.6°C

Step Time=50 min
Temperature=909.4°C
Using the basic model without soil is not representative of the structural behavior.

Using the 2-D modeling approach is not conservative and is not recommended for the investigated building.

The effect of soil-structure interaction is significant specially for the higher intensity earthquakes.

Using the 3-D models increases the expected probability of failure because more failure mechanisms are being captured.

Estimating the hospital losses is a function of the modeling resolution and the earthquake direction and intensity.

Evaluating the hospital functionality is not only dependent on the surrounding lifelines but also on the finite element resolution used to model the building.
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Thanks for Your Attention!