A Modified Response Spectrum Analysis Procedure (MRSA) to Determine the Nonlinear Seismic Demands of Tall Buildings
The Earthquake Problem

Seismic waves lengthen and diminish in strength as they travel away from the ruptured fault. Ground motion can be amplified by soil. Site Response:

Future ground shaking

Building

Linear/Nonlinear Analysis Model

Characterization of Seismic Ground Motions

Estimation of Linear/Nonlinear Seismic Demands

- Global-level Responses
- Inter-story Responses
- Component-level Responses
Simplified Estimation of Seismic Demands

Simplified Structural Models

Any combination of simplified approaches

Models accounting for only shear deformations
Models accounting for only flexure deformations
Models accounting for both shear and flexural deformations
Equivalent MDOF models

Nonlinear Static Procedures (NSPs)
Linear Static Procedure (LSP)
Multi-mode Pushover Analysis
Response Spectrum Analysis (RSA)

Simplified Seismic Analysis Procedures

Simplified Loading

Triangular
Uniform
Varying
Modal Expansion
Dynamic Response of Structures – The Concept of Vibration Mode Shapes
The World of Linear Elastic Seismic Analysis of Structures

Structural Models

- Detailed 3D Linear Model
- Linear Elastic MDF Model
- The Equivalent Lateral Force Procedure (LSPs)
- Linear Elastic SDF Model

Seismic Loading

- Static Single Lateral Load Vector
- Static Multiple Lateral Load Vectors
- Ground Motions

Relative Uncertainty

- Low
- High

The Linear Response History Analysis (LRHA) Procedure (Direct Integration)

Modal Analysis, Spectral Analysis, Standard Response Spectrum Analysis (RSA) Procedure

The Equivalent Lateral Force Procedure (LSPs)

Seismic Loading
The NLRHA Procedure
using Simplified SDF Model

The Nonlinear Static Procedures (NSPs)

Detailed 3D Nonlinear Model

Equivalent Nonlinear MDF Model

Equivalent Nonlinear SDF Model

Static Single Lateral Load Vector

Static Multiple Lateral Load Vectors

Ground Acceleration Records

The Detailed Nonlinear Response History Analysis (NLRHA) Procedure

The Multi-mode Pushover Analysis Procedures

The NLRHA Procedure using Simplified MDF Model

The NLRHA Procedure using Simplified SDF Model

Structural Models

Relative Uncertainty

Low

High

Seismic Loading

The World of Nonlinear Seismic Analysis of Structures
Linear Elastic Model

Eigen-value Analysis

\[[K - \omega^2 M]\Phi = 0\]

Determine Modal Properties

\[T_i, \phi_i, I_i\]

N Stories

Determine Modal Properties

\[T_1, T_2, T_3\]

Spectral Acceleration (SA)

\[SA_1, SA_2, SA_3\]

For Initial Viscous Damping

Time Period (sec)

\[T_1, T_2, T_3\]

Determine Spectral Acceleration for each Significant Mode

\[V_{b1}, V_{b2}, V_{b3}\]

\[V_{b1} = \sum_{i=1}^{N} m_i \cdot \phi_{i,n} \cdot SA_n\]

\[V_{el} = \sqrt{(V_{b1})^2 + (V_{b2})^2 + (V_{b3})^2 + \ldots}\]

Determine Elastic Base Shears

\[F_{e1}, F_{e2}, F_{e3}\]

\[F_{ei} = R \cdot V_{el}\]

\[\Delta_{el} = \Delta_{in}\]

Reduce Elastic Base Shear to account for inelasticity

\[R = \text{Response Modification Factor, ASCE 7 (or Behavior Factor, EC 8)}\]

\[V_{in} = \frac{V_{el}}{R}\]

\[\Delta = \frac{C_d \sqrt{\Delta_{e1}^2 + \Delta_{e2}^2 + \Delta_{e3}^2 + \ldots}}{R}\]

Problem

- Different modes undergoes different levels of nonlinearity.
- Reducing elastic responses of every mode by the same \(R\) factor is not correct.
- Several ‘modified’ RSA procedures have been proposed—using different \(R\) factor for different mode.

\[F_{in} = \frac{F_{e1}}{R}\]

\[\Delta_{in} = \Delta_{el}\]
The Original Intent of R

- **Basic Idea:**
  - A structure can be economically designed for a “fraction” of the estimated elastic seismic design forces, while maintaining the basic life safety performance objective.

- The intent of R is to simplify the structural design forces such that only linearly elastic static analysis is needed for most building design.

- “R” factor can be traced back to a “K” factor which appeared in the first edition of the Blue Book (SEAOC Recommended Lateral Force Requirements and Commentary) in 1959.
### What “R” to use?

<table>
<thead>
<tr>
<th>Structural Type and Material</th>
<th>US West Coast</th>
<th>Japan</th>
<th>New Zealand**</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Frame</td>
<td>8</td>
<td>1.8 – 3.3</td>
<td>9</td>
<td>5.85</td>
</tr>
<tr>
<td>Concrete Structural Wall</td>
<td>5</td>
<td>1.8 – 3.3</td>
<td>7.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Steel Frame</td>
<td>8</td>
<td>2.0 – 4.0</td>
<td>9</td>
<td>6.3</td>
</tr>
<tr>
<td>Steel Eccentrically Braced Frame</td>
<td>8</td>
<td>2.0 – 4.0</td>
<td>9</td>
<td>6.0</td>
</tr>
<tr>
<td>Masonry Walls</td>
<td>3.5</td>
<td>-</td>
<td>6</td>
<td>3.0</td>
</tr>
<tr>
<td>Timber Structural Walls</td>
<td>-</td>
<td>2.0 – 4.0</td>
<td>6</td>
<td>5.0</td>
</tr>
<tr>
<td>Pre-stressed Wall</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dual Wall/Frame</td>
<td>8</td>
<td>1.8 – 3.3</td>
<td>6</td>
<td>5.85</td>
</tr>
<tr>
<td>Bridges</td>
<td>3 – 4</td>
<td>3.0</td>
<td>6</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**$S_p$ factor of 0.67 incorporated**

Source: “Direct Displacement-based Design” by Priestley MJN et al., 2007
What “R” to use?

Is it justified to “equally” modify the response of each vibration mode?

R ???

Our Approach
Lets separate them and check one-by-one

What actually happens to the structure during the time history analysis?
The Concept of Modal Decomposition
Modal Decomposition of Nonlinear Seismic Responses

Classical Modal Analysis

A Detailed 3D Elastic Structural Model

The Uncoupled Modal Response History Analysis (UMRHA)

A Detailed 3D Inelastic Structural Model

Mode 1

Mode 2

Mode 3

+$\ldots$
The Uncoupled Modal Response History Analysis (UMRHA) Procedure
The Equivalent Single-degree-of-freedom (SDF) System

- Full 3D Nonlinear MDF Model
- Monotonic Pushover Analysis
- Determination of Pushover Curve
- Idealization of Pushover Curve
- Equivalent SDF System
Monotonic Pushover Analysis

A 44-story Case Study Building

Base Shear vs. Roof Drift Ratio

Pushover Curve (Strong Direction)

3D View

Elevation View

No Crack

Cracked
Cyclic Pushover Analysis

<table>
<thead>
<tr>
<th>Base Shear (V)</th>
<th>Roof Drift (Δ)</th>
</tr>
</thead>
</table>

Δ

V
Mapping the Cyclic Response to an Equivalent SDF System

Normalized Base Shear ($V_{b1}/W$) vs. Roof Drift ($x_{T}/H$)

- Reversed-cyclic Pushover Analysis (Solid Line)
- Response of an equivalent SDF system under a ground motion
The CONCLUSION – Each Mode is Different …

Normalized Base Shear ($V_{b1}/W$)

$V_{b2}/W$

$V_{b3}/W$

Cyclic pushover curve

Idealized SDF system
The CONCLUSION – Each Lollipop is Different …
From UMRHA to The Modified Response Spectrum Analysis (MRSA)
What Happens when a System Starts Experiencing Nonlinearity?

- Natural Period Elongation
- Additional Hysteretic Damping
Natural Period Elongation

Mode 1 - Roof Drift (Δ/H)
44-story building – Strong Direction

Uncoupled Modal Response History Analysis (UMRHA)

Peak Amplitude Cycle with Scale Factor of 0.1

Period Elongation with increasing Scale Factor

Scale Factor to Ground Motion
- 0.1  - 0.5
- 1   - 1.5
- 2   - 2.5
- 3   - 4
- 5   -
The Basic Concept of Modified Response Spectrum Analysis (MRSA)

Nonlinear Structure

Detailed 3D Nonlinear Response History Analysis (NLRHA)

Uncoupled Modal Response History Analysis (UMRHA)

Modified Response Spectrum Analysis (MRSA)
The Basic Concept of Modified Response Spectrum Analysis (MRSA)

Linear Elastic Structure

\[ F_{1} + F_{2} + F_{3} + \ldots \]

\[ T_1 \quad S_A_1 \]

\[ T_2 \quad S_A_2 \]

\[ T_3 \quad S_A_3 \]

For Initial Viscous Damping
Conversion of a Nonlinear System in to an “Equivalent Linear” System

Equal-Energy Assumption

Energy dissipated by total damping in a Nonlinear System

= Energy dissipated by equivalent viscous damping in an equivalent linear system

\[ \begin{align*}
\xi_h &= \frac{1}{4\pi} \frac{E_D(x)}{E_{so}(x)} = \frac{E_D(x)}{2\pi K_e x_o^2} \\
E_{so}(x) &= \frac{1}{2} E_D(x) \int_{x_o}^{x} K_i \, dx
\end{align*} \]

A Nonlinear System

Converted to

An Equivalent Linear System with Elongated Period and Additional Damping

Total \( \xi_{eq} \) = Sum of Equivalent Inherent Damping and Equivalent Hysteretic Damping
Evaluation of the MRSA Procedure - 3 Case study Buildings

- Located in Bangkok, Thailand
- Heights vary from 20 to 44 stories
- RC slab-column frames carry gravity loads
- RC walls & cores resist lateral loads
- Masonry infill walls extensively used
- Designed for wind loads, but not for seismic effects
- Possess configuration irregular features commonly found in typical tall buildings, such as podium and non-symmetrical arrangement of RC walls, etc.
Ground Motions

Short-Period Target Spectrum and Matched Ground Motions – Set 2

UHS Target Spectrum and Matched Ground Motions – Set 1

Long-Period Target Spectrum and Matched Ground Motions – Set 3

Spectral Acceleration (g) vs. Time Period (sec)
Ground Motions

![Ground Motions Graph](image)

- **5%-damped Target Response Spectrum**
- **Mean of Matched Ground Motions**
- **Individual Ground Motions**

- **Typical Code Target Spectrum and Matched Ground Motions**
  - Set 4

- **Parameters**
  - $\xi = 2.5\%$
  - $\xi = 5\%$
  - $\xi = 10\%$
Nonlinear Modeling of Case Study Buildings

Masonry Infill Wall Model (FEMA 356)

Lumped Fibers for RC Columns

MVLEM for RC Walls

Fiber section element (concrete and steel fibers)
Linear-elastic frame element (shear deformation excluded)
Linear shear spring

Rigid Link

Level m

Linear shear spring
Concrete and Steel fibers

Level m-1

Rigid Link

Level m

Linear shear spring
Concrete and Steel fibers
Cyclic Pushover
Monotonic Pushover in Positive Direction
Monotonic Pushover in Negative Direction

Brick walls begin to crack
Shear walls begin to crack
Columns begin to Crack
Shear wall’s steel reinforcement bars begin to yield in tension
Shear wall’s steel bars begin to yield in compression
Concrete crushing in shear wall
Column’s steel bars begin to yield in tension
Column’s bars begin to yield in compression

Strong (x) Direction

Normalized Base Shear ($V/W$)

Roof Drift ($x_r/H$)
Cyclic Pushover Analysis – Strong Direction

Normalized Base Shear ($V_b/W$)

19-story Building
Mode 1

20-story

33-story Building
Mode 1

33-story

44-story Building
Mode 1

44-story
UMRHA vs. NLRHA

Displacement Envelope

Inter-story Drift Ratio

Story Shear Envelope

Overturning Moment

44-story case study building in Strong Direction
Modal Decomposition of Nonlinear Response

44-story case study building in Strong Direction
Modal Decomposition of Nonlinear Response

44-story case study building in Strong Direction
Shear Wall Cracking

- UHS-Matched Ground Motion Set 1
- 0.2 sec CMS-Matched Ground Motion Set 2
- 3 sec CMS-Matched Ground Motion Set 3

- 25% of Cracking Strain
- 50% of Cracking Strain
- 80% of Cracking Strain
- Already Cracked
“Equivalent Linear” Properties

(a) $T_{sec,i}/T_i \ vs. \ Roof \ Drift \ Ratio \ (x_i^T/H)$
“Equivalent Linear” Properties

Hysteretic Damping from Area Enclosed by Cyclic Pushover Curves

\[ \xi_{h,i} \] (%)

Roof Drift ratio, \( x_i^T / H \) (%)

(b) \( \xi_{h,i} \) vs. Roof Drift Ratio (\( x_i^T / H \))

20-story (Mode 1) - Each loop start from initial unloaded condition

20-story (Mode 1)

33-story (Mode 1)

44-story (Mode 1)
Performance of MRSA at Individual Mode Level – EQ 1

Modal Story Shears of a 44-story case study building in Strong Direction
Performance of MRSA at Individual Mode Level – EQ 2

Mode 1

Mode 2

Mode 3

Modal Story Shears of a 44-story case study building in Strong Direction
Performance of MRSA at Individual Mode Level – EQ 3

Modal Story Shears of a 44-story case study building in Strong Direction
Overall Performance of MRSA – EQ Set 1

Displacement Envelope

Inter-story Drift Ratio

Story Shear Envelope

Overturning Moment

44-story case study building in Strong Direction
Overall Performance of MRSA – EQ Set 2

Displacement Envelope

Inter-story Drift Ratio

Story Shear Envelope

Overturning Moment

44-story case study building in Strong Direction
Overall Performance of MRSA – EQ Set 3

Displacement Envelope

Inter-story Drift Ratio

Story Shear Envelope

Overturning Moment

44-story case study building in Strong Direction
Local Response - Bending Moment in Columns (EQ Set 4)

44-story case study building (Strong Direction)
Local Response – Shear Walls (EQ Set 4)

44-story case study building (Strong Direction)
Local Response – Axial Strain in Shear Walls (EQ Set 4)

44-story case study building (Strong Direction)
Seismic Analysis Practice for Structural Design - The Case of Pakistan
How Safe are Our Buildings Against Earthquakes?
CHAPTER 2

SEISMIC HAZARD

2.1 Scope

This Chapter defines the minimum seismic hazard that has to be considered for the design of buildings.

2.2 Design Basis Ground Motion

Unless otherwise required, buildings shall be designed for a level of earthquake ground motion that has a 10% probability of exceedance in 50 years.

2.3 Seismic Zones

For the purpose of seismic design of buildings, Pakistan has been divided into five zones. These zones are based on the peak ground acceleration ranges summarized in Table 2.1.

The seismic zoning map of Pakistan is given in Figure 2.1. Seismic zoning map of each province is shown in Figures 2.2 to 2.5.

Table 2.2 lists the seismic zones for all tehsils of the country.

2.4 Site-specific Hazard Analysis

The requirements of the seismic zoning map shall be superseded if a site-specific hazard analysis, probabilistic, deterministic or both, is carried out for a building or structure.

2.5 Modeling of Ground Motion

The results of site-specific seismic hazard analysis may be represented by response spectra and acceleration-time histories. The pertinent details are included in Chapter 5.
FIG. 2.1
SEISMIC ZONING MAP OF PAKISTAN

Seismic Zones
Zone 1 → 0.05 to 0.08g
Zone 2A → 0.08 to 0.16g
Zone 2B → 0.16 to 0.24g
Zone 3 → 0.24 to 0.32g
Zone 4 → > 0.32g

Peak Ground Acceleration (g)

For enlargement of this map refer Figs. 2.2 to 2.5.
Abbottabad, 8th October 2005

How much we understand?
Peak Ground Acceleration

Source: Zaman and Warnitchai (2016)
Spectral Acceleration at 0.2 sec

Source: Zaman and Warnitchai (2016)
Spectral Acceleration at 1 sec

Source: Zaman and Warnitchai (2016)
Thank you for your attention