Introduction

Recent devastating earthquakes in Haiti and Chile revealed that we, sometimes, know nothing about the possible earthquake performance of our seemingly properly engineered building structures. This inspired the current team of investigators to step forward with this project.

Figure 1. Residents look at the Concepción 20-story building Alto Río which overturned and collapsed at February 2010 Chile earthquake. Courtesy of AP.

1. Earthquake performance

Earthquake performance is an execution of a structure's ability to sustain its due functions, such as safety and serviceability, at and after a particular earthquake exposure. A structure is, normally, considered safe if it does not endanger the lives and wellbeing of those in or around it by partially or completely collapsing. A structure may be considered serviceable if it is able to fulfill its operational functions for which it was designed.

Basic concepts of the earthquake engineering, implemented in the major building codes, assume that a building should survive The Big One (the most powerful anticipated earthquake) though
with partial destruction. Drawing an analogy with a human body, it will have dislocated joints, fractured ribs, traumatized spine and knocked out teeth but be alive and, therefore, quite O.K. according to the prescriptive building codes. This situation is a major barrier to implementation of any structural innovations in the earthquake engineering technologies employing the seismic vibration control and, particularly, the most effective brands of base isolation.

![Figure 2. A collapsed parking structure at the 1994 Northridge earthquake](image)

Actually, alternative performance-based design approaches already exist but they are implemented, mostly, at earthquake engineering research projects. Some of them, for assessment or comparison of the anticipated seismic performance or for seismic performance analysis, use the Story Performance Rating \( R \) as a major criterion (see A NEW CONCEPT OF DESIGN CODE FOR SEISMIC PERFORMANCE) while the Seismic Performance Ratio (SPR) is used for a rather accurate prediction of seismic performance of a building up to the point of its state of severe damage (see SGER: Testing of a New Line of Seismic Base Isolators).

However, replacement of the present prescriptive design standards with the future codes of performance is not an easy task: most of the designers would be reluctant to accept any additional legal obligations.

### 2. Online performance evaluation

The current educational software called EPETO is to be used for calculation and graphical presentation of horizontal displacements (velocities, accelerations) of each story of a multistory building, with or without a special kind of vibration control, subject to a horizontal input of a
real or synthetic earthquake in two orthogonal horizontal directions. Results of those calculations will be available online from our portal which may be of interest by civil-structural engineering community, including students, practicing engineers, building officials and insurers.

![Figure 3. The UN headquarters in Port-au-Prince, Haiti after the earthquake of January, 2010](image1.png)

### 3. Performance scenarios

The users of EPETO will be able to perform the following basic operations:

- View the mathematical model of a building structure engaged in EPETO (now – up to 10 stories high).
- Specify values of parameters of the building structure to be input.
- Specify the vibration control system (if any) to protect the building structure against the possible earthquake.
- Choose a simulated or real earthquake time-history for a virtual experiment.
- Initiate a virtual process of the building excitation under the impact of earthquake time-histories applied horizontally at the level of building foundation.
- Analyze performance of the virtual building structure during the virtual earthquake excitation with the help of predetermined performance evaluating parameters.
- Display results of the performance analysis in the formats of building performance tables and/or building performance animations.
4. Building model

At the current virtual seismic performance analysis of a building structure, the mathematical model presented below in Figure 4 should be applicable for both orthogonal directions of lateral earthquake inputs.

5. Equations and performance parameters

The mathematical model of a building for each orthogonal lateral direction of a seismic impact is a one-dimensional multiple-degree-of-freedom lumped-mass system that can be analyzed with the help of equations of dynamic equilibrium (1). The system of those equations contains the following parameters:

- \( n \) is the number of stories;
- \( m_n \) is the lumped mass of the \( n \)th story;
- \( u_n \) is the lateral displacement of the \( n \)th story;
$C_n$ is the cumulative velocity related resistance of the $n^{th}$ story which may include both damping ability of the building structure itself and that of special vibration control devices called seismic dampers;

$K_n$ is the displacement related resistance of the $n^{th}$ story (stiffness).

Each of the $n$ non-linear equations (1) represents conditions of equilibrium of a particular story:

$$m_n u_n + C_n (u_n - u_{n-1}) + K_n (u_n - u_{n-1}) = 0$$
$$m_{n-1} u_{n-1} + C_n (u_{n-1} - u_n) + C_{n-1} (u_{n-1} - u_{n-2}) + K_{n-1} (u_{n-1} - u_n) + K_{n-1} (u_{n-1} - u_{n-2}) = 0$$

$$
\vdots
$$

$$m_1 u_1 + + C_2 (u_1 - u_2) + C_1 (u_1 - u_0) + K_2 (u_1 - u_2) + K_1 (u_1 - u_0) = 0
$$

Figure 5. EPETO mathematical model.

For assessment or comparison of the anticipated building performance, the Story Performance Rating $R$ will be used as a major criterion:

$$R = \frac{v}{v_e}$$

where $v = u_n - u_{n-1}$ is an actual or calculated inter-story drift and $v_e$ is an inter-story drift at the assumed elastic limit of horizontal deformation.

The ultimate allowable value of $R$ will occur when

$$R = R_w = \frac{v_u}{v_e}$$
where *Quality Factor* $R_w$ is the ratio of the ultimate allowable story drift $v_u$ that can be tolerated by the structure without collapse to the maximum elastic story drift $v_e$ (Figure 5).

The case $R < 1$ relates to a purely elastic performance.

The case $1 < R < R_w$ defines how far the structure extends into the plastic range.

The case $R > R_w$ means a possibility of either collapse of the story under consideration or occurrence of other life threatening damage. However, this will not immediately and necessarily result in losing full value of the structure.

Ratio $R/R_w$ called *Seismic Performance Ratio* may be chosen as a primary parameter, which would control the anticipated physical losses due to seismic exposure of the building structure.

### 6. Parametric sampling of building structures

The quantitative building identification system employed in the current project is based on the following characteristics:

a) Number of stories $n$.

b) Quality Factor $R_w$ of a building structural system depending on the limit of seismic performance which the structural system can be allowed to reach. In ASCE/SE17 Table 12.2-1, it corresponds to Response Modification Factor $R$.

c) Specific Lateral Stiffness $K_e/m$ of the story under consideration where:

$$K_e$$ is an aggregate lateral stiffness of the story. This value corresponds to the elastic range of horizontal deformations (Figure 5) of the vertical and/or horizontal load-carrying elements, whichever is less;

$m$ is a lumped mass of the story.

Wide variety of building design can be covered with the parameters $K_e/m$, $R_w$ and $n$; see, e.g., http://www.seaint.org/papers.asp.

### 7. Story stiffness and damping

Story stiffness of the basic structural types of the model building may be approximated with a non-linear force-deflection diagram incorporating parameters $K_e$, $m$ and $R_w$ (Figure 5). In particular, for the drift range of $0 \leq v \leq 0.05R_w$ where $v$ is in cm, the normalized story stiffness corresponds to the elastic area:

$$\frac{K_e}{m} = 0.5 \cdot 10^3 - 6.0 \cdot 10^3 \text{ 1/sec}^2$$

(4)
For the drift range of \( v > 0.05R_w \), the normalized story stiffness corresponds to the plasticity area:

\[
\frac{K}{m} = \frac{0.05 K_C R_w}{m v} \exp \left(1 - \frac{0.05 R_w}{v}\right) \text{1/sec}^2
\]  

(5)

Normalized velocity related resistance of a story \( C/m \) (so called normalized "damping" coefficient), corresponding to the range of damping ratio \( \zeta \) from 0.05 through 0.10, may be taken equal to:

\[
C/m = 8.36 \text{ 1/sec}
\]

(6)

To account for system of viscous dampers on a particular story, the above value should be multiplied by the Added Damping Factor \( \alpha = 1.1 - 3.0 \).

8. Damage ratio

Anticipated building damage due to a seismic exposure is characterized by the Damage Ratio \( D.R. \) that may be related to the Seismic Performance Ratio \( R/R_w \). As the first degree of approximation, the following formula may apply:

\[
D.R. = 0.296 \left(\frac{R}{R_w}\right)^3 100 \%
\]  

(7)

The formula is represented graphically in Figure 3 which demonstrates that when \( R = R_w \) (any current building standard’s moment of truth when Demand is equal to Ultimate Capacity), \( D.R. = 30 \% \). If \( R \) value reaches 1.5 \( R_w \), the building’s losses may approach its replacement value, see http://www.ecs.csun.edu/~shustov/Topic8.htm.

9. Range of structural parameters

1. Each story should have the normalized damping coefficient \( C/m = 8.36 \text{ 1/sec} \) (default) if no special story dampers are installed. Otherwise, \( C/m \) may be taken equal to 8.36n 1/sec where n = 1.5, 2.0, 2.5 or 3.0.

2. It is necessary to account for a possibility of basement failure of base-isolated buildings which may happen when the relative displacement of the first floor exceeds the allowable by design value of that displacement. The allowable default values of relative displacements for each type of base isolators are:

To account for a basement failure of base-isolated buildings, the allowable default values and the range of possible deviations of relative displacements for each type of base isolators should have the default values (in the brackets – the range of possible values):

- AFMS Isolation System – 25 cm (15 – 35 cm)
- AFMS CD Isolation System 25 cm (15 – 35 cm)
- Sliding Isolation System (Friction Pendulum Bearing) – 25 cm (15 – 35 cm)
- Earthquake Protector – 60 cm (25 – 100 cm)
- Shear Viscous Isolation System – 50 cm (30 – 70 cm)
• Shear Hysteretic Isolation System – 50 cm (30 – 70 cm)

The default values and the range of possible deviations of friction coefficients for the sliding types of base isolators should be:

• AFMS Isolation System – 0.03 (0.02 – 0.04)
• AFMS CD Isolation System 0.03 (0.02 – 0.04)
• Sliding Isolation System (Friction Pendulum Bearing) – 0.05 (0.04 – 0.06)
• Earthquake Protector – 0.025 (0.02 – 0.03)

10. Parametric sampling of ground motion

Lack of specific time-histories is a concern to many engineers. However, there has been no evidence as so ever of any structure in this country that had inadequate performance due to an inaccurate prediction of the ground motion (at least, during the last decades).

A common cause of building performance below expectations is, instead, inadequate analysis, design and/or construction. On the other hand, "a real time-history" or "an actual earthquake record input" can be neither "real" nor "actual" for a hypothetical earthquake.

Due to foregoing, the most reasonable seismic input for the purpose of this study would be the one that possesses only essential features of the design earthquake, see https://central.nees.org/data/get/NEES-2006-0283/Public/REPORT.pdf.

Therefore, the time-histories known as an earthquake imitation regime Cone (Figure 8) described by Eq.8 will be applied to the building foundation in addition to some recorded time-histories.

\[ u_g = a t \sin 2\pi \log_b[(b-1)t/bT_o + 1] \]  

where

\[ a = \frac{(u_g)_{\text{max}}}{\sqrt{1 + (2\pi/\ln b)^2}} \]

\[ b = \frac{t_s}{t_f - T_s + T_f} \]

\[ t_s = \text{duration of ground shaking per Cone;} \]
\[ T_s = \text{initial instantaneous period of ground shaking;} \]
\[ T_f = \text{final instantaneous period of ground shaking.} \]
Sequence of earthquake intensities will be expressed through *average peak ground velocities* \((u_g)^{ave}\) correlated to the *Modified Mercalli Scale*. In particular, the following *Cone* parameters will be tried:

- average peak ground velocities \((u_g)^{ave} = (u_g)^{max}\) will take the following values: 10, 20, 30, 40, 60 and 80 cm/sec;
- instantaneous periods of vibration: \(T_s = 0.03\) sec and \(T_e = 3\) sec during each earthquake simulation lasting \(t_s = 15\) seconds.

Therefore,
\[
b = \frac{t_s}{t_s - T_e + T_s} = \frac{15}{15 - 3.00 + 0.03} = 1.25 \quad \text{and}
\]

*Cone* displacement time-history is
\[
u_g = 0.527 (u_g)^{max} \sin \left[ 2\pi \log \left( 6.685t + 1 \right) \right]
\]

Application of the *Cone* does not leave chances for missing any hazardous earthquake frequencies: all natural periods of vibration between \(T_s\) and \(T_e\) are rung up in the state of transient resonance.

### 11. Earthquake performance evaluation tool online (EPETO)

The current improved software *Earthquake Performance Evaluation Tool Online* (EPETO) is to be used to calculate and present graphically horizontal displacements, story drifts, velocities and accelerations of each story of a multistory building, with or without some kind of base isolation or structural dampers, for the purpose of performance comparison of the corresponding building models subject to a horizontal input of a real or synthetic earthquake.

Database of the basic building structure parameters is specified in Table 1 and formulas (9) and (10) below in compliance with the designations accepted previously in the Technical Report BCS-9214754 (see [http://www.osti.gov/bridge/servlets/purl/10181073-rbd7LK/10181073.PDF](http://www.osti.gov/bridge/servlets/purl/10181073-rbd7LK/10181073.PDF)) where:

- \(m_n\) is mass of the \(n^{th}\) story to be due from on each isolator; for a regular building structure, assume: \(m_n = 10,000 – 25,000\) kg;
- \(v_n\) is the current drift of the \(n^{th}\) story;
- \(v_{en}\) is the drift of the \(n^{th}\) story at the assumed elastic limit of the story shear deformation;
- \(v_{un}\) is the ultimate allowable drift of the \(n^{th}\) story.

Current stiffness \(K_n\) of the \(n^{th}\) story is calculated per the following formula:
\[
K_n = K_{in} - \frac{10^{3}m_n}{R_w n} \sqrt{\frac{v_n}{v_{en}}} \tag{9}
\]
TABLE 1

DATABASE OF BASIC BUILDING STRUCTURE PARAMETERS

<table>
<thead>
<tr>
<th>PRIMARY BUILDING PARAMETERS: GIVEN or ASSUMED</th>
<th>SECONDARY PARAMETERS: CALCULATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stories N</td>
<td>Elastic limit of the ( n^{th} ) story drift ( v_{en} ) [cm]</td>
</tr>
<tr>
<td></td>
<td>Rigidity coefficient of the ( n^{th} ) story ( k_n ) [s(^{-2})]</td>
</tr>
<tr>
<td></td>
<td>Initial stiffness of the ( n^{th} ) story ( K_{in} \approx k_n m_n/\omega_{wn} ) [s(^{-2})kg]</td>
</tr>
<tr>
<td></td>
<td>Initial coefficient of damping of the ( n^{th} ) story ( C_{in} \approx 1.233 m_n ) [kg/s]</td>
</tr>
</tbody>
</table>

RANGE OF PARAMETERS

<table>
<thead>
<tr>
<th>Integer</th>
<th>Integer</th>
<th>0.5 – 1.0</th>
<th>3,000-10,000</th>
<th>Depends on ( m_n ) and ( \omega_{wn} )</th>
<th>Depends on ( m_n ) value</th>
</tr>
</thead>
</table>

Current damping coefficient \( C_n \) of the \( n^{th} \) story is calculated per the following formula:

\[
C_n = C_{in} \left(1 + \frac{1}{\omega_{wn}} \sqrt{\frac{v_n}{v_{en}}} \right)
\]  

(10)

The isolation system called *Earthquake Protector* is specified by the following Table 2 and formulas (11) and (12) below:

TABLE 2

<table>
<thead>
<tr>
<th>TYPE OF ISOLATOR</th>
<th>DATABASE OF BASIC ISOLATOR PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake Protector</td>
<td>Radius of the sliding surfaces: ( r = 300 – 600 ) cm</td>
</tr>
<tr>
<td></td>
<td>Sliding friction coefficient: ( f = 0.02 – 0.03 )</td>
</tr>
<tr>
<td></td>
<td>Calculated velocity of the isolator relative to the ground: ( v_\circ [\text{cm/s}] )</td>
</tr>
</tbody>
</table>

Stiffness of *Earthquake Protector* is calculated per the following formula which is generic for all sliding isolators:

\[
K_o = \frac{gM}{r}
\]  

(11)

where \( M \) is the total mass of the structure.

Damping coefficient of the Earthquake Protector is calculated per the following formula:

\[
C_o = \frac{fgM}{v_\circ}
\]  

(13)

Earthquake performance of structural system of a building is presented in the following Table:

Quantitative performance evaluation of a virtual building structure during a virtual earthquake excitation is done with the help of the \( n^{th} \) story *Seismic Performance Ratio* (SPR):

\[
SPR = \frac{v_n}{\omega_{wn}v_{en}}
\]  

(14)
There will be the following three basic situations:

\[ 0 \leq \text{SPR} \leq 1 \quad \text{Acceptable performance of a story, called: GOOD.} \]
\[ 1 < \text{SPR} \leq 1.5 \quad \text{Possibility of structural failure, called: FAILURE.} \]
\[ 1.5 < \text{SPR} \quad \text{Structural collapse, called: COLLAPSE.} \]

In this research, the maximum drift value \( v \) at each story will be used for computation of the corresponding values of \( \text{Performance Rating} \ R \) (Eq.2), \( \text{Seismic Performance Ratio} \ R/R_w \), and \( \text{Damage Ratio} \ D.R. \) (Eq.7). \( \text{Damage Ratio} \ D.R. \) of each story may fall into one of the five damage categories presented in Table 4.

### TABLE 3

<table>
<thead>
<tr>
<th>Sketch of deformed building Structure</th>
<th>The maximum value of the ( n^{th} ) story drifts [cm]</th>
<th>Time from the beginning of ground shaking [s]</th>
<th>The ( n^{th} ) story maximum acceleration [cm/s(^2)]</th>
<th>The ( n^{th} ) story shear [N]</th>
<th>The ultimate value of the ( n^{th} ) story SPR</th>
<th>The ( n^{th} ) story seismic performance evaluation</th>
</tr>
</thead>
</table>

### TABLE 4

<table>
<thead>
<tr>
<th>Damage index</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage category</td>
<td>No damage</td>
<td>Slight (non-structural)</td>
<td>Considerable</td>
<td>Severe</td>
<td>Collapse</td>
</tr>
<tr>
<td>( R/R_w )</td>
<td>&lt; 0.167</td>
<td>0.167 – 0.5</td>
<td>0.5 – 1.0</td>
<td>1.0 – 1.5</td>
<td>&gt; 1.5</td>
</tr>
<tr>
<td>D.R. (%)</td>
<td>&lt; 0.14</td>
<td>0.14 – 3.75</td>
<td>3.75 – 30</td>
<td>30 – 99</td>
<td>100</td>
</tr>
</tbody>
</table>