NUMERICAL SIMULATION OF BASE ISOLATED BUILDINGS DURING THE GREAT EAST JAPAN EARTHQUAKE AND A PROPOSAL FOR A DESIGN PROCEDURE OF BASE ISOLATION SYSTEM IN PERU

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MEE11619

ABSTRACT

A numerical simulation to evaluate responses of seismically isolated buildings during the Great East Japan Earthquake in 2011 is carried out in this study. The numerical simulation includes non-linear analyses of the base isolation system based on a Simple Bi-Linear Model and Modified Bi-Linear Model, which take into consideration the degradation of the secondary stiffness.

From the result of those analyses, it was proved that the response of seismically isolated buildings is as follow: the base isolation system has non-linear behavior and the upper-structure behaves in the elastic range, because the base isolation decouples the movement from the ground motion, the displacement concentrates at the isolation level and the upper-structure behaves as a rigid body.

A proposal for the design procedure for base isolated buildings in Peru is made in this study. This procedure is based on the recommendation of CIB (International Council for Research and Innovation in Building and Construction), using the preliminary design procedure for seismically isolated buildings (CW2012) and taking into consideration the Peruvian seismic code.

Keywords: Base Isolation, Modified Bilinear Model, Design Procedure.

1. INTRODUCTION

Peru is located in a high seismic hazard zone, the Ring of Fire, which defines the area with highest seismic activity. The area includes some countries such as Japan, USA, Mexico, Chile and Peru, which are affected mainly by earthquakes and aftershocks, as well as tsunamis which can be originated by earthquakes. In the case of Peru, earthquakes are caused mainly by sudden release of energy, which is generated by the subduction movement between the Nazca Plate and the South American Plate. In addition to the subduction mechanism, there are earthquakes generated by geological fault mechanism and volcanism.

The last March 11, 2011, Japan was struck by The Great East Japan Earthquake of magnitude 9.0Mw followed by a tsunami that affected the east coast of Japan, the epicenter of which was located off the Pacific coast of Tohoku. The earthquake caused many casualties, economic losses, and damages on buildings, transportation facilities, and lifeline facilities among others due to the main shock and aftershocks.

The lesson learnt from the past disasters: "It is necessary to improve the seismic response of buildings against earthquakes". The Base Isolation System, as a technology which permits to minimize the damage and reduce economic losses and casualties, will be a great choice.

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2. THEORETICAL STUDY

The principle of the seismic-resistance design is based on: the energy dissipation capacity of the structure must be higher than the demand of hysteretic energy. Moreover, the technologies to improve the seismic behavior of the structures are based fundamentally on the reduction of the input energy as well as in the increment of the energy dissipation of the structure. In that sense, the reduction of the input energy is possible trough the seismic isolation system, whereas the energy dissipation devices help to increase of the dissipation energy capacity.

There are several types of multi-layer rubber bearing device, such as Natural Rubber Bearing (NRB), Lead Plug Rubber Bearing (LRB) and High Damping Rubber Bearing (HRB); the main difference among them is the energy-dissipation capacity through shear deformation.

Using the base isolation system, it can be expected that the response of the upper-structure will behave in elastic range, whereas the base isolation system should have a non-linear behavior, which is represented by a hysteretic model (Bi-Linear Model or Modified Bi-Linear Model). This study will focus in base isolation system using Lead Plug Rubber Bearing (LRB).

2.1 BI-LINEAR MODEL (BImod)

The Bi-Linear hysteresis of LRB is defined as a combination of an elastic model derived from the lateral stiffness of rubber K_r and the additional stiffness K_p derived from plastic model of lead plug. See Equation (1) and (2).

Where: G_r is the shear modulus of the rubber, G_p is the shear modulus of the lead, A_r is the cross section area of laminated rubber, A_p is the cross section area of lead and H_r is the total height of rubber.

The Bi-Linear Model has an initial elastic stiffness K_1, a secondary stiffness K_2, See Equation (3) and (4).

Moreover, the equivalent stiffness and equivalent damping ratio are shown in Equation (5) and (6) Equation respectively, where D_{max} is the displacement peak per loop.

$$K_r = G_r \frac{A_r}{H_r} \qquad (1)$$

$$K_p = G_p \frac{A_p}{H_r} \qquad (2)$$

$$K_2 = K_r + K_p \qquad (3)$$

$$K_1 = \beta K_2 \quad , \quad \beta = 10 \sim 15 \qquad (4)$$

$$K_{eq} = K_2 + \frac{Q_d}{D_{max}} \qquad (5)$$

$$h_{eq} = \frac{2}{\pi} \frac{Q_d \left(D_{max} - \frac{Q_d}{(\beta - 1)K_2} \right)}{K_{eq} {D_{max}}^2} \qquad (6)$$

2.2 MODIFIED BI-LINEAR MODEL (MBImod)

Modified Bi-Linear Model is based on Bi-Linear Model. The secondary stiffness of lead rubber bearing ($K_2 = K_d(\gamma)$) depends on the strain level, where $C_{Kd}(\gamma)$ is a modification factor of the secondary stiffness. See Equation (7).

Also, the yielding shear force is defined as shown in Equation (8), where $C_{Qd}(\gamma)$ is a modification factor of the yielding shear force and σ_p is the yielding shear stress of lead and A_p is the cross section area of lead plug.

$$K_d(\gamma) = C_{Kd}(\gamma)(K_r + K_p) \qquad (7)$$

$$Q_d(\gamma) = C_{Qd}(\gamma)\sigma_p A_p \qquad (8)$$

$$C_{Kd(\gamma)} = \begin{cases} 0.779\gamma^{-0.43} & \rightarrow \quad \gamma < 0.25 \\ \gamma^{-0.25} & \rightarrow \quad 0.25 \le \gamma < 1.0 \\ \gamma^{-0.12} & \rightarrow \quad 1.0 < \gamma \le 2.5 \end{cases} \qquad (9)$$

$$C_{Qd(\gamma)} = \begin{cases} 2.036\gamma^{0.41} & \rightarrow \quad \gamma \le 0.1 \\ 1.106\gamma^{0.145} & \rightarrow \quad 0.1 < \gamma < 0.5 \\ 1 & \rightarrow \quad 0.5 < \gamma \end{cases} \qquad (10)$$

To understand how it works the hysteresis loop shown in Figure 1, three rules are introduced as follows:

- ***Rule 1***: The initial elastic stiffness corresponds to the 5% of strain of the skeleton curve using parameters type 1 or 2.
- ***Rule 2:*** The stiffness can be equal or less than stiffness in the previous loop but never can be greater.
- ***Rule 3:*** The force should be equal or less respect to the skeleton curve.

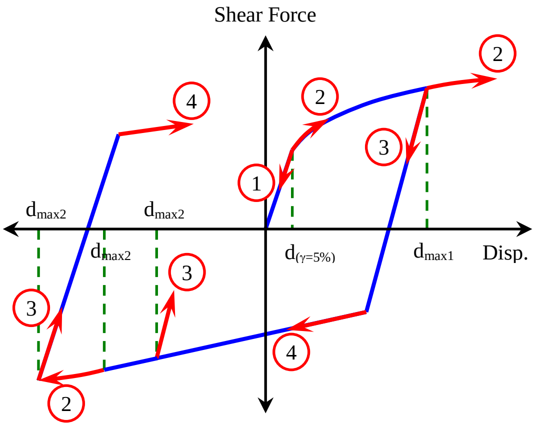

Figure 1. Hysteresis Loop of MBImod

Following the rules described above, the levels which defines the hysteresis loop (See Figure 1) are shown below:

- ***Level 1 – Elastic Stage (Loading):***

  If $d \leq d(\gamma=5\%) \rightarrow K_1 = \beta * K_d(\gamma=5\%)$
- ***Level 2 – Plastic Stage (Loading):***

  If: $d < d_{max1} \rightarrow K_2 = K_d(\gamma)$
- ***1st Peak: $d_{max1} \rightarrow \gamma_{max1}$***

  $K_2 = K_d(\gamma_{max1})$, $K_1 = \beta K_d(\gamma_{max1})$
- ***Level 3 – Elastic Stage (Unloading):***

  If: $d < d_{max1} \rightarrow K_1 = K_1$
- ***Level 4 – Plastic Stage (Unloading):***

  If: $d < (d_{max1} - 2dy) \rightarrow K_2 = K_2$
- ***If: $|d_{max2}| \leq |d_{max1}|$:***

  $K_1 = K_1$, $K2 = K_2$
- ***If: $|d_{max2}| > |d_{max1}| \rightarrow$ Level 2 continues***

  $K_2 = K_d(\gamma)$, $K_1 = \beta K_1$
- ***2nd Peak: $d_{max2} \rightarrow \gamma_{max2}$***

  $K_2 = K_d(\gamma_{max2})$, $K_1 = \beta K_d(\gamma_{max2})$

3. NUMERICAL SIMULATION AND COMPARISON WITH RECORDED DATA

Two buildings in Japan were selected to conduct this research; either of buildings implemented a base isolation system. Also, the buildings were equipped with strong motion sensors to register the seismic response of those buildings; the buildings chosen are: H-Building and T-Building.

H-Building is located in Aomori Prefecture. The building is steel reinforce concrete (SRC) structure, has 10 stories above the ground, 1 story penthouse, 1 story Basemen and a Base Isolation System composed of LRB. T-Building is located in Ibaraki Prefecture. The building is reinforce concrete (RC) structure, and it has 7 stories and a Base Isolation System composed of NRB, LRB and Steel Damper.

The analysis was carried out using BImod and MBImod. The results presented in this paper, corresponds to the analysis of H-Building and T-Building in X and Y direction respectively. Figure 2 shows the comparison of the maximum response displacement for both buildings. The shear force – displacement relationship of the base isolation system is shown in Figure 3.

H-Building has strong motion sensors at B1F, 01F and 10F. T-Building has strong motion sensors at B1F, 01F and 06F. The comparison of the response acceleration from the analysis and the recorded data during the Tohoku Earthquake is shown in Figure 4 and Figure 5.

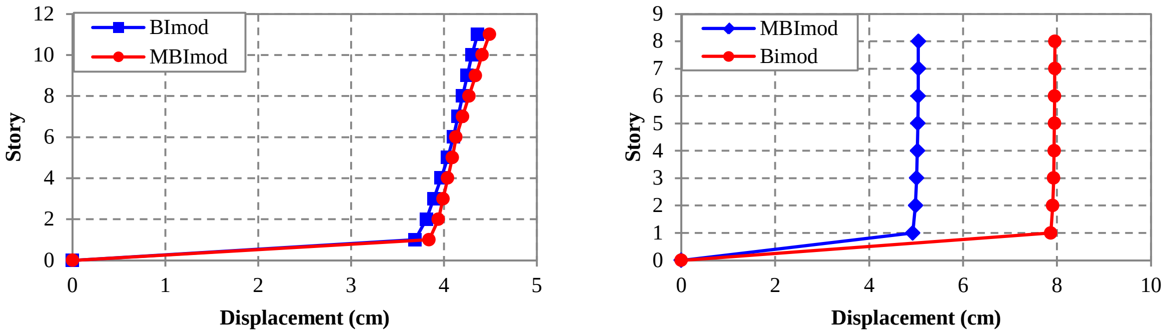

Figure 2. Comparison of the Maximum Response Displacement.
Left: H-Biulding (X-direction). Right: T-Building (Y-direction)

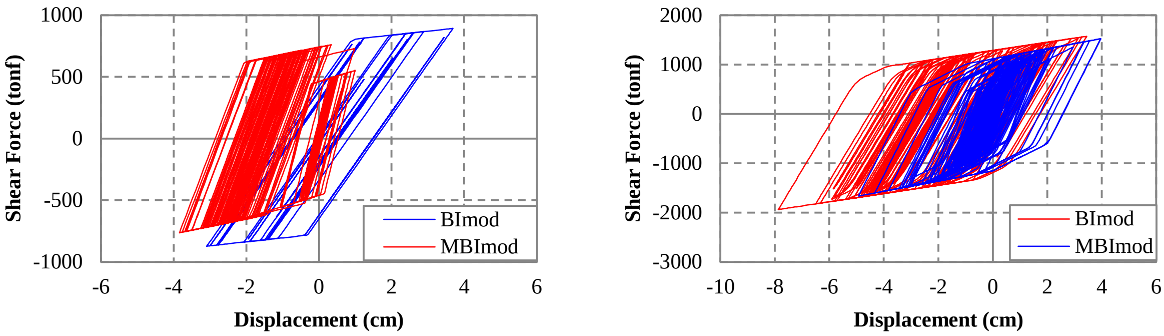

Figure 3. Comparison of Shear Force – Drift Relationship of Base Isolation System
Left: H-Biulding (X-direction). Right: T-Building (Y-direction)

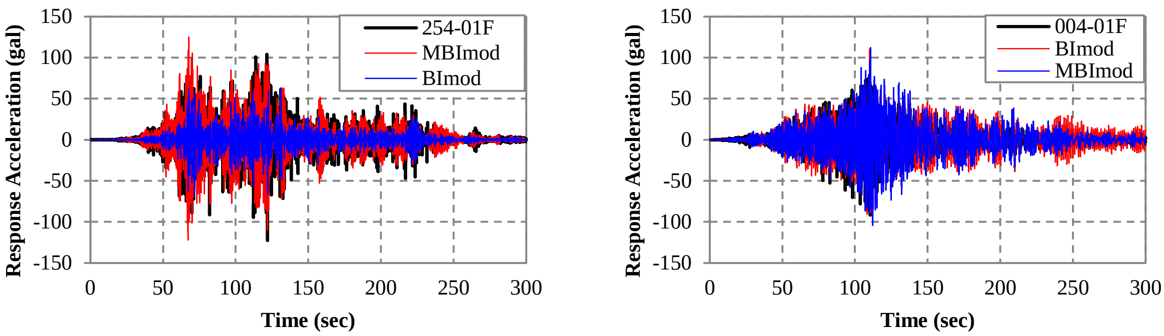

Figure 4. Comparison of Response Acceleration.
Left: 01F-H-Biulding (X-direction). Right: 01F-T-Building (Y-direction)

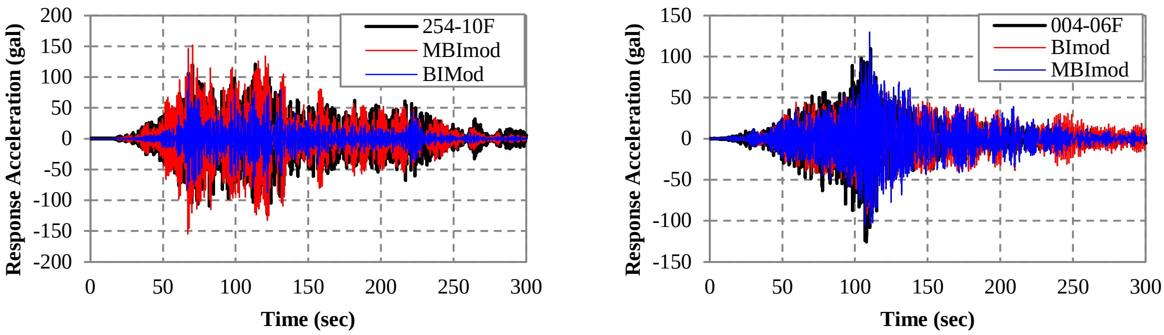

Figure 5. Comparison of Response Acceleration.
Left: 10F-H-Biulding (X-direction). Right: 06F-T-Building (Y-direction)

4. A PROPOSAL FOR A DESIGN PROCEDURE OF BASE ISOLATION IN PERU

The proposal for a design procedure of seismically isolated buildings in Peru presented in this research is based on the recommendation of CIB (International Council for Research and Innovation in Building and Construction) using the preliminary design procedure for seismically isolated buildings (CW2012) and taking into consideration the Peruvian seismic code.

This research presents the design procedure using an equivalent linear analysis method. The limitations for this method are:

- Building height: Less than 45m.
- Type of soil: Medium and hard soil, Type S1 and S2.
- Location of seismic isolated layer: Base isolation.
- Special case: For masonry buildings, the height limitation is 15m
- For other case Time History Analysis is recommended.

The design procedure of base isolated buildings and convergence procedure following the Equivalent Linear Method (ELM) is shown in Figure 6.

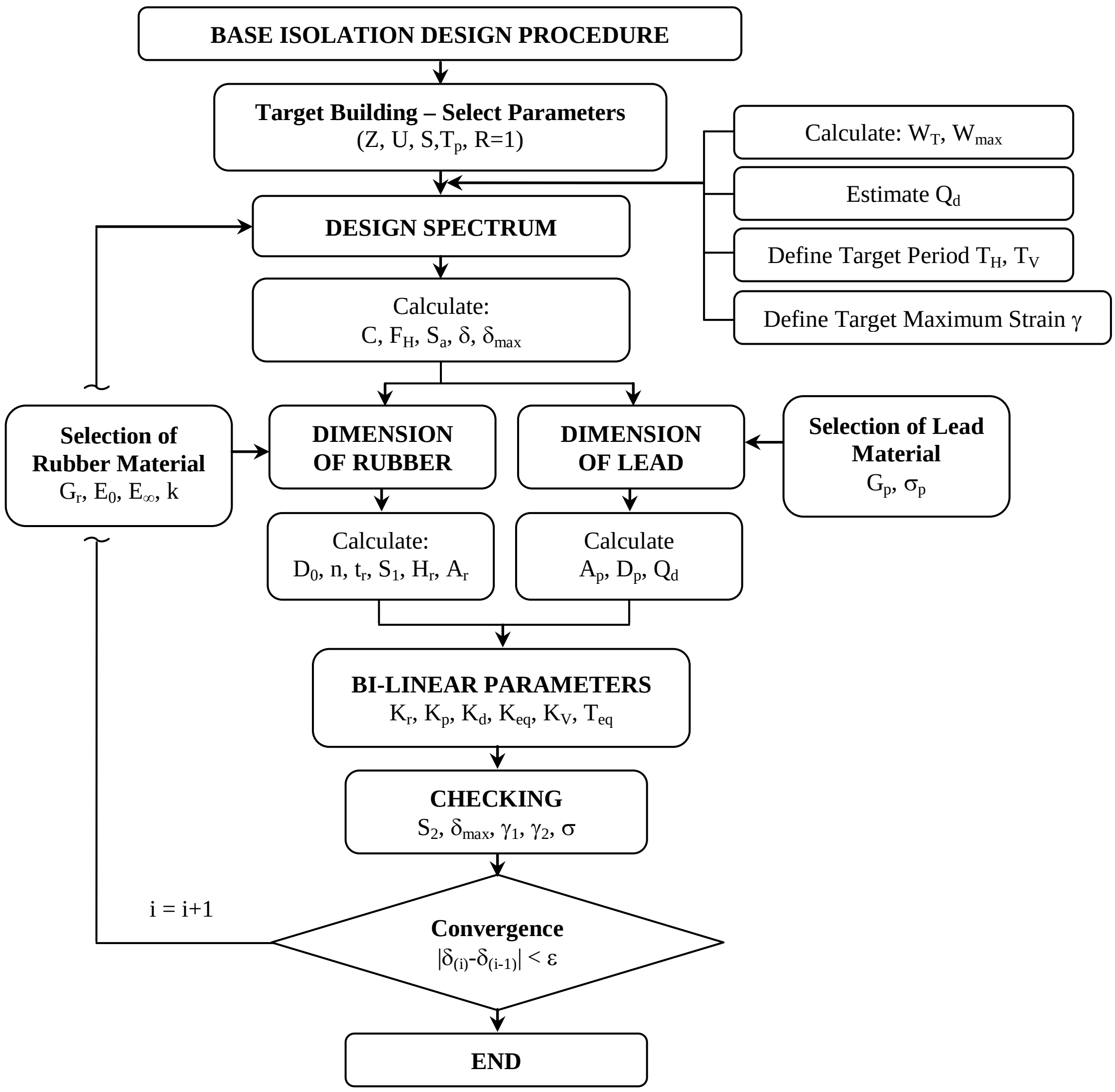

Figure 6. Base Isolation Design Procedure

5. CONCLIDING REMARKS

The expected response of two buildings during the Tohoku Earthquake is a non-linear behavior on the isolation system and a linear behavior in the upper-structure.

Using a Modified Bi-Linear Model to model the H-Building, the simulation has more accurate response of the building. On the other hand, the analysis of the T-Building using MBImod has higher response in comparison with the analysis using BImod.

The parameters used in the analysis should be checked to get better response accuracy in order to predict the response recorded during the Tohoku Earthquake and further earthquakes.

The proposal for a design procedure of base isolation buildings in Peru is based on Equivalent Linearization Method (ELM), taking into consideration the Peruvian Design Spectrum.

Base Isolation System can be applied for designing new buildings or as a retrofitting technique in Peruvian buildings, even for masonry buildings and also to protect old buildings, such as historical heritage in Peru.

6. FURTHER STUDIES

Further studies are needed to get the parameters of a hysteretic model to predict the non-linear response of base isolated buildings, because the parameters used in this research depends on the manufacturer of base isolation devices.

For base isolated building in Peru, the mechanical characteristics and non-linear properties of isolation devices manufactured with different materials should be researched, also taking into account damper devices.

A proposal for a design procedure is presented in this research, expecting to be the initiative for developing Seismic Isolation Code for seismically isolated buildings in Peru

7. ACKNOWLEDGEMENT

I would like to express gratitude to Dr. Carlos Zavala, Director of Japan-Peru Center for Earthquake Research Engineering and Disaster Mitigation (CISMID) for his support and collaboration.

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