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State of Practice of Performance-Based Seismic Design in Korea

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Abstract

Today, a great effort to develop PBSD procedure to be utilized in Korea is given by domestic structural engineers, academics, and governmental organizations. After Great East Japan Earthquake (2011) took place, lots of clients in Korea became to concern of their buildings so that requests of seismic performance evaluation and seismic rehabilitation for existing buildings have been gradually increased. Such interests in seismic events initiated a rapid development of a series of guidelines for seismic performance evaluation and seismic performance enhancement. For new buildings, however, design guidelines for PBSD are yet well prepared in Korea and prescriptive design methods are dominant design procedure still. Herein, seismicity demands used in seismic performance evaluation and some important design parameters in NLRH are introduced. Some project examples for seismic performance evaluation and rehabilitation applying passive energy dissipation devices are also described in the latter part of paper.

Keywords: Performance-Based Seismic Design (PBSD), Seismic performance evaluation, Seismic rehabilitation, Non-Linear Response History (NLRH) Analysis, Passive energy dissipation device

1. Introduction

Currently, development for a design procedure based on seismic performance has been accelerated by Great East Japan Earthquake which occurred near Korea in 2011. Particularly, a series of guidelines for seismic performance evaluation and rehabilitation process for existing building were published in recent years. In case of new buildings, especially apartment-type building which is inhabited by more than half population in the country, a design procedure utilizing passive energy dissipation devices begins to be applied to certain apartment building projects.

For typical types of new buildings, however, the application of PBSD is rare, since prescriptive design procedure is prevailing as ever in structural engineering fields. It is because, not only, the structural engineers have insufficient experiences and relevant knowledge of PBSD but governmental officials do not recognize immense need of PBSD, since Korea has never experienced strong earthquakes. Thus, PBSD has a limited influence on design for new buildings. For example, specific lateral load resisting system determined by height limit according to Seismic Design Category (SDC) in prescriptive design procedure cannot be replaced by PBSD.

The typical types of buildings designed using a PBSD approach is as follows,

- Apartment buildings: PBSD using passive energy dissipation devices in coupling beams
- School buildings, public offices: seismic performance evaluation and seismic rehabilitation
- Complexed-tall buildings including tilted/twisted/tapered diagrid, braced tube systems: seismic performance evaluation

2. Code Requirements

In Korean Building Code 2009 (KBC 2009), design parameters used in NLRH are described roughly. These parameters include damping ratio of target elastic response acceleration spectrum, scaling method for selected ground motions and a minimum/maximum number of ground motion for determining seismic response values. The specific design values for the requirements are mostly identical to ASCE 7-05.

3. Definition of Seismic Demand Levels

In KBC 2009, the Design Based Earthquake (DBE) is established as two thirds of return period of 2400 years earthquakes (Maximum Considered Earthquake, MCE). Some guidelines in Korea such as “Seismic Performance Evaluation for Existing Buildings(MLTM, 2010)” only define seismic demand level as two thirds of return period of MCE. This is because Korea is recognized of low-seismicity region so that check for service level earthquakes or MCE tends to be considered excessive works. The typical seismicity range of MCE is from 0.14 g to 0.22 g which is representative of the peak ground acceleration (PGA).

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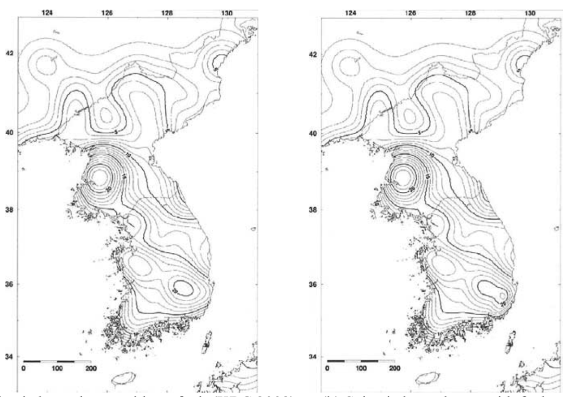
Table 1. Seismic hazard factor (Earthquake Engineering Society of Korea, 1997)

Return Period	50 year	100 year	200 year	500 year	1000 year	2400 year
Hazard Factor	0.4	0.57	0.73	1.0	1.4	2.0



(a) Seismic hazard map without fault (KBC 2009) (b) Seismic hazard map with fault

Figure 1. 2400 year return period seismic hazard map (KIGAM, 2012).

Since the overall seismicity hazard is low and the number of shaking records is quite limited enough to establish site-specific hazard in Korea. Seismic hazard map in KBC 2009 is now formulated without considering fault location. Thus, Korean National Emergency Agency is preparing new seismic hazard map considering a fault influence, as shown in Fig. 1. It could be a useful source to conduct accurate PBSD.

The seismic hazard in accordance with return periods for Korea peninsula is determined hazard factors described in a guideline published in 1997 by Earthquake Engineering Society of Korea, as shown in Table 1. This table represents that DBE is $2*(2/3) = 1.33$ times of return period of 500 years earthquake, since DBE is two thirds of return period of 2400 years earthquake. Thus, DBE represents less than return period of 1,000 years earthquake.

4. Performance Objectives

According to "Seismic Performance Evaluation for Existing Buildings (MLTM, 2010)", published in Korea, 2011, performance objectives are defined by the importance of the buildings which is classified in accordance with occupancy categories. The occupancy categories include Special, 1, 2 and 3 levels in KBC 2009. The Performance objectives are connected with Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP), respectively (MLTM, 2010).

Typical methods how to measure performance objectives are divided to two different levels.

First, for component level which consists of lateral force resisting system, the acceptance criteria for performance objectives suggested in the guideline "Seismic Performance Evaluation for Existing Buildings (MLTM, 2010)" are utilized to see if primary members are satisfied to each performance level. This measurement is applied to the case of ductile behavior such as moment in columns, girders, and walls which also is classified as deformation-controlled behavior. Meanwhile, in case of brittle behavior such as shear and axial force in girders and columns, the forces are not allowed to exceed nominal strength calculated by codes.

Table 2. Allowable drift ration according to performance objectives

Occupancy Category	Performance Objectives	Allowable Drift Limit
Special	Immediate Occupancy (IO)	0.01
1	Life Safety (LS)	0.015
2,3	Collapse Prevention (CP)	0.02

Inter-story drift ratio is also measured in order to check if performance level is satisfied in system level. After ground shaking which utilizes two thirds of MCE is performed, maximum inter-story drift ratio is checked. The allowable inter-story drift ratio per performance level is shown in Table 2.

5. Modeling Procedures

The common analytical modeling procedures used in Korea is divided mainly into two procedures: Linear Procedure and Nonlinear Procedure.

When preliminary seismic evaluation needs to be conducted, linear procedure is used. Since linear procedure requires less effort to perform than nonlinear procedure, it is preferred in early stages of seismic evaluation procedure. Forces in each component are evaluated from response spectrum analysis with a spectrum of DBE level. For deformation-controlled components, demand-capacity ratios (DCRs) are estimated per performance levels using M-factor (Fig. 2). M-factor is used to account for expected ductility from DCR. For force-controlled components, DCR is estimated based on nominal strength which indicates that they remain under elastic range.

When the results from linear procedure are judged to be investigated more accurately, then nonlinear response history analysis (Fig. 6) or push-over analysis (Fig. 5) is conducted. First of all, axial force and shear in all lateral force resisting members are estimated from preliminary design. Members are classified into force-controlled and deformation-controlled members. For components that are expected to behave nonlinearly, hinge properties are calculated according to ASCE 41 or appropriate experimental data (Figs. 3, 4). After performing NLRH analysis, performance level of components and inter-story drift ratio are checked. If nonlinear procedure is performed in advance of linear procedure, linear procedure needs not to be conducted.

Push-over analysis can provide sensitivity information on the effects of changing the strength and stiffness more quickly than NLRH. In addition, it requires less time than NLRH. Also, when it is used for low-rise building, it provides reasonable results. For high-rise buildings in which higher mode effect is significant, however, NLRH is more accurate than push-over analysis.

Modeling procedures in detail are described as follows.

1) Preliminary design is conducted to determine required member size and reinforcement. Then, forces on each member such as axial force and shear are calculated to determine nonlinear capacity parameters, allowable performance level for nonlinear procedure, or m-factors for linear procedure.
2) If necessary, nonlinear hinge properties per primary elements are imported to analysis program.

3-1) After conducting push-over analysis, inter-story drift and DCR at performance point are checked.

3-2) After conducting NLRH analysis, inter-story drift and DCR from more than seven ground motions.

6. Foundation Interaction

Generally, foundation conditions are not considered in analysis. If foundation condition, however, is severely soft, the spring stiffness of foundation calculated by soil-structure interaction analysis or the value geo-tech engineer suggests is applied to an analytical model. When a building is subjected to lateral soil pressure large enough to affect overall behavior of building, it is directly applied to modeling. Also, if the area of underground retail facility charges a relatively large portion compared to floor area, frame stiffness is reflected to tower by modeling a certain portion of retail frames.

7. Damping

In Korea, for determining target response spectrum, DBE is utilized and is also represented by 5% of critical damping ratio. In case of NLRH analysis, 5% elastic

No. of Element	Name	M-FACTOR			DCR CHECK		
		IO	LS	CP	IO	LS	CP
4015	C1	2.00	2.00	3.00	0.0686	0.0686	0.0305
4016	C1	2.00	2.00	3.00	0.0864	0.0864	0.0384
4017	C1	2.00	2.00	3.00	0.0834	0.0834	0.0371
4018	C2	1.90	1.93	2.86	0.0701	0.0676	0.0308
4019	C2	2.00	2.00	3.00	0.0653	0.0653	0.0290
4020	C3	2.00	2.00	3.00	0.0563	0.0563	0.0250
4021	C3	2.00	2.00	3.00	0.0405	0.0405	0.0180

Figure 2. Evaluation sheet of m-factor and DCR for linear procedure (example).

No. of Element	Name	θy	a/θy	b/θy	c	IO/θy	LS/θy	CP/θy
4015	C1	0.0029	3.093	6.232	0.200	2.744	2.744	3.093
4016	C1	0.0029	3.093	6.232	0.200	2.744	2.744	3.093
4017	C1	0.0029	3.093	6.232	0.200	2.744	2.744	3.093
4018	C2	0.0023	3.401	7.151	0.200	2.971	2.971	3.401
4019	C2	0.0029	3.093	6.232	0.200	2.744	2.744	3.093
4020	C3	0.0029	3.093	6.232	0.200	2.744	2.744	3.093
4021	C3	0.0029	3.093	6.232	0.200	2.744	2.744	3.093

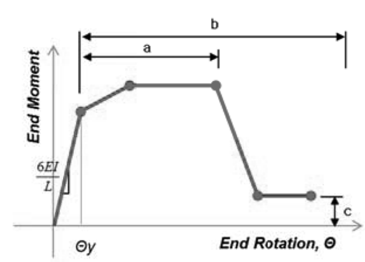


Figure 3. Evaluation sheet of nonlinear capacity parameters and allowable performance level (example).

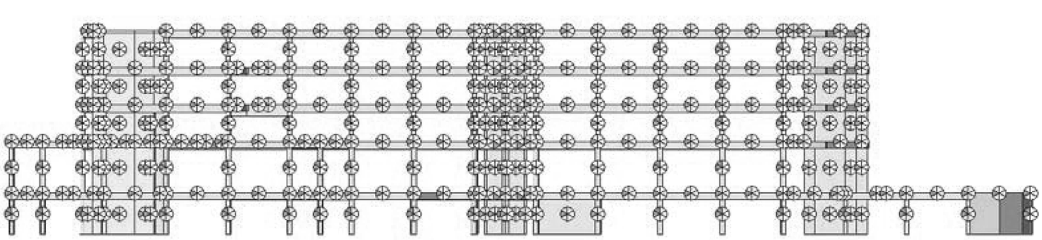


Figure 4. Hinge property importing to analysis program (example).

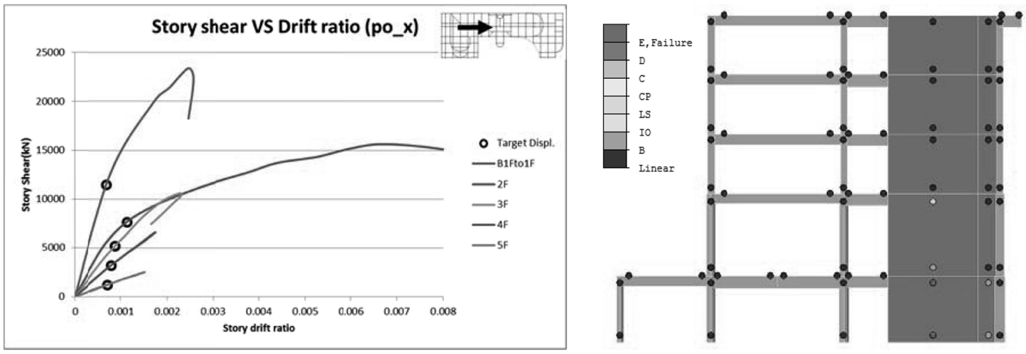


Figure 5. Responses of push-over analysis at performance point (example).

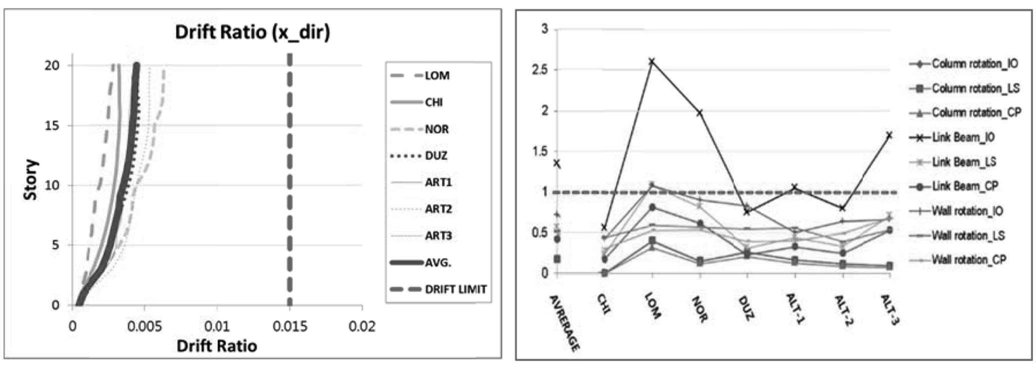


Figure 6. Responses of NLRH analysis (example).

viscous damping ratio is usually applied to analytical models. When modal damping is utilized, additional 0.2% stiffness-dependent damping ratio is applied to damp out higher mode motions effectively. Since only displaced shapes corresponding to mode shapes are set to have damping, there will be many displaced shapes that are undamped. In actual structure, total number of degree of freedom is essentially larger than number of modes. Thus, the use of highest number of modes and 0.2% stiffness-dependent damping ratio is recommended (CSI, 2006b).

8. Gravity Load-resisting Systems

When conducting PBSD, gravity load-resisting systems such as slabs and sub-beams generally are not modeled. Instead, rigid diaphragm on floors is applied to transfer lateral loads to core effectively. However, in case of flat slab system, slabs are modeled using elastic beam or plate element with stiffness reduction caused by cracking.

When a building consisting of core wall and perimeter columns is used, if axial force and moment induced by lateral force is not significant, elastic property is only applied in analysis and checked for DCRs.

9. Non-structural Systems

In Korea, non-structural system in typical buildings is not considered as lateral force resisting system. However, in case of a building with lots of partitions, if considered as another lateral force resisting member, these elements are modeled as axial strut component to account for the contribution to lateral resistance.

10. Project Examples

Some specific examples using PBSD are described as follows,

10.1. Residential apartment building

- 21 floors / 2 basement floors (Fig. 7)
- RC core wall + Gravity Columns
- Performance evaluation for the building designed by a prescriptive code using push-over analysis, nonlinear response history analysis for seven ground shakings including three artificial earthquakes
- Analysis program: PERFORM 3D
- Featured points
  - PBSD can reduce maximum 80% of lateral stiffness in seismic force resisting system compared to conventional design.
  - Coupling beams are most critical component of seismic force resisting system.
  - Core walls in long height in lower stories are susceptible to lateral force.

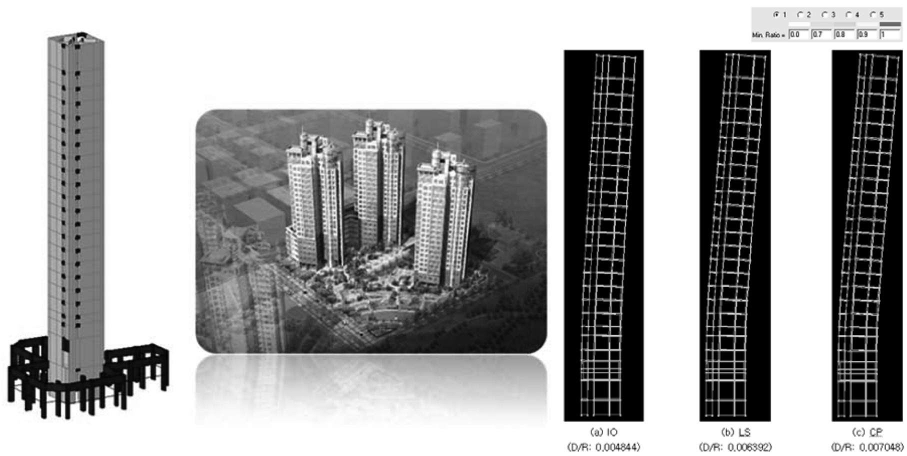


Figure 7. Images of apartment building and DCR check results.

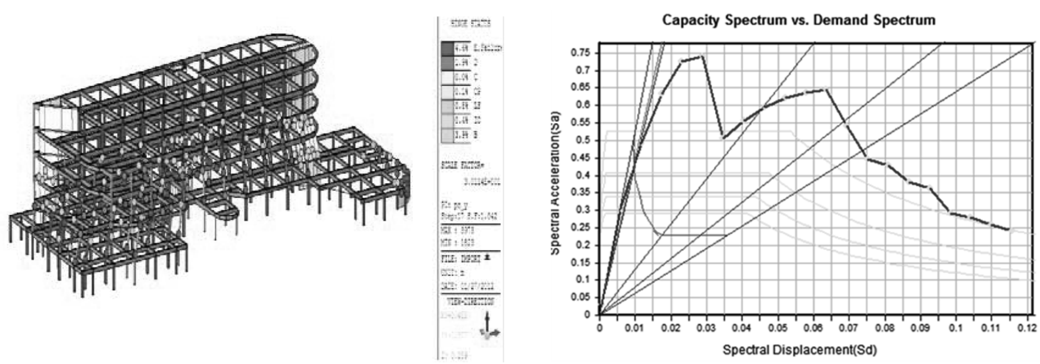


Figure 8. Push-over analysis results.

10.2. City hall

- 5 floor / 1 basement floor (Fig. 8)
- RC core wall + Columns
- Performing Push-over analysis
- Installing passive energy dissipation device to enhance ductile behavior of the existing building
- Analysis program: Midas Gen.
- Featured points
  - Torsional effect is dominant in overall behavior since mass center is deviant to stiffness center.
  - To control seismic force effectively, damper with appropriate stiffness is needed to control torsional effect.
  - Rehabilitation with dampers can enhance structure performance effectively.

10.3. Super tall building

- RC core wall + Mega column, outrigger, belt truss system (Fig. 9)
- Seismic performance evaluation for un-scaled Kobe earthquake (2004) by request of clients.
- Analysis program: PERFORM 3D
- Featured points
  - Outrigger system can control seismic response effectively in tall building.
  - Outrigger system is most critical to seismic force in this project.
  - NLHR provides a useful information regarding seis-

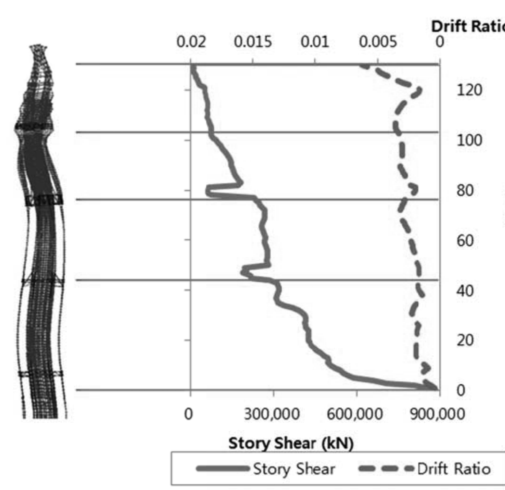


Figure 9. Story shear and drift ration induced by Kobe earthquake.

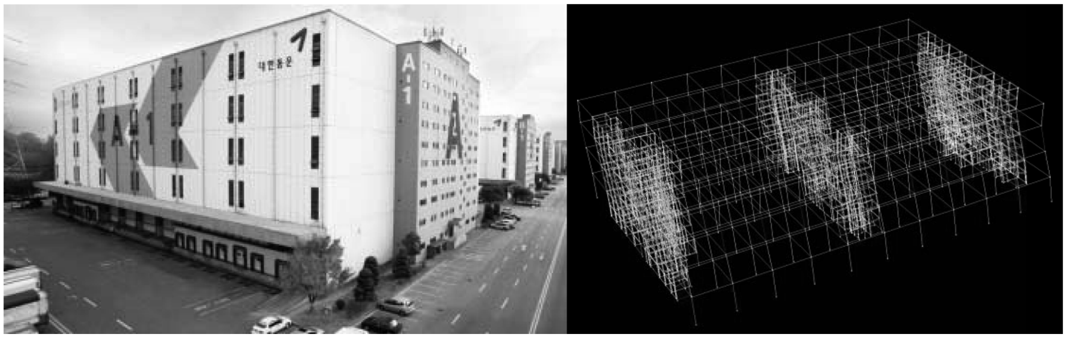


Figure 10. Image of freight terminal and results of push-over analysis.

mic performance evaluation for buildings designed according to code based design.

10.4. Freight terminal

- 10 story building with no floor diaphragm every 2 story (Fig. 10)
- RC core wall + RC girders + RC columns
- Performing Push-over analysis
- Analysis program: PERFORM 3D
- Featured points
  - Although long columns (7.8m) are affected significantly by lateral force, this building meets its performance objective (LS) at performance point.
  - Some coupling beams in core walls shows CP level performance at performance point.

11. Other Items of Interest

11.1. Coupling beam type of passive energy dissipation devices installed between rigid shear walls

In Korea, apartment buildings takes part 60% of total residential buildings. This type of building typically consists of shear wall in core. Thus, friction dampers as a type of coupling beam are utilized to control seismic action.

According to ASCE 7-05, Chapter 18, the design base shear can be reduced to 75% of that if passive energy dissipation devices prove to provide effective damping other than inherent damping. Unfortunately, some engineers might misuse it without verifying the device's effectiveness in damping. In this case, NLRH analysis in detail first should be conducted and the energy dissipated by damping devices is needed to be reasonably estimated.

11.2. TBI recommendation for elastic viscous damping ratio

According to Tall Building Initiative (TBI), it is reasonable approach to apply 2.5% elastic viscous damping in NLRH for MCE, since other damping could be compensated by inelastic behaviors due to strong earthquake. However, many engineers are in doubt about the statement that ground shakings of MCE level are represented by 5% damped elastic response spectrum (Table 3). The same elastic viscous damping ratio is needed to be applied to both in selecting ground motion and in conducting NLRH.

Table 3. TBI recommendation for elastic viscous damping ratio

Seismic Demand	Elastic Viscous Damping Ratio	
	Target Spectrum for Selecting and Scaling Ground Motion	Structural Nonlinear Analysis
Service Level Earthquake (SLE)	2.5%	Lower than 2.5%
Maximum Level Earthquake (MCE)	5%	Lower than 2.5%

11.3. Suggestions when using modal damping

A case study is introduced regarding the comparison between responses from Rayleigh damping and modal damping. The building used in case study is 21-story structure with shear core and coupling beam. All shear wall elements in PERFORM 3D are modeled using fiber elements which show inelastic behavior (CSI, 2006a). All coupling beams also are modeled by inelastic shear link. It is described in Example Project 1).

Figure 11 shows the comparison of story shear between 5% Rayleigh damping (5% mass-dependent and 5% stiffness-dependent damping ratio) and 5% modal damping using 10 modes and 50 modes, respectively. Basically, 0.2% stiffness-dependent damping ratio is applied for modal damping.

Rayleigh damping and modal damping with 10 modes have a significant difference in story shear at upper stories. When the modes are increased up to 50, the story shear reduced to 60~70%. In the end, it showed that Rayleigh damping and modal damping with a large number of damping provide a similar response result.

Thus, when apply modal damping, the use of a large number of modes is highly recommended.

11.4. Special shear wall

Taking into accounting that Korea is located in low-

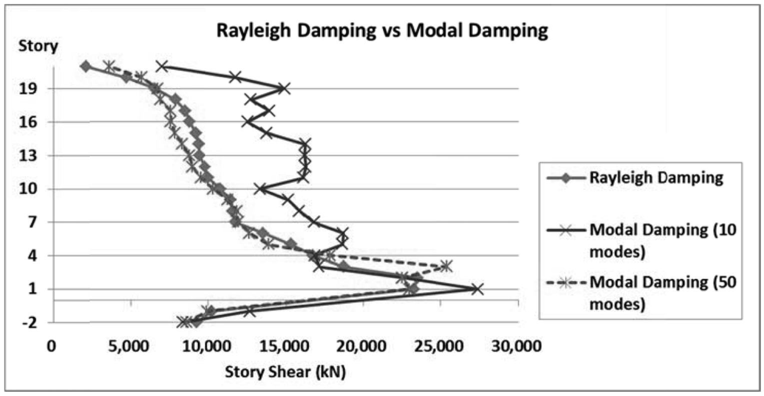


Figure 11. Comparison of story shear between Rayleigh damping and modal damping.

intermediate seismicity region, there are many arguments that details of special shear wall are necessary to be less strict, since rebar spacing is extremely narrow so that lots of construction troubles are issued in recent years. Thus, a few alternatives that have a similar capacity with the original detail are introduced by researcher.

12. Review Procedures

Because of the increase of apartment building design using passive energy dissipation, the committee of damping devices has initiated to form a check list for that kind of building design. Through regular hearings, it has received appropriate consensus from engineering and academic field. This check list includes a variety of energy evaluation items induced by different kinds of damping.

13. Guidelines for PBSD

A series of chief references commonly used as a guideline for PBSD is as follows,

- Seismic Performance Evaluation for Existing Buildings, 2011 (MLTM, 2010)
- An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region (LATBSDC, 2011)
- Guidelines for Performance-Based Seismic Design of Tall Buildings (TBI, 2010)
- ASCE 41, Seismic Rehabilitation of Existing Buildings (ASCE, 2006)

14. Conclusion

PBSD is not be used in Korea to bypass the prescriptive code restriction. Thus, most works are focused on seismic performance evaluation. However, lots of engineers and organizations in Korea recognize the needs for PBSD and are attempting to publish PBSD guidelines and enroll this to structural codes. As the results of the efforts, design procedure for passive energy dissipation device will be included in next version of KBC. Also, Korean National Emergency Management Agency is trying to renew seismic hazard map according to recent fault research in order to conduct more accurate PBSD.

Acknowledgements

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