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# 철근콘크리트 구조물 내 부착된 수계 관망시스템의 내진거동 및 손상예측

# Seismic Performance and Damage Prediction of Existing Fire-protection Pipe Systems Installed in RC Frame Structures

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**국문 요약** >> 구조물 내 설치된 파이프시스템은 주로 내부구성원들의 인간생활에 근간이 되는 기반시설로서 현대 도시생활의 생명선과 같은 역할을 한다. 이들 구조물 내 파이프시스템이 만약 지진발생에 의하여 손상될 경우 1차적으로 구조물 내 기능성이 저하되고 구조물 내 많은 정신적, 물질적 피해가 발생할 수 있다. 실제 내진공학에서 지진발생에 따른 비구조재요소의 거동은 크게 중요하게 고려되지 않으나 인적 및 물적 피해와 매우 밀접하게 연관되는 가스 혹은 수계파이프시스템에 대한 비구조적 요소의 거동예측 및 성능평가 연구는 보다 효과적인 구조물 유지관리를 위하여 그 필요성이 크다고 판단된다. 본 연구는 현재 일반적으로 널리 시공되어져 있는 노후 철근콘크리트 빌딩구조물 내 설치된 가스 혹은 수계파이프시스템에 대하여 실제 지진발생이 예측되는 거동을 살펴보고 이들 거동에 따른 성능평가 및 현 설계기준에 대한 검토도 병행하여 수행하고자 한다. 이를 위하여 본 연구에서는 해석적으로 발생 가능한 총 10회의 지진파에 대하여 현재 실제 건물 내 기설치된 수계파이프시스템 모델링 및 해석을 통하여 그 결과를 검증, 평가하였으며 부가적으로 실제 발생 가능한 파괴유형 분석을 통하여 현 설치된 수계파이프시스템의 설계에 대한 적절한 내진보강방법에 대하여도 제안하고자 한다.

**주요어** 지진, 내진거동, 손상, 파이프, 내진보강, 철근콘크리트

**ABSTRACT** >> Reliability of piping systems is essential to the safety of any important industrial facilities. During an earthquake, damage to the piping system can occur. It can also cause considerable economic losses and the loss of life following earthquakes. Traditionally, the study of the secondary system was less important than primary structure system, however it has recently been emerging as a key issue for the effective maintenance of the structural system and to help reduce nonstructural earthquake damage. The primary objectives of this study are to evaluate seismic design requirements and the seismic performance of gas and fire protection piping systems installed in reinforced concrete (RC) buildings. In order to characterize the seismic behavior of the existing piping system in an official building, 10 simulated earthquakes and 9 recorded real earthquakes were applied to ground level and the building system by the newmark average acceleration time history method. The results developed by this research can be used for the improvement of new seismic code/regulatory guidelines of secondary systems as well as the improvement of seismic retrofitting or the strengthening of the current piping system.

**Key words** Earthquake, Seismic Performance, Damage, Pipe system, Seismic Retrofit, Reinforced Concrete

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## 1. Introduction

The damages by strong earthquakes over magnitude 6.0 on the Richter Scale are reported frequently in different countries. In 2009, the number of times of earthquakes was total 60 times in Korean Peninsula. It is true that Korea is exposed to the risk of earthquakes. Therefore, it is necessary to consider seismic design to reduce the damage of structural and nonstructural components such as mechanical equipment, ceiling systems, and piping systems. Pipelines are essential to provide energy such as water supply, electric power, and gas as

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fundamental social infrastructure. Specifically, piping systems such as fire suppression and water distribution in major facilities, public institutes and nuclear power plants, must be operated on fully and protected from leakage and fractures immediately after strong earthquakes. In addition, nonstructural components are directly related to loss of life and injury from seismic hazards and the construction cost of nonstructural components is also more costly than that of structural components. In spite of such a critical issue, most building design codes in Korea have been concentrated on primary structural systems.

Consequently, in order to minimize extensive damage during an earthquake, this research is focused on understanding of the seismic behavior of nonstructural components, especially, fire protection piping system. To characterize the seismic performance of complicated piping system, a real piping configuration in an office building is selected and the analyses of multiple linear time histories by the OpenSees Software are conducted for the fire protection piping system.

## 2. Nonstructural Element Damages in Earthquake

### 2.1 Kobe and Tokachi-Oki Earthquake in Japan

On January 17, 1995, at local time 05:46 a.m. the magnitude 6.9 earthquake struck Kobe, considerably industrialized city in Japan. Kobe earthquake was one of the strongest earthquakes and it was recorded as the first earthquake occurred in the heart of major city in Japan history. The earthquake damages were valued at $200 billion. 102,000 buildings were collapsed and 46,203 people were either killed or injured. Furthermore, as shown in figure 1, during the earthquake, the secondary systems were significantly damaged. In particular, water, wastewater, gas, and other lifeline systems were shut down and nonstructural building components caused another major or minor damage.

On September 26, 2003, this earthquake known as Tokachi-Oki earthquake hit Hokkido in Japan. 2003 Tokachi-Oki earthquake is 10 times larger than 1995 Kobe earthquake and it caused a lot of losses of both life and property. Also, lifeline systems were considerably damaged. More specifically, electric power systems were stopped in many places and telecommunication systems were temporary suspended. Water distribution piping systems were shut down due to leakage by the ground motion.

〈Fig. 1〉 Nonstructural Earthquake Damage in Oriental Hotel Lobby in 1995 (Photo: Western Washington University)[1]

〈Fig. 2〉 Nonstructural Earthquake Damage by Sichuan Earthquake in 2008, Photo: Report on the 2008 Great Sichuan Earthquake, 2009)[3]

### 2.2 Sichuan Earthquake in China

On May 12, 2008, Richter scale Mw 7.9 earthquake occurred in Sichuan Providence of central inland region in China. This earthquake was the worst earthquake in china history and it caused huge economic losses and killed about 69,197 people. During the earthquake, the functionality of school buildings and hospital buildings were lost by collapse of structural systems or sever damages of nonstructural components. Water piping systems and electric power systems were not available for about a month. Figure 2 shows an example of damages of secondary systems.

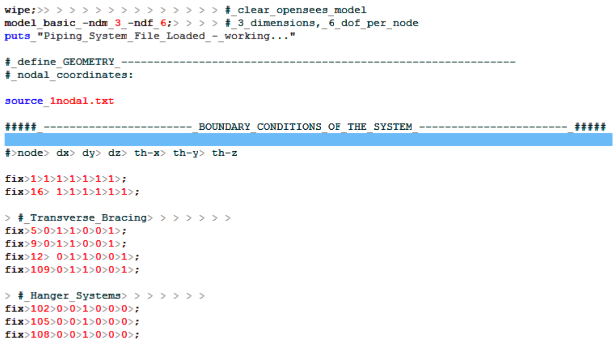
〈Fig. 3〉 Plan View of Current Piping Design System

## 3. Analytical Modeling of Current Piping System for Fire Protection in Building

In order to identify seismic performance of piping system installed in RC building system, fire protection piping system in figure 3 was selected. The piping configuration below was modeled after a fire sprinkler piping system of top floor in education research center, Gangneung-Wonju National University, Kangwon-do. Typically, for multiple linear time history analyses, the piping system in the rectangular area was selected as seismically critical zone. This sprinkler piping system was incorporated with a main piping system and branch piping systems. 5-inch and 1-inch schedule 40 black steel pipes were included and two anchors at the end of the main piping system and unbraced hangers are used as supporting system in the piping system.

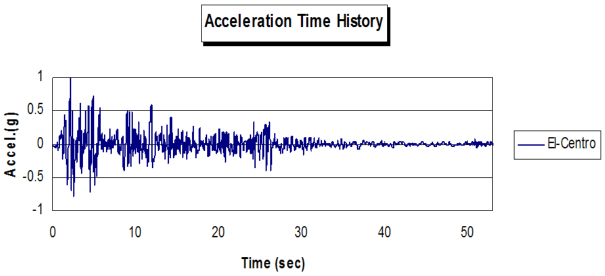
Open System for Earthquake Engineering Simulation (OpenSees) was used as finite element (FE) analysis tool for time history analysis. A key feature of OpenSees software using Tcl/Tk language is the interchangeability of components and the ability to integrate existing libraries and new components into the framework (not just new element classes) without the need to change the existing code (Mazzoni, S. et al., 2006).[5]

For FE analysis of piping system, nodes, masses, and elements were created as a modeling part and newmark average acceleration method was used for analysis procedure. Additionally, 2% Rayleigh damping ratio for black iron steel piping system was assumed. An example of modeling procedure of OpenSees was shown in figure 4.

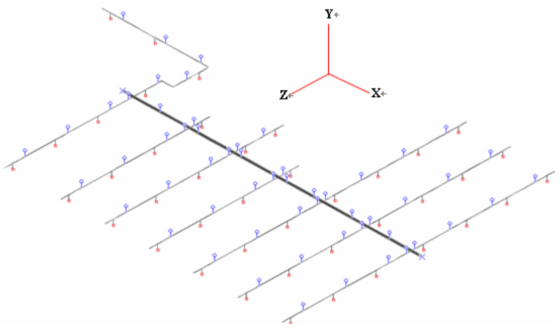


```
wipe;>> > > > > > > > > > > > > # clear opensees model
model basic -ndm 3 -ndf 6;> > > > # 3 dimensions, 6 dof per node
puts "Piping System File Loaded - working..."

# define GEOMETRY ------------------------------------------------------------
# nodal coordinates:

source 1nodal.txt

##### ---------------------- BOUNDARY CONDITIONS OF THE SYSTEM ---------------------- #####

#>node> dx> dy> dz> th-x> th-y> th-z

fix>1>1>1>1>1>1>1>;
fix>16> 1>1>1>1>1>1>;

> # Transverse Bracing> > > > > >
fix>5>0>1>1>0>0>1>;
fix>9>0>1>1>0>0>1>;
fix>12> 0>1>1>0>0>1>;
fix>109>0>1>1>0>0>1>;

> # Hanger Systems> > > > > >
fix>102>0>0>1>0>0>0>;
fix>105>0>0>1>0>0>0>;
fix>108>0>0>1>0>0>0>;
```

〈Fig. 4〉 OpenSees Modeling and Analysis Protocol[5]



〈Fig. 5〉 Ground Acceleration Time History Based on El-Centro Earthquake-PGA 1



〈Fig 6〉 Current Sprinkler Piping System Layout

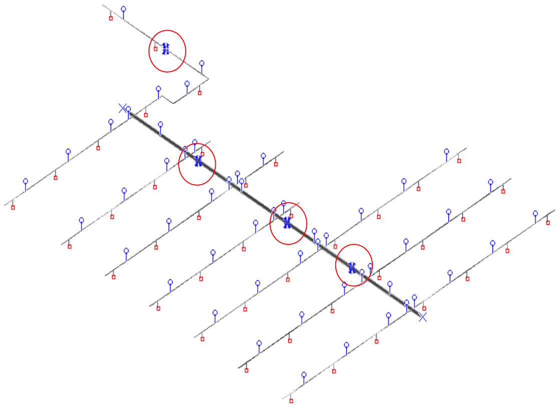
## 4. Seismic Performance and Evaluation of the Piping System installed in RC Frame

### 4.1 Deficiency of the Current Sprinkler Piping System

In order to analyze the below piping system, it was subjected to El-Centro earthquake normalized to PGA 1g in figure 5. Newmark Average Acceleration Method was used to evaluate the time history responses. Also, the direction of the earthquake was applied the horizontal direction, z-direction in figure 6. As can be seen in table

〈Table 1〉 Seismic Responses of Current Sprinkler Piping System

| Max. Displacements (in) | | | 1st Mode Frequency(Hz) | | Max. Stress (Psi) |
|---|---|---|---|---|---|
| Dx | Dy | Dz | 0.3227 | | 65,732 |
| 15.738 | 0.056 | 45.027 | | | |
| Max. Forces (lbs) | | | Max. Moment (lb-ft) | | |
| Fx | Fy | Fz | Mx | My | Mz |
| 95.986 | 9.497 | 2091.262 | 6.6455 | 22117.869 | 7.185 |



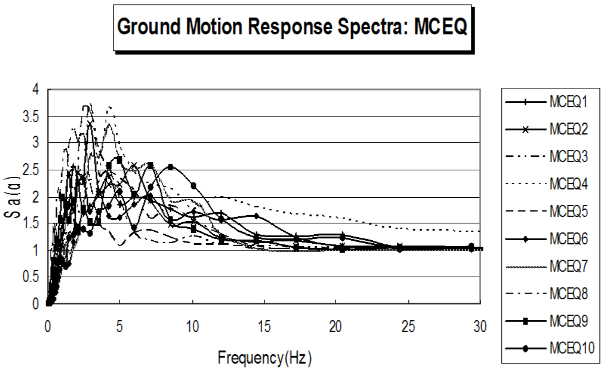
〈Fig. 7〉 Retrofitted Sprinkler Piping System Layout

1, the first mode frequency was 0.3227 (Hz) and the maximum displacement was considerably large, 45.027 (in). The current piping system is highly vulnerable to seismic events and this need to be addressed.

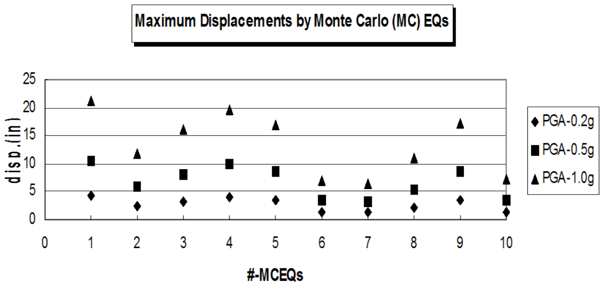
## 4.2 Seismic Retrofit of the Current Piping System

Through the previous dynamic analysis, current fire protection piping system installed in RC building system fails due to large displacements. The results indicate clearly that the possibility of damage and losses to non-structural components is much larger than that of structural components. In next four analyses, to understand improved seismic performance of piping system, the researches were performed by considering various analysis parameters.

The proposed piping system in figure 7 was added with 4 seismic sway transverse bracing systems at critical locations. The first mode dominating the response was little changed from 0.3227 Hz to 0.3750 Hz by the addition of braced hanger systems. To characterize seismic performance, 10 simulated earthquakes and 9 recorded real earthquakes were selected for linear acceleration time histories. In addition, in order to understand the effect of the building motion to the nonstructural components, a 5-storey RC building was selected for the dynamic analysis.



〈Fig. 8〉 Ground Motion Response Spectra Based on MC Simulation



〈Fig. 9〉 Maximum displacements Subjected to 10 MC Earthquakes

### 4.2.1 Seismic Risk Analysis 1 - Using 10 Simulated Earthquake Ground Motion

This seismic risk analysis 1 is to determine seismic performance of improved piping system by 10 earthquake ground motions obtained from Monte Carlo (MC) Simulation. It also help us to evaluate reduced responses at different PGAs due to retrofit of bracing systems. Figure 8 shows 5% damping response spectra of ground motions normalized to the same PGA, 1g and figure 9 describes the maximum responses due to 10 ground motions at the critical location in the piping system. As seen in figure 9, the maximum displacements were calculated by newmark Average Acceleration Method at PGA 0.2g, 0.5g, and 1g, respectively. In particular, the maximum displacements were various about from 21.18 (in) to 6.5 (in) at PGA 1g. Also, the maximum displacement of strengthened piping system was about 50% less than that of current piping system, but the maximum displacement was still excessively large.

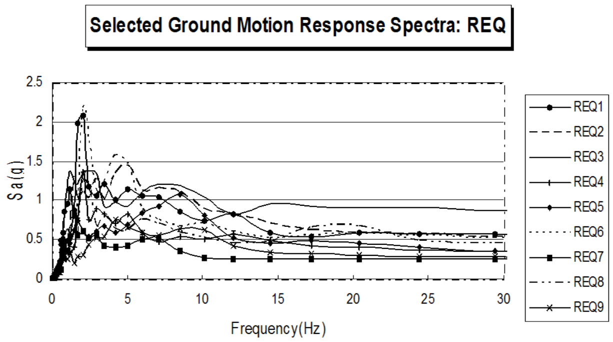
### 4.2.2 Seismic Risk Analysis 2 - using 9 recorded real earthquake ground motions

In seismic risk analysis 2, 9 selected real earthquake ground motions are used to analyze the past major earthquakes to current strengthened piping system. Table 2 showed details of 9 earthquake ground motions from PEER-NGA database (PEER, 2009) and figure 10 was also 5% damping response spectra corresponding to selected ground motions. Each maximum displacement was evaluated by the same methodology of seismic risk analysis 1.

As can be seen in figure 11, the maximum displacement was 20.31 (in) at selected ground motion #1. As a result, the displacement by the 1st ground motion was larger than other ground motions, relatively because the system response was dominated by the first mode frequency in seismic response and most displacements were over 5 (in) in the piping system.

〈Table 2〉 9 Earthquakes Selected from PEER-NGA[4]

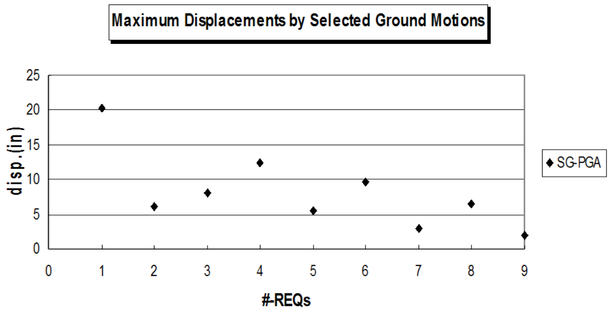
| | Seismic Event | Year | Magnitude | PGA (g) |
|---|---|---|---|---|
| 1 | Northridge / USA | 1994 | 6.7 | 0.5165 |
| 2 | Northridge / USA | 1994 | 6.7 | 0.482 |
| 3 | Duzce / Turkey | 1999 | 7.1 | 0.8224 |
| 4 | Hector / Hector | 1999 | 7.1 | 0.3368 |
| 5 | Imperial Vally / Delta | 1979 | 6.5 | 0.3511 |
| 6 | Kobe/Japan | 1995 | 6.9 | 0.5093 |
| 7 | Kobe/Japan | 1995 | 6.9 | 0.2432 |
| 8 | Superstition Hills / ElCentro | 1987 | 6.5 | 0.4463 |
| 9 | SanFernando/USA | 1971 | 6.6 | 0.2099 |



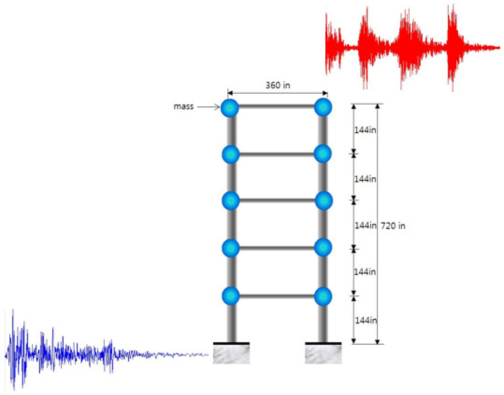
〈Fig. 10〉 Selected Ground Motion Response Spectra

### 4.2.3 Seismic Risk Analysis 3 - using 10 filtered accelerations through a 5-storey RC Frame

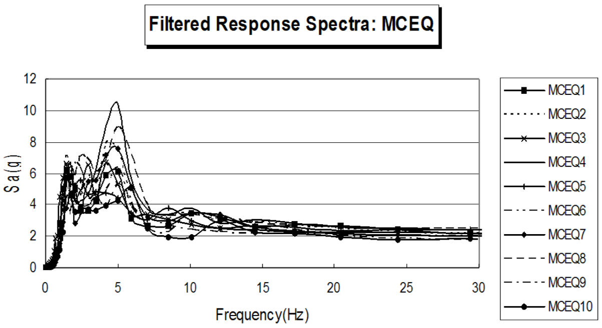
Current seismic design codes are more concerned with primary structural system than with nonstructural components. Often, while the structural components are not damaged, the nonstructural components can be damaged during an earthquake. The goal of this analysis is therefore to characterize the seismic performance of nonstructural components (e.g., piping system) due to 5-storey RC building. Figure 12 illustrates the 5-storey RC building used “beamwithhinges” elements in OpenSees and the first mode of building system is 0.314 (Hz). 10 ground motions generated by Monte Carlo simulation at PGA 1g were filtered through the 5-storey building and applied to strengthened piping system. The filtered response spectra in figure 13 were obtained from the top floor of the 5-storey reinforced concrete building. The maximum displacement responses through filtered



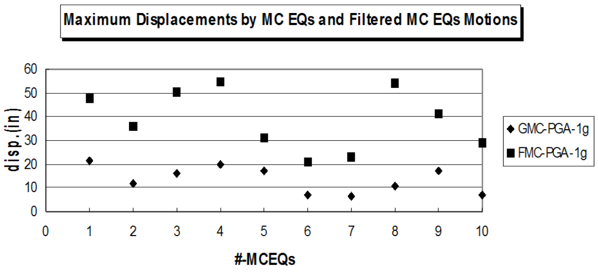
〈Fig. 11〉 Maximum displacements Subjected to Selected Ground Motions



〈Fig. 12〉 5-Storey Building Model Configuration



〈Fig. 13〉 Filtered Floor MC Response Spectra through 5-Storey Building

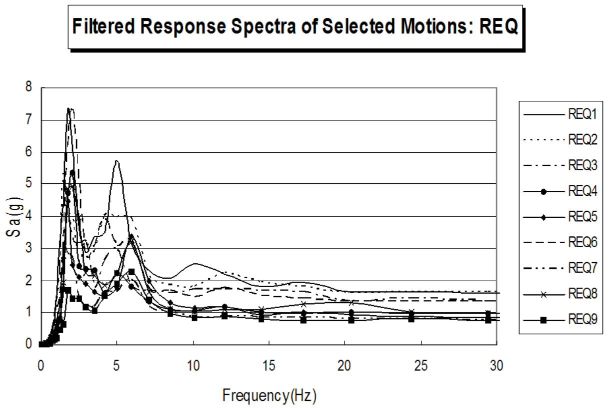


〈Fig. 14〉 Maximum displacements of MC Ground Motions and Filtered MC Ground Motions

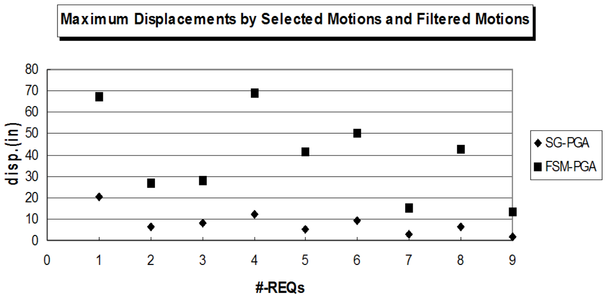
accelerations of the 10 ground motions have considerably increased in figure 14. Specifically, the maximum displacement at seismic event #8 was nearly 4 times larger compared to seismic risk analysis 1 and 5 responses were over 40 (in) by seismic risk analysis 3. Such investigated results show that the piping system is completely failed at filtered motions by PGA 1g.

### 4.2.4 Seismic Risk Analysis 4 - using 9 filtered accelerations through a 5-storey RC Frame

This study is to compare the responses from seismic risk analysis 4 with those from seismic risk analysis 2 when the real earthquakes are applied. Like seismic risk analysis 3, 9 selected ground motions were filtered though each floor of 5-storey RC building. The response spectra of 9 filtered accelerations were derived in figure 15 and Peak Floor Accelerations (PFA) were between 0.75g and 1.58g. From the above seismic risk analysis 3, the maximum displacements were significantly increased from 2.3 times to 6.6 times in accordance with increased PFA in figure 16. The piping system showed huge deformations about 70 (in) at seismic event #1 and #4. This deformation was much larger than that of seismic risk analysis 3.



〈Fig. 15〉 Filtered Floor Response Spectra of Selected Motions through 5-Storey Building



〈Fig. 16〉 Maximum Displacements of Selected Ground Motions and Filtered Ground Motions

## 5. Conclusions

The key aspect of this framework is to reduce the damages of nonstructural components, especially, gas and fire protection piping system in the event of seismic loading.

Through preliminary elastic time history analysis, current piping system shows the vulnerability to seismic events because current piping system was designed using only unbraced hanger system and anchors.

To strengthen current piping system following earthquakes, seismic sway bracing systems were used at four different critical locations based on a preliminary elastic time history analysis. Using the improved piping system, the maximum response was about 20 (in) by each ground motion. This result indicates that the maximum displacements are still excessively large although piping system has been retrofitted.

To determine the effect of building motion to nonstructural components in seismic risk analysis 3 and 4, a 5-storey RC building was modeled by OpenSees. each ground acceleration was obtained from the top floor through the RC building and applied to developed piping system. Such analysis consequently resulted in increasing the maximum displacements from 0.8 times to 6.65 times. That means that piping system is particularly sensitive according to seismic response of building motion.

From the four different types of the acceleration time history analyses, we can conclude that current guidelines for fire protection piping system is not acceptable for seismic activities in current RC frame structures. Future development of seismic design methodologies is needed to improve seismic qualifications for secondary system subjected to strong earthquake motions. In addition, further study for the nonlinear behavior of piping system in current RC frame buildings must be achieved and also the capacity of supporting system such as unbraced hangers, braced hangers, and anchors in piping system must be evaluated for the seismic design of nonstructural components.

## Acknowlegment

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