Evaluation of Performance Requirements for Seismic Design of Piping System

Bu Seog Ju and Woo Young Jung

Abstract**—**The cost of damage to the non-structural systems in critical facilities like nuclear power plants and hospitals can exceed 80% of the total cost of damage during an earthquake. The failure of nonstructural components, especially, piping systems led to leakage of water and subsequent shut-down of hospitals immediately after the event. Consequently, the evaluation of performance of these types of structural configurations has become necessary to mitigate the risk and to achieve reliable designs.

This paper focuses on a methodology to evaluate the static and dynamic characteristics of complex actual piping system based on NFPA-13 and SMACNA guidelines. The result of this study revealed that current piping system subjected to design lateral force and design spectrum based on UBC-97 was failed in both cases and mode shapes between piping system and building structure were very different.

Keywords**—**Nonstructural component, piping, hospital, seismic, bracing.

I. Introduction

NONSTRUCTURAL components that make up a considerable part of the building construction cost in offices, hotels, and hospital buildings, are (a) piping systems, (b) ceilings building contents, and (c) mechanical and electrical equipment.

The total installation and construction cost of non-structural elements in any critical facility like a hospital or a nuclear power plant is almost 80% of the total cost [1]. Furthermore, damage to these systems can result in a major economic loss, injuries, and loss of life in critical buildings in the event of an earthquake. During the 1994 Northridge earthquake, 85% of the total $7.4 billion damage is attributed to non-structural systems [2]. The Olive View Hospital had to be shut down soon after the 1994 Northridge earthquake due to water damage caused by failure of sprinkler systems [3]. Similarly, during the 1971 San Fernando earthquake, 4 of 11 medical facilities in the area incurred significant economic losses due to damaged non-structural components [4]. Damage to components such as fire protection piping system, Heating, Ventilating, and Air Conditioning (HVAC), and water piping systems have resulted in direct economic loss and injuries or loss of life in many seismic events.

In recent years, the seismic protection of nonstructural systems has been one of the most important agenda in building designs. Guidelines for performance based design of nonstructural components have been developed. The 1997 Uniform Building Code (UBC-97) considered the "design-force" based on building height [7], and it laid the foundation for the 2010 California Building Code (2010 CBC) [8]. The National Earthquake Hazards Reduction Program (NEHRP) also specified the performance requirements of seismic design for nonstructural components. The design of fire sprinkler piping systems was challenged in the 2003 Edition of NEHRP Provisions [9], and the NEHRP proposal, which addressed the issues of lateral design force, anchor capacity and brace spacing, served as a motivation for changes in National Fire Protection Association (NFPA-13) [10] specifications for installation of fire sprinkler piping [5]. The Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) [11] prescribes the type of bracing, spacing and seismic restraints based on the NFPA requirements. Therefore, these guidelines form the basics of the extensive review of the performance requirements for seismic design of hospital piping systems in this paper.

This paper recommends that research is needed to evaluate the seismic performance of nonstructural systems such as fire sprinkler piping systems in hospital buildings. The specific objectives of such a research are (1) to use rigorous analysis for evaluating the seismic performance of actual hospital piping, (2) to evaluate the validity of performance requirements as specified in the existing design guidelines, and (3) to identify the static and dynamic characteristics of complex piping system.

II. Piping System Earthquake Damage

Fig. 1 showed the failures of piping systems during the 1971 San Fernando Earthquake turning point in seismic design of buildings and nonstructural components. It was following this earthquake that the California Office of Statewide Health Planning and Development (OSHPD) started requiring that the hospital buildings remain fully operational following an earthquake.

During the 1994 Northridge earthquake, failures were observed in several different piping systems such as HVAC systems, sprinkler piping systems, and water piping systems. The major reason of the damage to fire sprinkler piping systems has been identified as the excessive vertical acceleration. Vertical acceleration led to impact of piping with ceiling and caused the failures in fire sprinkler piping systems. Another reason for significant damage in sprinkler systems was attributed to bracing type and brace spacing of pipe lines. Unbraced pipe lines, less than 1 inch diameter, experienced

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wide spread failures [6]. Fig. 2 illustrated a typical failure of fire sprinkler piping system in the Northridge Earthquake. Fig. 3 showed an example of a failure of fire sprinkler head due to vertical acceleration.

Fig. 1 Piping Failures in 1971 San Fernando Earthquake (Gates, 2005)

Fig. 2 Piping Failures in 1994 Northridge Earthquake (Miranda, 2004)

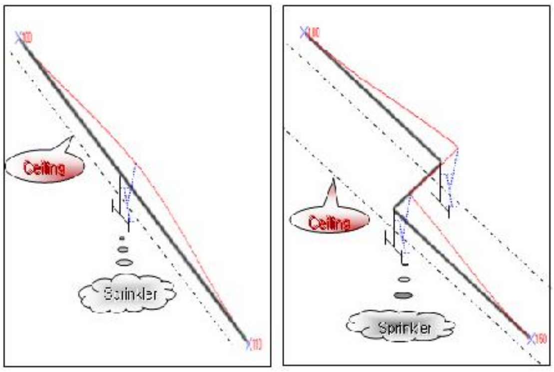

Fig. 3 Failure of Fire Sprinkler Due to Vertical Acceleration

III. Design Codes for Nonstructural Components: Piping System

Since the 1971 San Fernando Earthquake, researchers and engineers have increased their focus on studying the seismic performance and vulnerability of nonstructural components. The seismic design methodologies for nonstructural components have been addressed by various design codes:

Uniform Building Code (UBC-97) [7]:

The 1997 Uniform Building Code (UBC-97) based on principles of strength design gives the lateral design force on structures, nonstructural components, and equipment. The total lateral design force (F_p) is given in equation (1) below. The minimum of F_p is $0.7I_pC_aW_p$ and the maximum of F_p is $4.0I_pC_aW_p$.

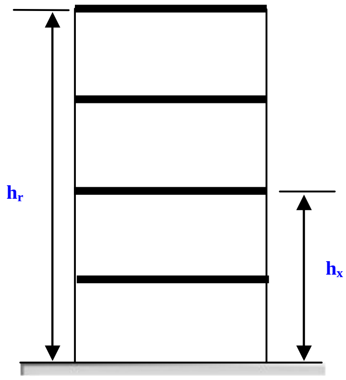

Fig. 4 4-Story Building

$$F_p = \frac{a_p C_a I_p}{R_p}\left(1 + 3\frac{h_x}{h_r}\right)W_p \qquad (1)$$

where,

F_p: The seismic total lateral design force
a_p: Component amplification factor (1.0 for piping elements)
C_a: Seismic coefficient based on the seismic zone and soil type
I_p: Importance factor (1.5 for hospital buildings)
R_p: Component specific inelastic response coefficient (3.0 for piping elements)
h_r: The total building height
h_x: The component elevation
W_p: Operating weight

When h_x is equal to h_r, the maximum amplification in any building is 4.0, and R_p is 3.0 for piping systems.

National Earthquake Hazards Reduction Programs (NEHRP) [9]:

The NEHRP provisions consider the second generation Engineering Demand Parameters (EDPs), such as site soil conditions, amplification of seismic force, and location of nonstructural components within a building. This design code is based on the principles of allowable stress design. The NEHRP provisions provide design performance requirements for force and displacements of nonstructural components (Gillengerten, 2003). In addition, the NEHRP provisions form the basis of other building design codes such as UBC, IBC, ASCE7 and NFPA-5000. The lateral force on secondary systems and nonstructural components is defined by (2):

$$F_p = \frac{a_p(0.4S_{DS})I_p}{R_p}\left(1 + 2\frac{z}{h}\right)W_p \qquad (2)$$

where,

F_p: The seismic total design lateral force
a_p: Component amplification factor
S_{Ds}: Design spectral response acceleration at short period
I_p: Importance factor
R_p: Component response modification factor

h: The total building height, h_r in fig. 4

z: The component elevation at point of attachment, h_x in fig. 4

W_p: Component operating weight

The minimum and maximum lateral force (F_p) is calculated as:

$$F_{p\,\min} = 0.3 S_{Ds} I_p W_p$$

$$F_{p\,\max} = 1.6 S_{Ds} I_p W_p$$

When *z* is equal to h, the maximum amplification in any building is 3.0, and R_p is 2.5 for piping systems.

IV. Piping System Layout

The hospital piping system shown in Fig. 5 consists of main piping runs along 4 sections with a total of 64 branches in all. Essentially, main piping system is made of 2-inch and 4-inch pipes while the branches comprise of pipes with smaller diameter than those of main pipes. This system is supported by unbraced single hangers, transverse braced hangers and longitudinal braced hangers. There are 4 anchors at the ends of the main piping system.

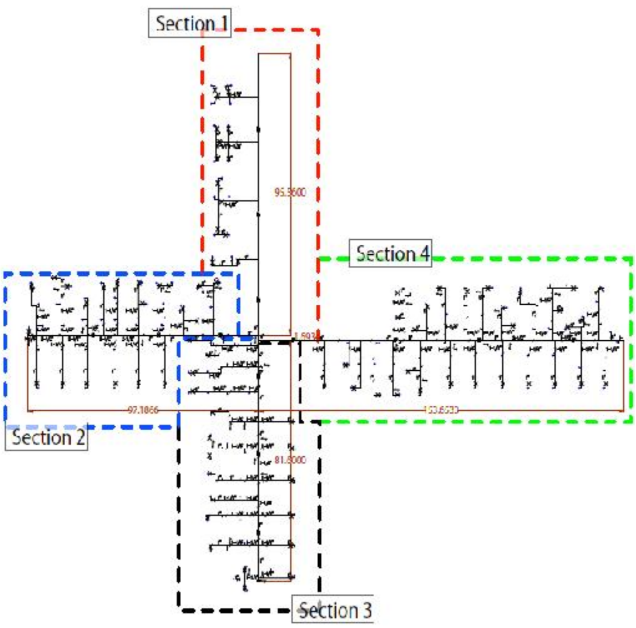

Fig. 5 Full Scale Piping System Layout

V. Evaluation of Seismic Performance of Existing Piping System

In this section, we performed design lateral force analysis for hospital piping system. Table I showed the lateral force coefficients. Specifically, the lateral force was conducted at the top floor, which is maximum lateral force in the building system. The lateral force based on UBC-97 was $0.95W_p$ and the force was applied to the piping system designed in accordance with National Fire Protection Association (NFPA-13) and Sheet Metal and Air Conditioning Contractors' National Association (SMACNA). SMACNA has provided the design guidelines and seismic restraints for piping and duct systems according to Seismic Hazard Level (SHL) [11].

TABLE I
THE LATERAL FORCE COEFFICIENT

Near-Sorce Factor (N_a)	1.08	Component Response Factor (R_p)	3.0
Seismic Coefficient (C_a: $0.44N_a$)	0.475 (zone 4)	Importance Factor (I_p)	1.5
Component Amplification Factor (a_p)	1.0	Building Height (*ft*)	195.5

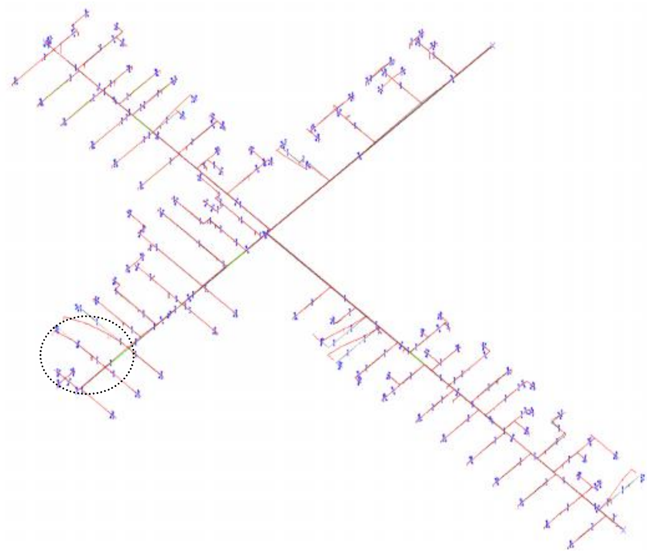

Fig. 6 Displacements of Piping System Subjected to the Lateral Force

Fig. 6 showed the displacements of piping system due to the lateral force. The maximum displacement (31.76 cm) caused in the circle area of piping system and additional results were given in Table II.

TABLE II
STATIC ANALYSIS RESULTS (MAXIMUM FORCES AND MOMENTS)

F_x	8.829 (*KN*)	M_x	5.48 (*N-m*)
F_y	39.32 (*N*)	M_y	2.94 (*KN-m*)
F_z	1.143 (*KN*)	M_z	17.83 (*N-m*)

Next, in order to understand the dynamic characteristics of piping system, the design spectrum (Fig. 7) based on UBC-97 was created for the piping system.

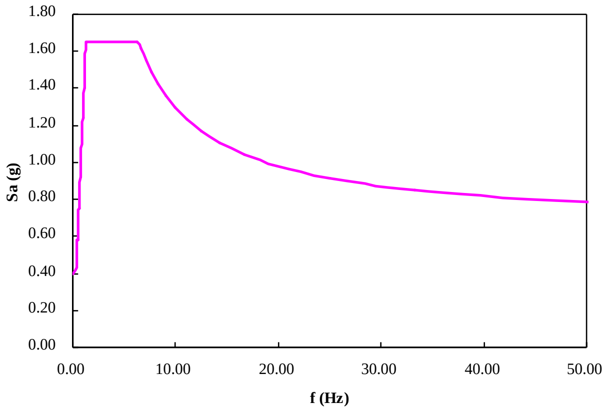

Fig. 7 Design Spectrum Based on UBC-97

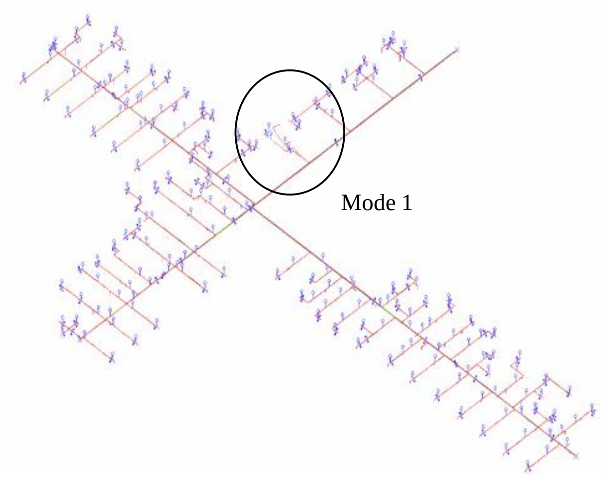

Fig. 8 Piping System Mode Shapes

Furthermore, the fundamental and second frequency of the piping system in fig. 8 was 0.6450 Hz and 0.8384 Hz, respectively. The design spectrum also was applied to the horizontal direction at the piping system. The maximum displacement was 70.13 cm at a branch piping system. Table III also was given the forces and moments in the dynamic analysis.

TABLE III
DYNAMIC ANALYSIS RESULTS (MAXIMUM FORCES AND MOMENTS)

F_x	8.869 (*KN*)	M_x	16.27 (*N-m*)
F_y	87.27 (*N*)	M_y	5.69 (*KN-m*)
F_z	7.122 (*KN*)	M_z	16.27 (*N-m*)

As can be seen in the results, the static and dynamic performance of piping system was significantly different. In the case of dynamic analysis, although the piping system was designed by NFPA-13 and SMACNA guideline, the maximum displacement was excessively large and the maximum moment (M_y) was almost doubled.

VI. CONCLUSION

This paper focuses on evaluating the performance of piping system and mitigating the seismic risk of piping system. The conclusions of this paper were as followings:

1) The current design methodology such as UBC-97 and the NEHRP provisions for design of nonstructural components is similar to that for buildings and the current methods are based on inertial forces. However, failures have been observed in piping systems that are designed to these requirements.
2) Piping mode shapes are very different from building mode shapes and piping failures are caused by relative support motion in many cases.
3) Furthermore, the guidelines on evaluation of sprinkler head displacements, velocities and accelerations must be evaluated. Sprinkler heads generally break due to large relative displacements and impact with ceilings.

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