Probabilistic Studies on Seismic Fragility of Different Pipe Sizes Based on Monotonic Experimental Tests

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***Abstract*— This paper presents the seismic fragility of piping systems based on monotonic experimental tests. The fragility, conditional probability of failure for a given level of intensity measure, generally used to evaluate the structural safety and indentify the fault tree with respect to seismically induced failures. The nonlinear FE models of threaded T-joint systems based on monotonic experimental results were developed in OpenSees, using the ElasticPPGap material. In order to evaluate the seismic fragility of T-joint piping systems, 1-inch and 2-inch threaded T-joint systems, were incorporated with main hospital piping system, and multiple nonlinear time history analyses related to Monte Carlo simulation were conducted. Consequently, seismic fragility of piping system at 1-inch and 2-inch threaded T-joint connections corresponding to ductility level was developed. It was interesting to observe that 2-inch threaded T-joint was more fragile rather than 1-inch threaded T-joint, based on the nonlinear FE model by monotonic tests and also location 1 was more fragile rather than location 2 for both 1-inch and 2-inch T-joint.**

Keyword - T-joint, Fragility, Earthquake, Pipe size, ElasticPPGap

I. INTRODUCTION

Pipeline as a nonstructural component is an essential element for energy and water supply; therefore it has very important functional and operational purpose in the critical facilities including nuclear power plants, high-tech factories, and hospitals. It is crucial that the piping system of the critical energy facilities and structures must remain functional at any circumstances. The typical piping system can be consisted of water resource, chemical/oxygen, and gas pipeline, and the failure of such piping system can cause the explosion or leakage problem during and after an earthquake. Furthermore, the failure or damage of the nonstructural components exposed a significant part of the construction investment can be directly related to public safety, economic losses, property value, and structural safety of the building systems subjected to seismic ground motions. For example, during the 1971 San Fernando earthquake (Mw 6.6) caused approximately 500 million dollars damage, many infrastructure systems such as sewers and water supply pipeline network system, highway structures, and electrical power facilities were damaged. In addition, four hospitals in the region of strong shaking were shut down and the nonstructural earthquake damage was reported unlike there was no structural damage in school, office, and hospital buildings [1]. Holy Cross and Olive View hospital rebuilt by the seismic design requirements after the San Fernando earthquake was forced to close due to air handling system (HVAC) damage and the sprinkler and chilled water distribution piping system damage, respectively, during the 1994 Northridge earthquake [2]. In Japan, the nonstructural earthquake damage, especially sprinkler piping system in Kobe city, was 40.8% in a total reported damage during the 1995 Kobe earthquake [3].

In spite of significant observations in serviceability due to the nonstructural components failures during earthquakes associated with the public safety, seismic design codes focused on the improvement of seismic performance for structural components rather than nonstructural systems over the past few decades. However, in recent years, the study with respect to nonstructural components such as piping systems and electric cabinets in nuclear power plants, hospitals, and high-tech factories was conducted. Pardalopoulos and Pantazopoulou [4] investigated the seismic performance of gas pipeline system installed in multi-story buildings using two different methods: 1) lumped secondary system based on acceleration-sensitive; 2) generalized secondary system in accordance with deformation-sensitive. Furthermore, fire protection piping system attached on hospital buildings was studied in order to understand the seismic behavior of the piping system, having many unknown aspects due to complexity of the pipeline and in order to mitigate the earthquake damage of the piping system based on fragility methodology [5]–[9]. In this paper, we focused on Probabilistic Seismic Risk Assessment (PSRA) of piping systems based on the fragility framework in terms of T-joint pipe sizes and ground motion uncertainty. To do so, nonlinear Finite Element (FE) model for the T-joint systems was developed, considering both 1-inch and 2-inch monotonic tests. More specifically, the T-joint FE models of different pipe sizes were incorporated into a main piping system to perform multiple nonlinear time history analysis. The seismic fragility corresponding to system level ductility obtained from monotonic test results was estimated and compared with results of using different T-joint branch piping system in sizes.

II. Description of Experimental Tests

The failure of water distribution, sprinkler, and chemical/oxygen piping systems due to leakage can cause system shut-down or explosion, such failure problem primarily occurred at the joint connection area of the piping system. In particular, the joint connections like T-joint system frequently show complex nonlinear behavior. In order to understand the complex behavior of the piping system, University at Buffalo, State University of New York (UB) conducted the experimental tests for two different threaded T-joint piping systems: 1-inch and 2-inch pipe size. Fig. 1 shows the test set-up of the threaded T-joint system. The results in terms of force-displacement and moment-rotation relationship to determine the stiffness of the system were obtained from the monotonic test with constant velocity (0.01 in/sec). Also, it was interesting to find that the leakage of the T-joint system was observed at threaded area due to slippage and crack by imposed rotation [10]–[11].

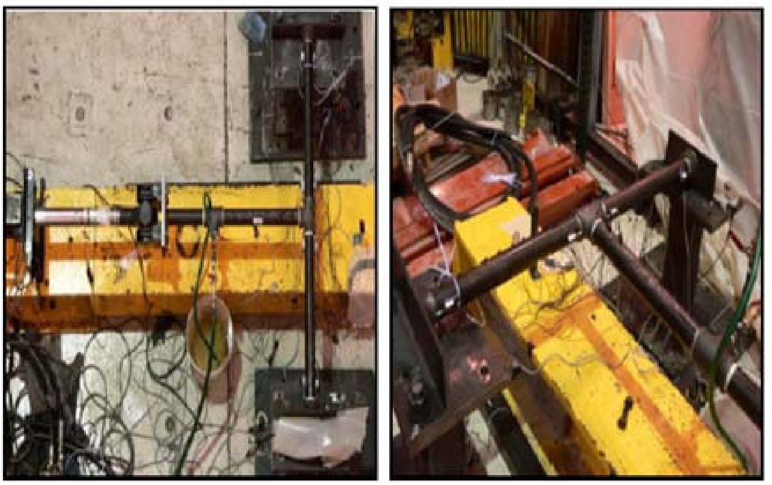


Fig. 1. T-joint Test Setup, Conducted by University at Buffalo [10-11]

III. FE Model of Piping System

A. Validation of T-joint FE Models

In order to evaluate the seismic fragility of piping system with respect to different sizes of threaded T-joint systems, the FE models based on the experimental results were developed using OpenSees for both 1-inch and 2-inch branch piping systems. As can be seen in Fig. 2, the T-joint systems were modeled by two nonlinear rotational springs at each end, using an Elastic Perfectly-Plastic Gap (ElasticPPGap) uniaxial material in [12]. Particularly, the ElasticPPGap material is shown in Fig. 3. It was constructed with various arguments such as tangent stiffness, stress/force, initial gap, hardening ratio, and damage. Fig. 4 shows the results between numerical analysis and experimental analysis and the stiffness value from FE models was extremely in good agreement with the moment-rotation curves obtained from the experimental test.

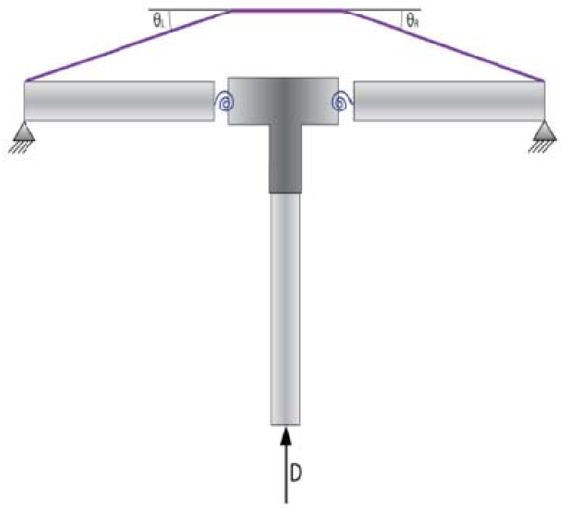
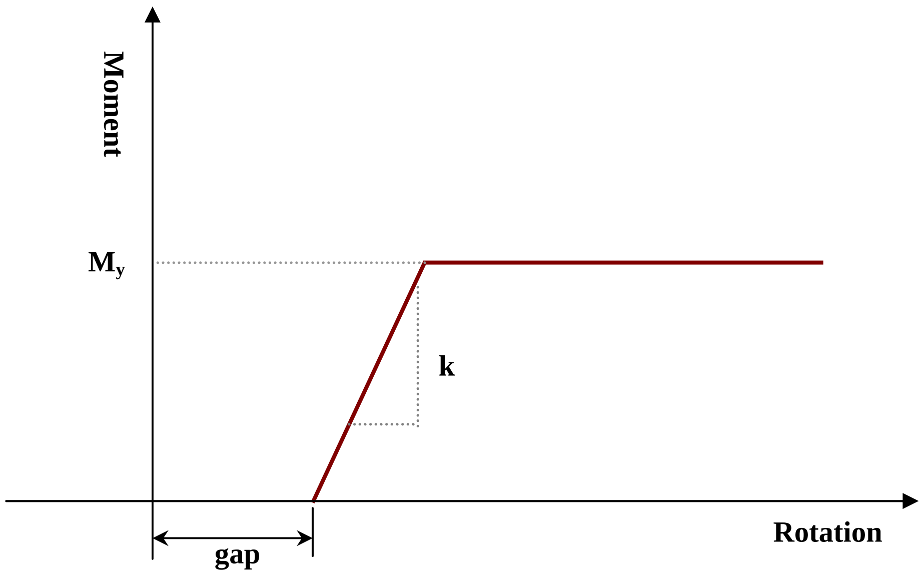
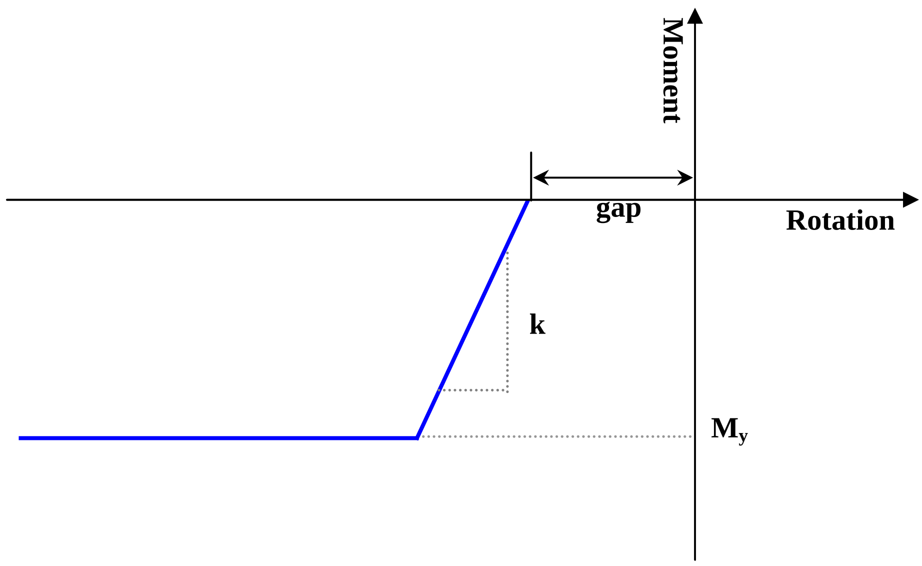


Fig. 2. T-joint Nonlinear FE Model (1-inch and 2-inch)

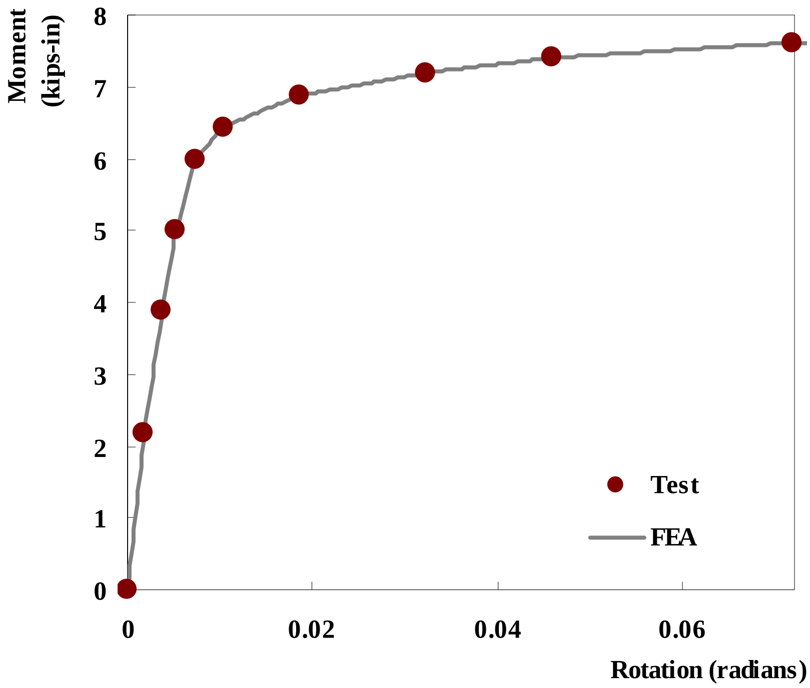


(a) Tension gap

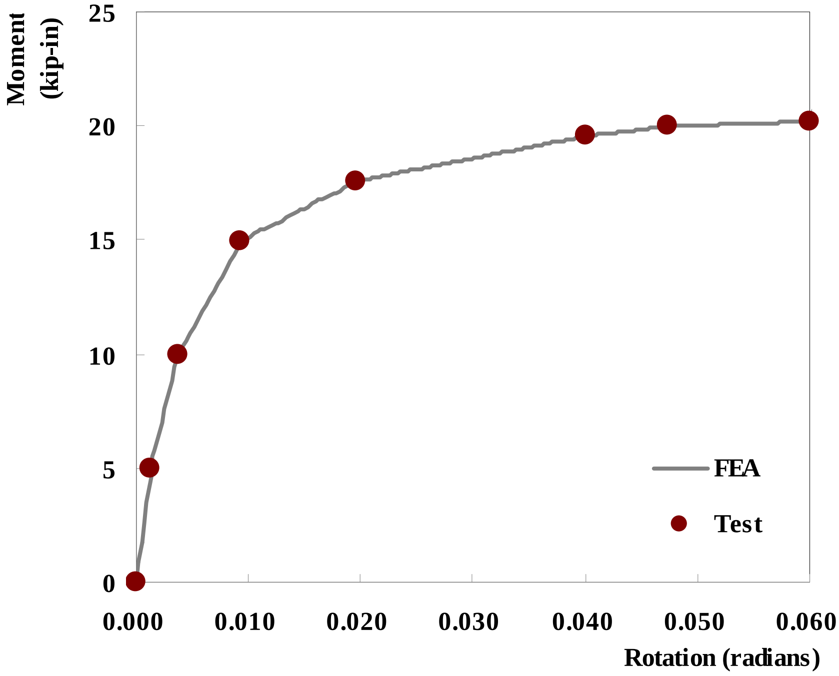


(b) Compression gap

Fig. 3. ElasticPPGap Material Model in OpenSees



(a) Validation of 1-inch FE Model



(b) Validation of 2-inch FE model

Fig. 4. Validation of FE Models in OpenSees

B. Full-Scale Piping System

Pipe lines such as, fire protection, chemical/oxygen, gas systems in a building were often exposed to extreme events. Therefore, the full scale piping system installed in hospitals was selected in this study to reduce earthquake damage, as shown in Fig. 5. The piping system basically consisted of 64 branches and sprinkler systems but this study considered only two branch systems due to the system complexity (nonlinearity), determined as the point of maximum displacements and rotations from linear time history analyses. In addition, anchor systems at the end of the piping system and hangers (unbraced, transverse braced, longitudinal braced) were used to support the piping system in the hospital. For the numerical analysis, the piping system was constructed by elasticBeamColumn elements, using various parameters (cross-sectional area, young’s modulus, shear modulus, torsional moment of inertia, and second moment of area) in OpenSees. Especially, the piping system was modeled by lumped mass system as an acceleration sensitive component, governed by the first few modes and periods. Consequently, the first mode and second mode frequency of the piping system with two T-joint branches was 1.82 (Hz) and 3.28 (Hz), respectively and the details can be found in [6].

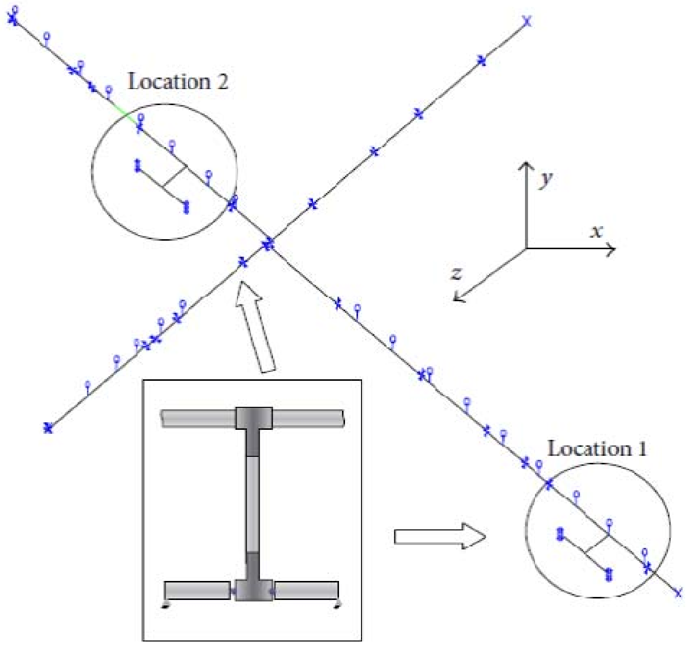


Fig. 5. Main Piping System with two nonlinear T-joint Systems

IV. Seismic Fragility of Piping System

Probabilistic Seismic Risk Assessment (PSRA) to nonstructural components in critical facilities is not only important from occupancy of the construction investment but also potential earthquake damage such as radiological release, chemical release, fire, and explosion [13]. This study used seismic fragility methodology as a key element of seismic risk assessment, in order to reduce business interruption and seismic induced fire due to system leakage failure in the piping system subjected to seismic ground motions. In recent years, the seismic fragility as the conditional probability of system failure at a given ground motion intensity was applied in structural system (e.g., nuclear power plants, bridges, and buildings) as well as nonstructural components (piping systems, electrical/mechanical equipments, and architectural system). For example, Kennedy et al. [14] conducted the safety assessment of the Oyster Creek nuclear power plant in accordance with the ground motion probability and the conditional probability of failure estimates. Also, Electric Power Research Institute [15] had studied a methodology for constructing fragility analysis for shear wall, typical of auxiliary or other concrete buildings by seismic probabilistic risk assessment at nuclear power plants. Finally, Shinozuka [16] showed two different types of fragility curves: 1) the empirical fragility of bridge structures obtained from 1994 Northridge and 1995 Kobe earthquakes; 2) analytical fragility characterizing nonlinear time history analyses for typical bridge structure in Tennessee, USA. Based on the aforementioned fragility methodology, two lognormal distribution parameters with the median and log-standard deviation given in Eq. (1) are needed in this study.

$$F(\lambda)_i = \Phi\left[\frac{\ln\left(\lambda_i / m\right)}{\zeta}\right] \tag{1}$$

Where, and are the median and log-standard deviation of the fragility, respectively. Also, is the ground motion intensity at the given levels of Peak Ground Acceleration (PGA). In order to construct the seismic fragility of piping systems in this study, Monte Carlo Simulation (MCS) was carried out as an empirical fragility analysis. More specifically, seismic fragility of piping systems considering ground motion uncertainties were evaluated by conducting multiple nonlinear time history analyses. The fragility equation was shown as following:

$$P_f(\lambda)_i = \frac{\sum_i^N (\theta_i \geq \theta_{\lim} \mid PGA = \lambda)}{\# EQs} \tag{2}$$

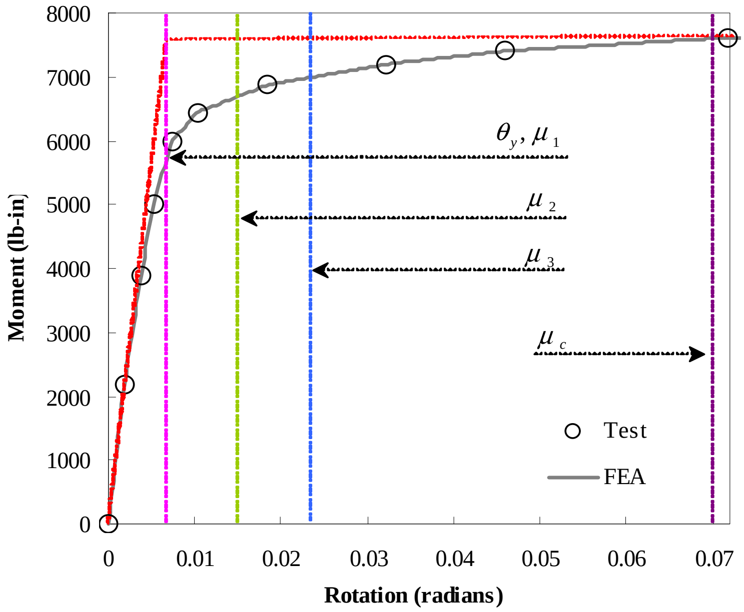
In which θ_i is the maximum rotation at T-joint systems subjected to seismic ground motions and #EQs represents the number of earthquakes. For the analytical fragility, the limit state of the system must be achieved and seismic fragility must characterize the uncertainties by seismic events, as shown in Eq. (2). Consequently, the limit state and ground motion uncertainty will be described in the next section.

A. Limit State of T-Joint Systems

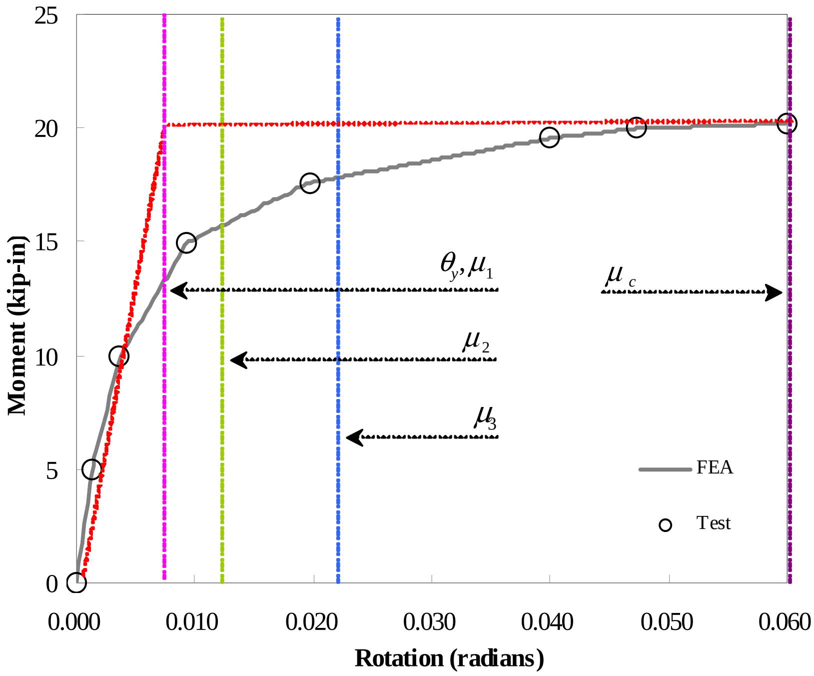
Based on earthquake technical manual from [17], the limit state of T-joint systems was quantitatively defined: minor damage, moderate damage, severe damage, and collapse. The each damage measurement was identified by the monotonic experimental tests and Fig. 6 described the limit state corresponding to ductility levels given in Eq. (3).

$$\mu = \frac{\theta_j}{\theta_y} \tag{3}$$

In which, μ is the ductility level factor obtained from inelastic dynamic analysis, θ_j is the rotation corresponding to the ductility level, and θ_y is the rotation at yield [18]. The various damage states considered in this study for seismic fragility of T-joint piping systems were also listed in Table 1.



(a) 1-inch Ductility Levels



(b) 2-inch ductility levels

Fig. 6. Limit States Corresponding to Ductility Levels

TABLE I. Limit States Corresponding to Ductility Levels

Ductility Level	**1-inch T-joint**	**1-inch T-joint**
μ_1 (Minor damage)	0.0075	0.00724
μ_2 (Moderate damage)	0.0150	0.01448
μ_3 (Severe damage)	0.0225	0.02172
μ_c (Collapse)	0.070	0.060

B. Seismic Ground Motions

As shown in the aforementioned definition, the fragility is related to two different uncertainties with respect to material and seismic ground motions. For the numerical analyses of structural fragility, 75 earthquake time histories obtained from [19] were applied.

V. Fragility Analysis

In the analysis of seismic fragility of threaded T-joint piping systems with respect to different sizes based on monotonic tests, a set of 75 real earthquakes normalized to the same Peak Ground Acceleration (PGA) from 0.4g to 3.0g at an interval of 0.1g was applied. 75 nonlinear FE analyses were carried out for each ground motion set and seismic fragilities were described in Fig. 7 to Fig. 10. In addition, Fig. 7 and Fig. 8 show the seismic fragility curves corresponding to each damage state for 1-inch T-joint piping system at location 1 and location 2, respectively. Fragility curves associated with the limit states for 2-inch T-joint piping system were depicted well in Fig. 9 and Fig. 10. As can be seen in probability of failure at each damage state, the lognormal distribution model for seismic fragility was extremely matched well with the results according to MCS. It was also clearly revealed that T-joint system at location 1 was more fragile than T-joint system at location 2, for both 1-inch and 2-inch size. Furthermore, the fragility for T-joint size was illustrated in Fig. 11 and in case of location 1; the probability of failure for 1-inch system and 2-inch system at 0.7g was 19.67% and 42.67, respectively. Also, overall, the probability of failure at location 2 was more about two times larger. It showed that 1-inch T-joint piping system rather than 2-inch T-joint piping system at the ductility aspect had more advantage with respect to the assurance of safety. In particular, 1-inch and 2-inch T-joint system corresponding to collapse level had no failure up to 1.5g. Fig. 12 shows Probability Density Function (PDF) and Cumulative Density Function (CDF) at location 1 for both 1-inch and 2-inch T-joint in accordance with minor damage state. PDF related to extreme variables from minor damage to collapse damage at location 1 for the threaded T-joint systems from was described in Fig. 13. The median peak ground acceleration capacity (50% probability of failure) in terms of each limit state for 1-inch threaded T-joint system was 1.0g, 1.7g, 2.0g, and 3.5g, respectively and also that of 2-inch threaded T-joint was 0.8g, 1.2g, 1.6g, and 3.3g, respectively.

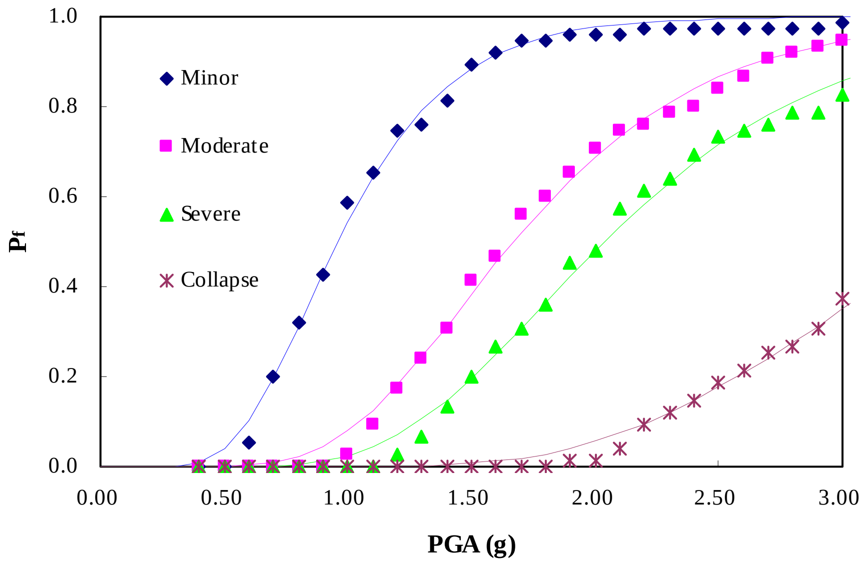


Fig. 7. Limit States Corresponding to Ductility Levels

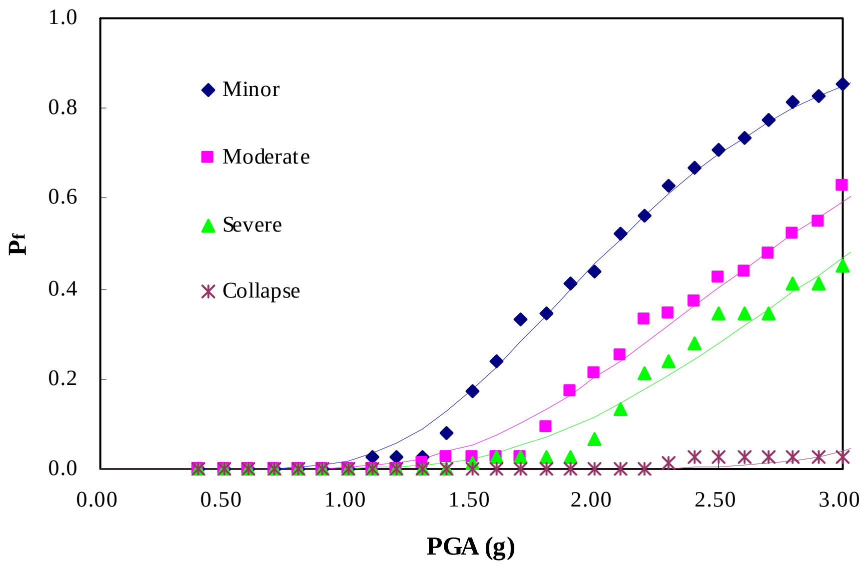


Fig. 8. Piping Fragility of 1-inch Threaded T-joint at Location 2

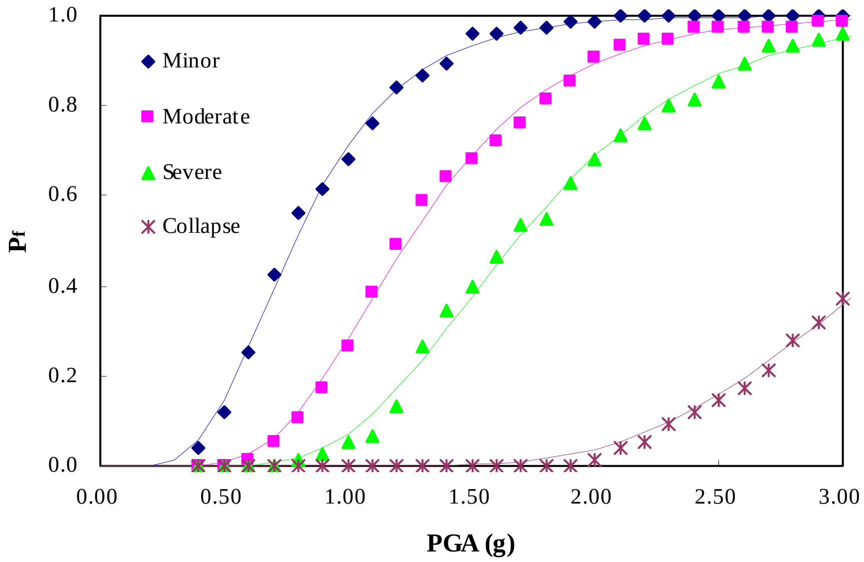


Fig. 9. Piping Fragility of 2-inch Threaded T-joint at Location 1

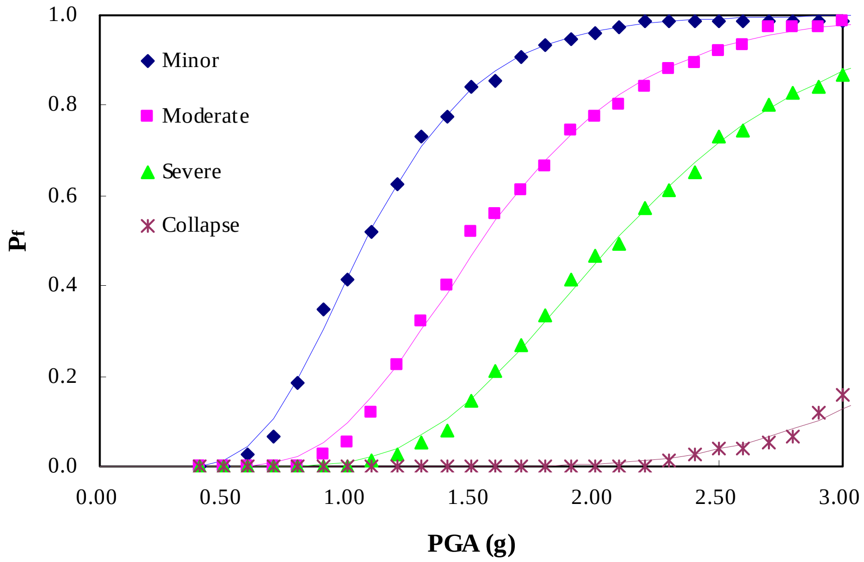
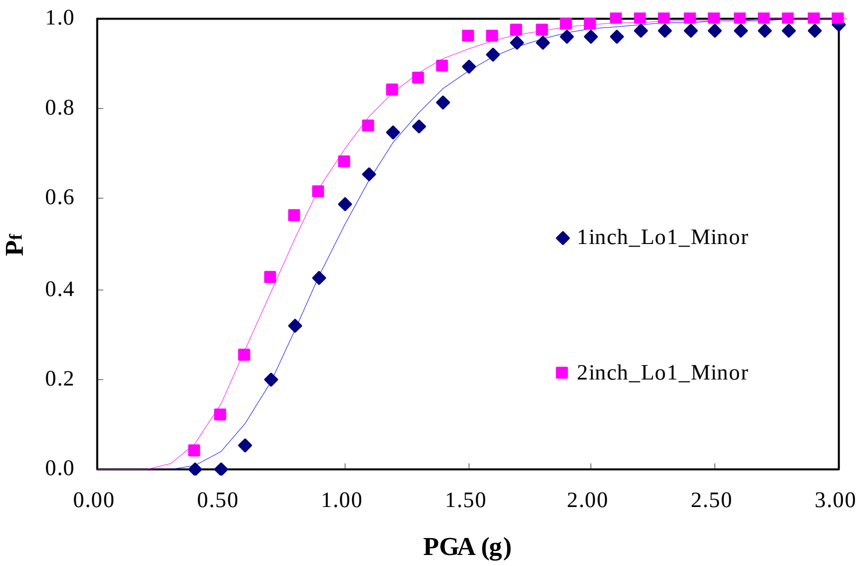
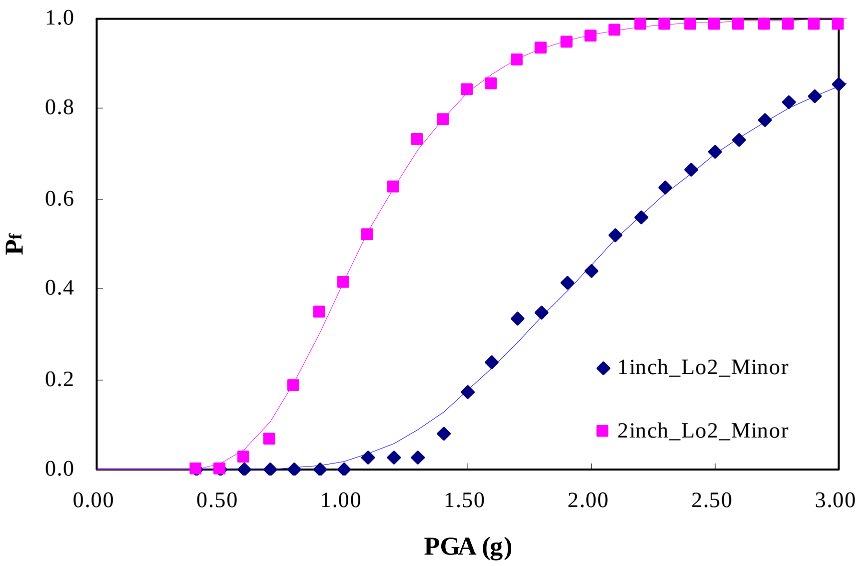


Fig. 10. Piping Fragility of 2-inch Threaded T-joint at Location 2

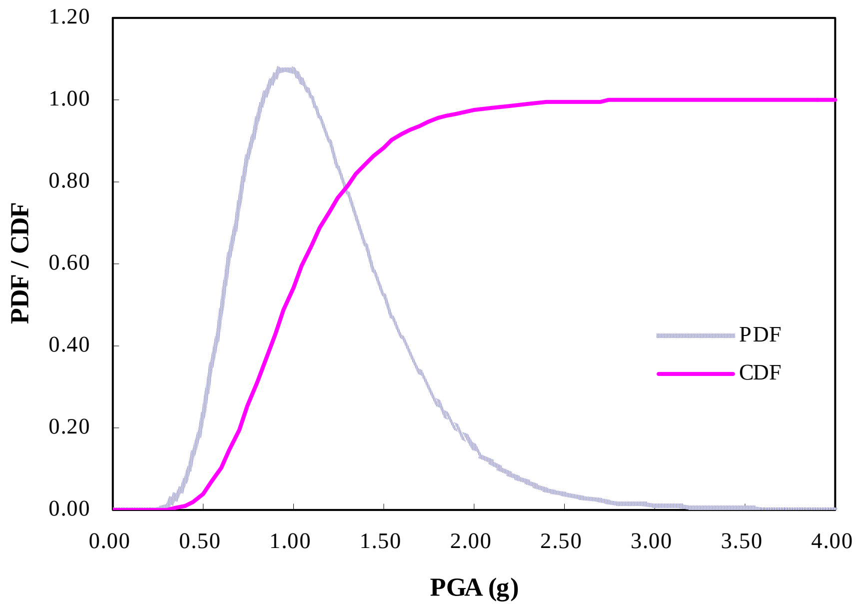


(a) Location 1

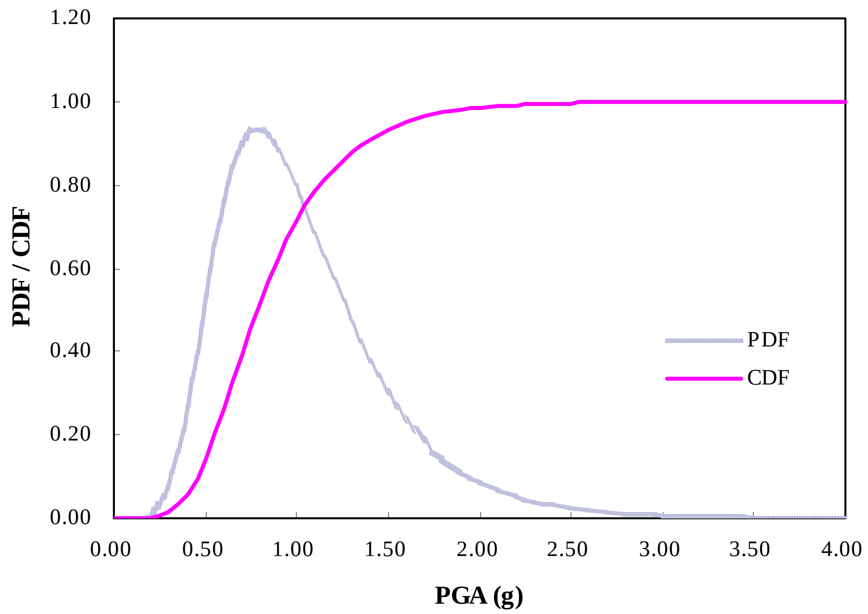


(b) Location 2

Fig. 11. Piping Fragilities for 1-inch and 2-inch T-joint Systems at Location 1

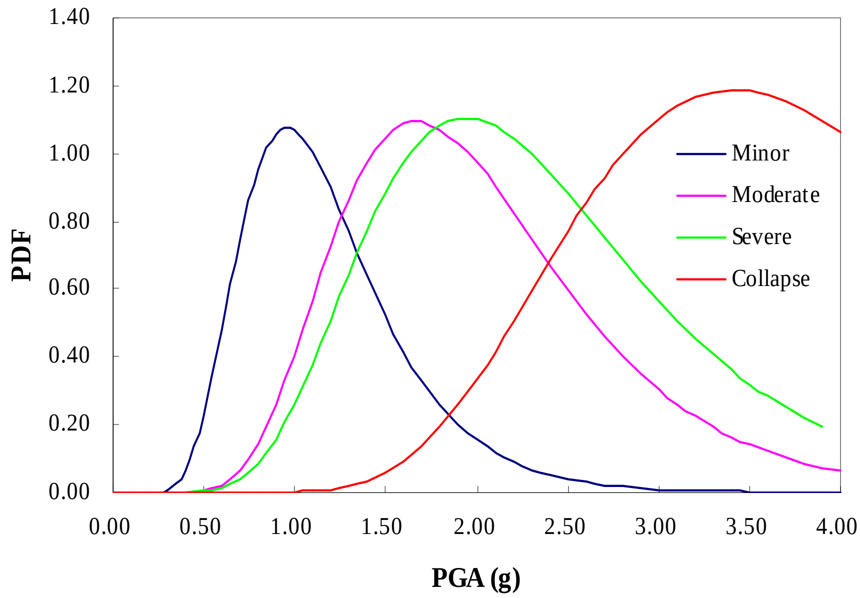


(a) 1-inch T-joint System

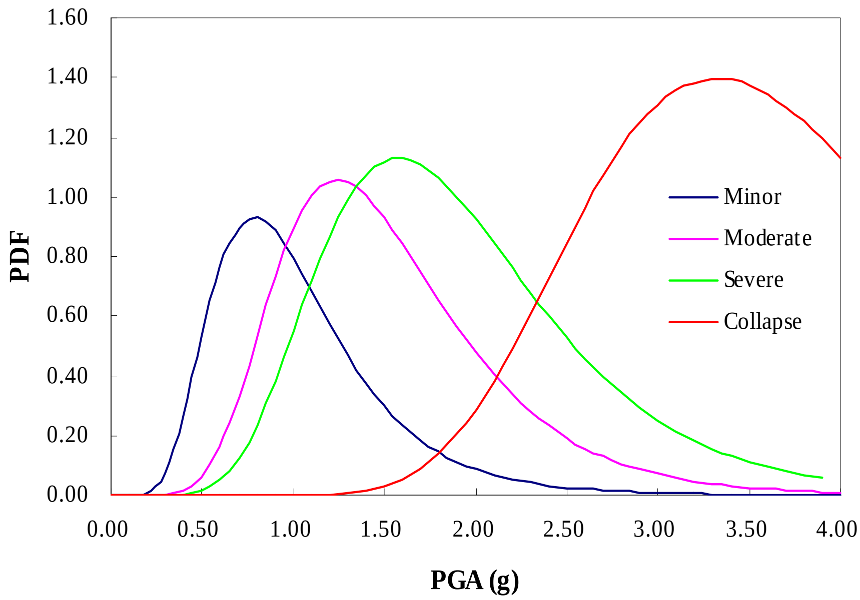


(b) 2-inch T-joint System

Fig. 12. PDF and CDF Corresponding to Minor Damage State of 1-inch and 2-inch T-joint Systems at Location 1



(a) 1-inch T-joint System



(b) 2-inch T-joint System

Fig. 13. Probability Density Function with respect to limit states for 1-inch and 2-inch T-joint System

VI. CONCLUSION

The seismic fragility associated with conditional probability of failure commonly used to evaluate the seismic risk for structural and nonstructural systems. This study presents seismic fragility of threaded T-joint piping systems with different pipe sizes based on monotonic experimental tests. Moreover, in order to evaluate the fragility, nonlinear FE model for the threaded T-joint was developed by using ElasticPPGap model in OpenSees. As a result, the nonlinear FE model was extremely matched well in comparison to the results obtained from monotonic experimental tests. Also, this nonlinear FE model relevant to threaded T-joint systems was incorporated with a main piping system using OpenSees. Consequently, in consideration of uncertainties in terms of materials and ground motions, piping fragility of threaded T-joint systems was constructed. It was important to note that 5% probability of failure commonly used to design and evaluate characteristic of strength in civil engineering structures, for 1-inch and 2-inch threaded T-joint systems at location 1 was caused at PGA level 0.6g and 0.4g, respectively. Therefore, 2-inch threaded T-joint system rather than 1-inch T-joint system was generally more fragile in overall piping system. In addition, the extreme random values from minor damage to collapse damage level was developed by ductility level and these extreme values from the fragility analyses can use the structural safety and performance based design of piping system subjected to seismic ground motions.

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