Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division IX, Paper 179 (include assigned division number from I to X)

A Framework for Evaluating the Probability of Seismically Induced Fire Hazard Due to Piping Leakage

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ABSTRACT

A key objective in the safety assessment of fast breeder reactor relates to the evaluation fire hazard due to leakages of liquid coolant. Any leakage of liquid coolant such as sodium can initiate an internal fire. A probabilistic risk assessment for fire hazard requires accurate evaluation of internal fire hazard due to leakages. The hazard is more likely in the event of what can be termed as “seismically induced fire” hazard wherein the leakages are initiated by a seismic event. Typically, such seismically induced leakages occur at the joints, elbows, or nozzles of piping systems carrying the liquid coolant. Even in nonnuclear structures such as hospitals, a leakage of oxygen or other toxic gases from pipelines can result in either explosions or fire hazard. Such damages have been observed in many past earthquakes including those during the 1971 San Fernando and 1994 North Ridge earthquakes in California. Seismically induced fires are also important in evaluating the safety of other critical facilities such as oil and natural gas facilities. This paper proposes a framework to evaluate the probabilities of seismically inducted leakages in distributed piping systems with localized nonlinearities. The framework is based on using the data from laboratory testing on components such as elbows and/or joints and incorporating this nonlinear data into a large scale analysis of the complete system. Actual failures observed in laboratory test data is used to propose a generic methodology to characterize limit-state and corresponding performance criterion needed in the evaluation of the probabilities of failure.

INTRODUCTION

In critical facilities typically nuclear power plants and hospitals, structural and nonstructural components must remain operational or functional after a seismic event. However, it has been observed that the nonstructural components such as piping systems, mechanical and electrical equipment, and building contents are much more fragile than the structural components during an earthquake. The 1971 San Fernando earthquake led to significant changes in seismic design of buildings and nonstructural systems. Due to the failures observed in this earthquake (e.g. see Figure 1), 4 of the 11 major medical facilities in the area had extensive damage to nonstructural systems (Wasilewski, 1998). The Olive View Hospital which was retrofitted for withstanding earthquake forces was shut down for a week because of damage to nonstructural components (Ayres and Phillips 1998).

The 1994 Northridge Earthquake resulted in the greatest economic loss to building structures, highways and bridges in United States history. During the Northridge earthquake, 51 people were killed and over 9,000 people were injured. Major highways collapsed and 9 hospitals were shut-down in Los Angeles area. A total of 2,500 beds were lost for usage in the hospitals. There were serious damages to nonstructural components, especially the piping systems. Inside the buildings, water lines were broken, and most hospital buildings suffered from significant water damage due to failure of water chilled and hot water pipe lines. Figure 2 illustrates a typical failure of fire sprinkler piping system and an example of water damage due to failure of water pipe lines (Miranda, 2004).

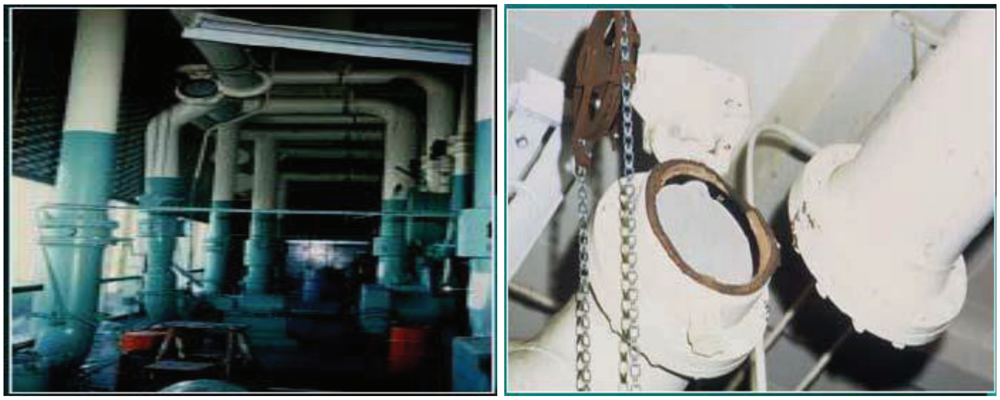

Figure 1. Failures of central plant pipe and valve to piping connection (Gates, 2005)

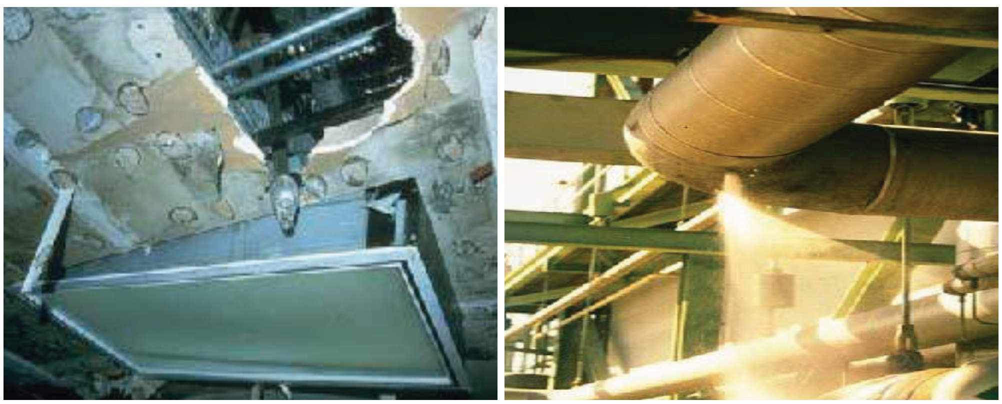

Figure 2. Failure of fire sprinkler piping systems and water damage due to failure of pipe lines (Miranda, 2004)

PROPOSED FRAMEWORK

As observed in many past earthquakes, damages to nonstructural components during an earthquake could initiate a fire hazard due to a leakage of toxic gases and eventually loss of life. This paper proposes a framework for probabilistic assessment of seismically inducted leakages in such distributed systems with localized nonlinearities. The proposed framework builds upon several individual parts which connect together to evaluate the respective fragilities for the first-leakage in piping systems. Figure 3 shows the flowchart for the proposed framework which builds upon utilizing the data from laboratory testing on components such as elbows and/or joints and incorporating this nonlinear data into a large scale analysis of the complete system. Each individual part of this framework is discussed in somewhat greater detail in the following itemized list:

- The starting point of the proposed framework lies in the ability to characterize the nonlinear behavior of piping joints under cyclic loading. This objective can be achieved by conducting laboratory experiments of the joints and the associated components such as elbows and Tee-joints. Typically, such experiments will characterize the nonlinear beavhior in terms of the corresponding force-displacement or moment-rotation curves at the location of component’s joint with the piping. This aspect is illustrated further in detail later in Section 3 this paper.
- The experimental data can then be used to fit the parameters of a material model for the purpose of including it in the finite element based simulation. Such a process is typically iterative in

which the material model parameters are updated and the simulated model is compared to the experimentally obtained model until the reconciliation is acceptable and considered validated.

- Like any other laboratory experiments, the measure data on the nonlinear behavior and the occurrence of first leakage point will exhibit non uniqueness and certain variation is expected depending upon the significance of uncertainties affecting the performance of a particular component and the associated joint. Therefore, it is important to characterize the performance of a joint using a generalized definition of a limit-state. Section 4 of this paper discusses one such generalization of limit-states in Tee-joints.
- The nonlinear model for the component joints can then be incorporated in the full scale finite element model of the piping system in which the distributed piping remains elastic and the nonlinearities are concentrated to the location of joints associated with components such as the elbows and the Tee-joints. It must be noted that validating such large-scale models against experimental data is not only impractical in most cases due to non-availability of large scale experimental facilities but also due to excessively high cost associated with testing even if such an experimental facility is available. Summary of one such large scale experimental study and reconciliation with the corresponding simulation models is presented later in this paper in Section – 5.
- Once the piping system model is developed, it is almost essential to couple it with the corresponding model of the building or supporting structure (primary system). Appropriate nonlinearities in the primary system should be included in such a model. Ju (2012) present one such study in which the piping system model with localized nonlinearities is coupled with concrete frame building models of varying heights. Ju (2012) considered fibre model for the concrete beams and columns to represent the formation plastic hinges. Coupling of building-piping model is essential to appropriately account for various factors which can influence the seismic behavior of piping systems significantly. These include the effects of non-classical damping, mass interaction between the building and the piping, and the phasing between the supports of piping system located at different elevations along the building height. If piping system is extremely light and the mass interaction significantly low (typical real life cases can be the order of 0.001 or less), the effect of mass interaction can be almost negligible. However, it is for such small mass interaction situations that the effect of nonclassical nature of damping becomes significantly more pronounced.
- Once the models needed for simulation are established, the next step lies determining the earthquake input needed in for conducting the fragility assessment. To be consistent with the objective of evaluating overall risk of a seismically induced failure/leakage, it is important that the earthquake motions are selected in accordance with the probabilistic seismic hazard assessment (PSHA) for the specific location of the site. PSHA can be used to evaluate uniform hazard spectra (UHS) for the particular site under consideration. The UHS can be evaluated at appropriate level of non-exceedence annual probability in accordance with the design requirements for the facility.
- Site specific UHS generated using the PSHA is then used to determine a preselected number of earthquake ground motions that are consistent with the statistical distribution desired in the PSHA. These ground motions are actual earthquake records from different sources, varying magnitudes, and at different distances from the source. The selected ground motions together form the suite of ground motions for use in the fragility assessment.
- The individual ground motions in the selected suite are then scaled to same value of the seismic demand parameter. Typically, seismic demand parameters used are either peak ground acceleration (PGA) or spectral acceleration SA. In general, scaling based on SA works well when the response is dominated by a single mode of the structure. While this is true for buildings and bridges, the behavior of piping systems is not so. The piping system is a distributed system in which a response quantity of interest can get significant contributions from multiple higher order

modes. Therefore, scaling based on a single period related SA is not appropriate in the fragility assessment of piping systems.

- A fragility assessment requires appropriate consideration of uncertainties in the model behavior in addition to the uncertainties in the hazard (represented through the use of a suite of earthquake ground motions). The coupled building-piping model framework presented above in this paper facilitates consideration of uncertainties in a relatively straightforward manner. As noted above, the system model is characterized by linear distributed system with localized nonlinearities in both the piping system and the primary system. The behavior of the system is governed by the uncertainties in the nonlinear model considered to represent the joints in a piping system or the plastic hinges in a primary system. A variation in the parameters of the nonlinear models can be used to characterize the uncertainties in the piping joints or the plastic hinges in the primary system.
- In addition to the uncertainties in the demand assessment, it is important to also characterize the uncertainties in the capacity assessment. This can be achieved by considering uncertainties in the model and quantities considered for characterizing the performance limit-state. The degree of uncertainty should be consistent with the variability exhibited in the experimental results for first leakage in the piping components.
- Lastly, a Monte Carlo simulation is performed in which each instance would represent a random selection of a set of uncertain quantities which would include the scaled earthquake input and the nonlinear models for the piping joints as well as that for the plastic hinges in the buildings. A Monte Carlo simulation within the proposed framework is then used to evaluate the probabilities of failure corresponding to each scaling of input ground motions which in turn gives the overall system level fragility curves.

COMPONENT LEVEL BEHAVIOR

A critical aspect of the proposed framework is related to understanding and modelling the nonlinear behavior of the piping components and joints. Laboratory experiments can be conducted to evaluate the beahvior of different component types under cyclic loading. These tests also help in characterizing the capacity in terms of an appropriate parameter. In almost all cases, the first-leakage occurs at the location of a joint between a component such as a Tee-joint or elbow and the straight pipe. The behavior at these joints under cyclic loading is primarily bending and the first-leakage occurs due to exceedance of rotations beyond elastic limit. One example of such laboratory tests on Tee-joints is given in Dow (2010). These tests were conducted on various different types of Tee-joints in a fire sprinkler piping system. The experimental setup used is shown in Figure 4. Both monotonic and cyclic loading tests were performed on pipe diameters of 1 inch, 2 inch, and 4 inch, respectively. Test data illustrated that the rotations corresponding to the first-leakage from a monotonic test were significantly greater than those observed in cyclic tests. Therefore, cyclic load results govern the performance of such components and their joints.

A non-linear finite element model for the Tee-joint system can be formulated and validated with the experimental results. The Tee-joint connection can be modelled by two non-linear rotational springs on either side of the Tee-joint. The spring can be characterized by the moment rotation curves obtained from the experimental tests. Straight pipe segments connected to the Tee-joint can be modelled with frame elements, and they can be connected to either side of the flanges. At far ends, the straight pipes are considered to be supported by a hinge on one end and a support that acts like a roller at the other as shown in Figure 5. The purpose is to ensure a pure bending behavior at the location of connection.

The test data can be used to define rotational spring properties for each T-joint connection. The rotational springs for hysteretic behavior can be characterized by different types of material models available in commercial finite element analysis packages. For the 1 inch diameter pipe discussed above, modelling was performed using the available material models in open source finite element package OpenSees (Mazzoni *et al*., 2006). The Tee-joint section (1-inch schedule 40) can be satisfactorily modelled using non-linear rotational springs based on the comparison of analytical results with test data as shown in Figure 6.

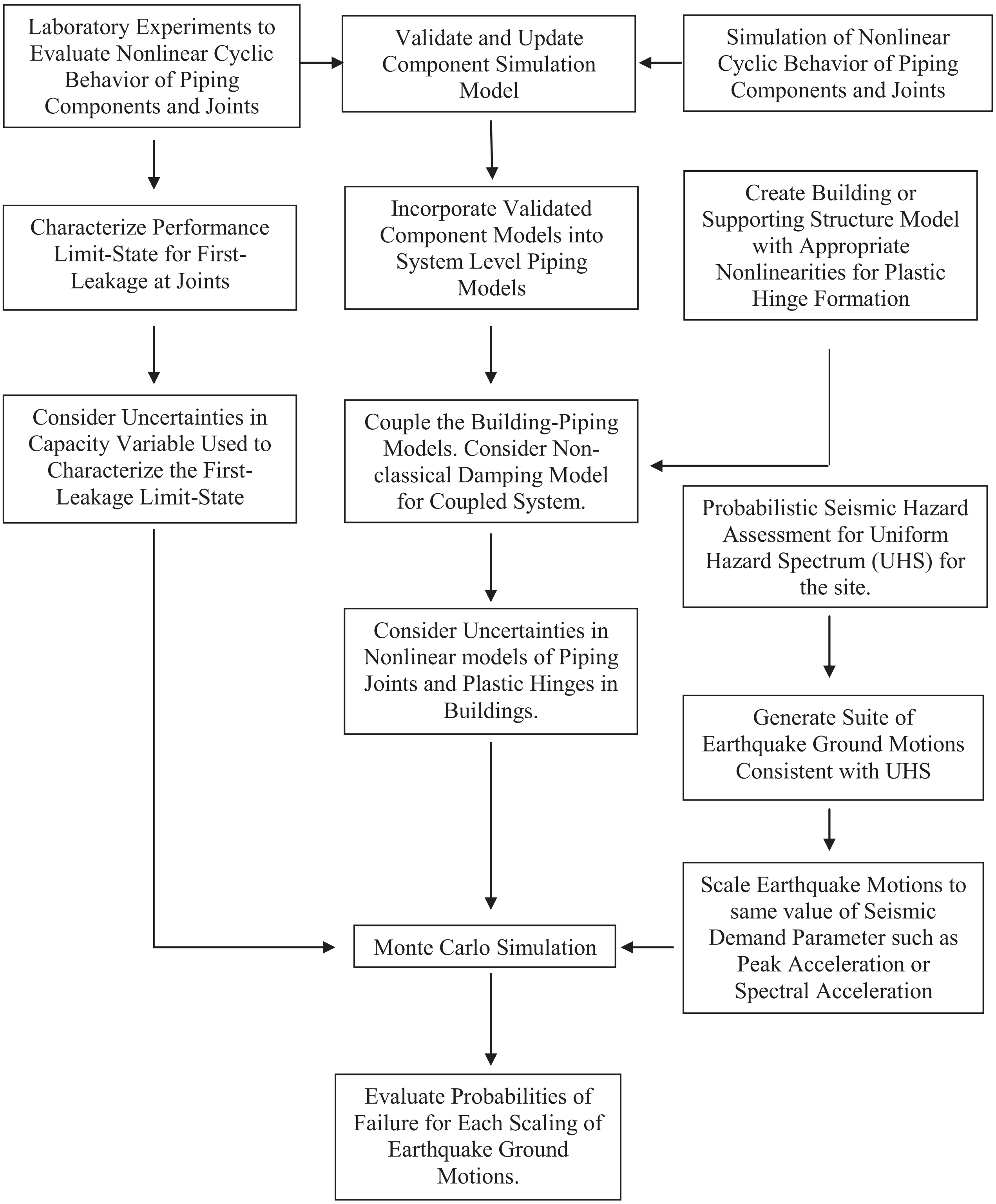

Figure 3. Flowchart for incorporating component level nonlinear data into large scale analysis

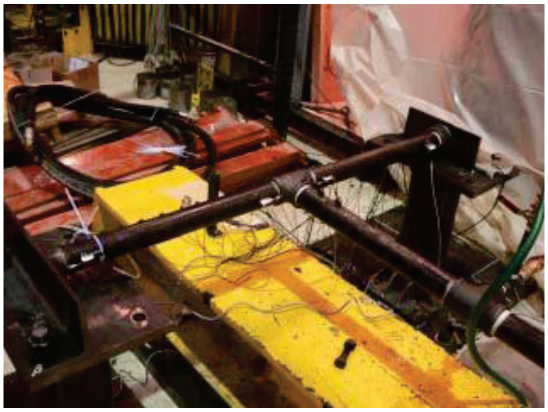

Figure 4. Experimental setup for Tee-joint tests (Tian, 2011)

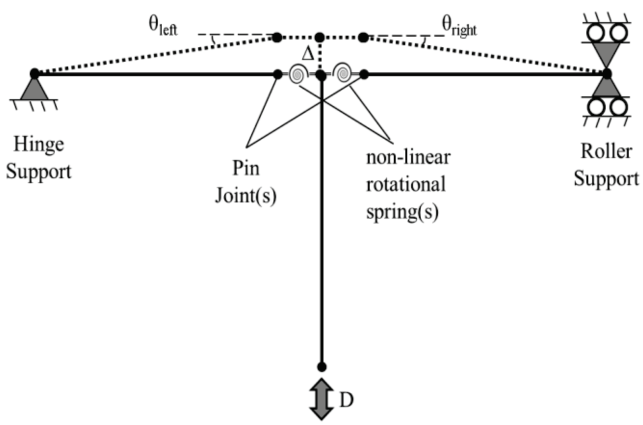

Figure 5. Component level analytical model

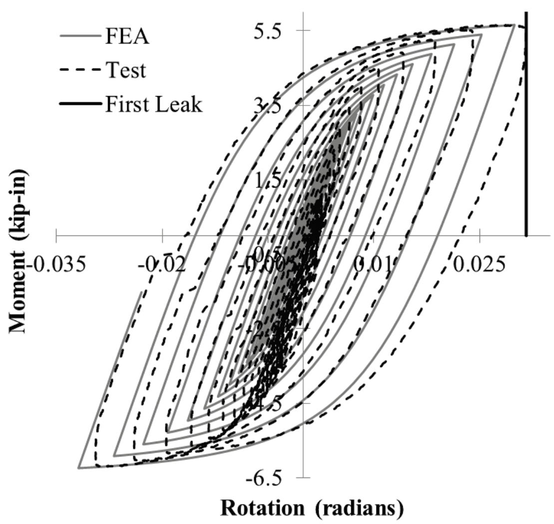

Figure 6. Experimental versus analytical results under cyclic loading condition, 1 inch diameter

CHARACTERIZATION OF LIMIT STATE FOR FIRST-LEAKAGE

In this section, we present a generalized characterization of the performance limit-state based on the observations made from the experimental results. The limit-state is representative of a formal criterion corresponding to the observed damage which in this case would be representative of first-leakage at piping component joint. Rotations at Tee-joint connections as observed from the cyclic tests can be a good engineering demand parameter to characterize the limit-state corresponding to the first-leakage instance. To characterize the capacity, the absolute values are likely to change significantly due to changes in material and/or geometrical properties of a piping component. Therefore, it is necessary to characterize the performance of the Tee-joint using a limit-state that can represent the behavior in a generalized form. To do so, we compare the experimental results presented above with the criterion that forms the basis of design guidelines specified in the ASME Boiler & Pressure Vessel Code (ASME 2007) which specifies the limit load criterion based on preventing the gross plastic deformation and large displacement of ductile materials. Gerdeen (1979) gives detailed guidance and explanations of this criterion. He defined the collapse limit by a comparison of elastic and plastic work contributions. In his approach, when the load reaches the collapse load, gross deformation occurs and the plastic work becomes significant compared to the elastic work. Using the same methodology, the criterion can be defined as limit rotation corresponding to the collapse moment in terms of performance characterization. Figure 7 shows the moment corresponding to the intersection of the moment-rotation curve and a collapse limit line such that $\tan\phi = 2\tan\theta$ relative to the ordinate axis (Ju *et al.*, 2011). Angle θ is defined as the initial slope of the moment-rotation curve with respect to the moment-axis. Since the angle θ is typically small, we can write $\phi = 2\theta$.

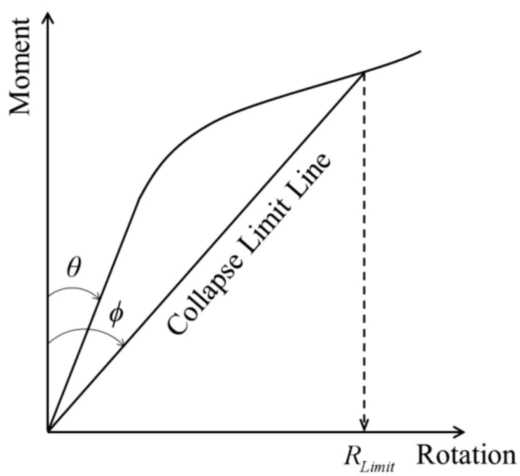

Figure 7. Definition of rotation limit state

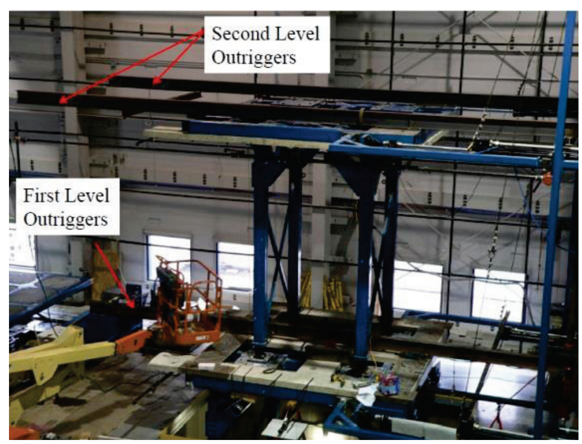

Figure 8. Full scale laboratory test setup (Tian, 2011)

SYSTEM LEVEL PIPING MODEL

In this section, we discuss a validation exercise to verify the proposed framework wherein the component level nonlinear models are incorporated into a system-level piping model. To do so, a 2-story piping system is considered. This piping system is shown in Figure 8 and a large-scale laboratory test was performed on it as explained in Tian *et al.* (2011). The two-story piping model consists of box-type ceilings, piping supports, and 1 inch, 2 inch, and 4 inch black iron pipes with two different types of T-joint connections. The main piping line and riser consists of 4 inch pipes, and the branches consist of pipes with 1 inch or 2 inch diameters. This supporting system consists of transverse sway braces, wire restraints, and vertical hangers. The configuration of sprinkler heads and ceiling boxes connected to the sprinkler heads is shown in Figure 9 (Ryu, 2013). A nonlinear time history analysis of piping system was performed by using a piping system model that incorporates localized nonlinearities through the use of experimentally validated nonlinear models of component level joints. The component level nonlinear models were considered for all the Tee-joint connections on the 4 inch main piping as well as on the 1 inch and 2 inch branch lines. The stiffness of the ceiling system is an important factor in detection of leakage locations in the piping system. The location of Tee-joint failure is dependent on the boundary condition of the ceiling system. To consider the interactions between the piping branch and ceiling system, we modelled the ceiling tiles as an elastic spring element. Four springs were attached between the sprinkler head and the four corners of the box frame. This spring boundary condition in the ceiling system provides a partial constraint to the deformation of piping branches. The analysis results show the same failure locations and chronological order as those observed in experimental study and are shown in Figure 10.

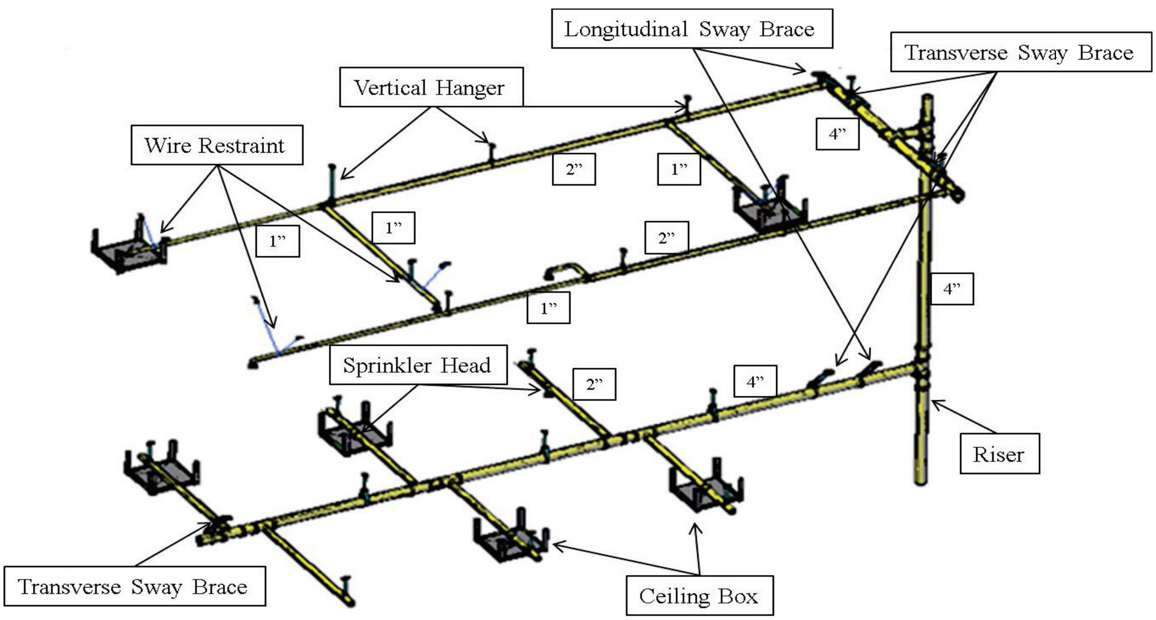

Figure 9. 2-Story full scale piping System FE model

CONCLUSIONS

A framework is proposed for evaluating seismically induced fire hazard due to leakage of flammable material from piping systems. Examples of such situations include leakage of liquid metal coolant in fast reactors or leakage of flammable gas such as hydrogen. Failures observed in the laboratory tests are used to propose a generalized characterization of the limit-state and the corresponding performance criterion needed in the evaluation of the piping fragilities. For a system level validation, the leakage location and progression of multiple failure locations in a piping system as evaluated from a nonlinear time history analysis are same as those observed in the system-level test. It must be noted that the failure locations and the progression of failure are sensitive to the definition of the limit-state. For brevity, the work on selection of ground motions consistent with PSHA and consideration of uncertainty in material models for evaluation of fragilities is not presented in this paper.

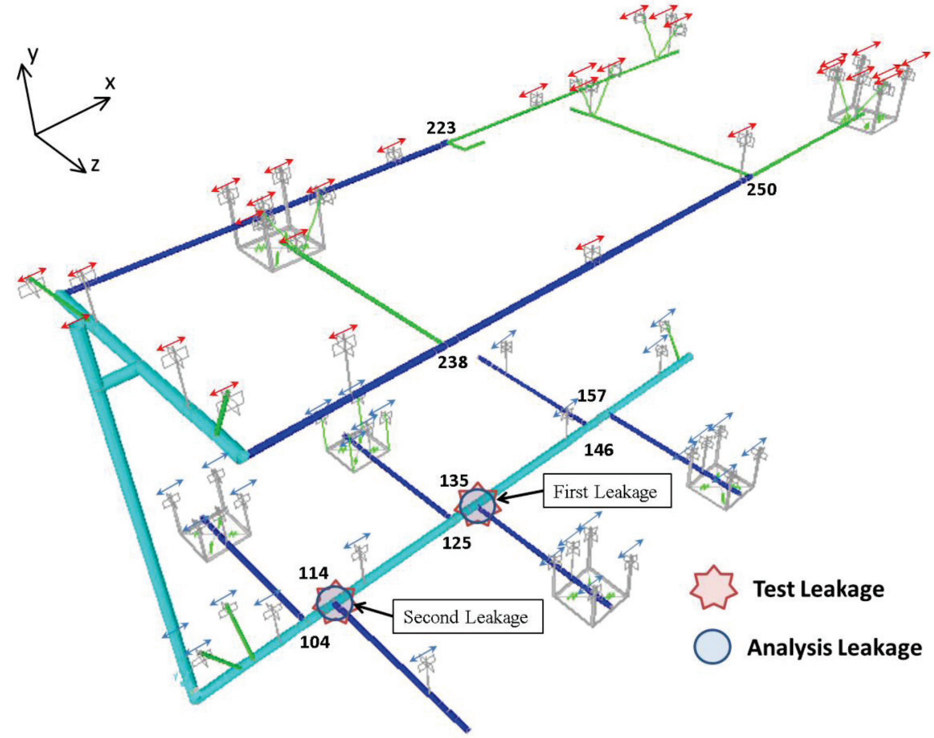

Figure 10. Test Results versus Analysis Results

ACKNOWLEDGEMENTS

This research was partially supported by the NSF's NEES GC Project on nonstructural systems and the Center for Nuclear Energy Facilities and Structures at North Carolina State University. Resource for the Center come from sponsoring industrial organizations, National Science Foundation, the Civil Engineering Department, and College of Engineering in the University. Some of the work in this paper was conducted after the completion of NSF project. This additional work and the resources for presenting this paper provided by the National Research Foundation of Korea [NRF] grant funded by the Korea Government [MEST] [No. 2012-0008762].

REFERENCES

American Society of Mechanical Engineer. (2007). Rules for construction of nuclear facility components, ASME Boiler & Pressure Vessel Code, Section III.

Ayres, J. M. and Phillips, R. J. (1998). "Water Damage in Hospitals Resulting from the Northridge Earthquake," ASHRAE Trans., Vol. 104, Part 1, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.

Dow, J. (2010). "Testing and Analysis of Iron and Plastic Tee-joint in Sprinkler Systems," NEESR-GC: "Simulation of the Seismic Performance of Nonstructural Systems," http://nees.org/site/oldnees/filedir_2/REU 2009_Dow_Paper.pdf.

Gerdeen J. C. (1979). "A critical evaluation of plastic behavior data and a united definition of plastic loads for pressure vessel components," WRC Bull 1979; 254.

Ju, B., Tadinada, S. K, and Gupta, A. (2011). "Fragility Analysis of Threaded Tee-joint Connections in Hospital Piping Systems," ASME 2011 Pressure Vessels and Piping Conference, Baltimore, Maryland, PVP2011-57958

Ju, B. (2012). “Seismic Fragility of Piping System,” Ph.D. dissertation, North Carolina State University, Raleigh, NC.

Mazzoni, S., Mckenna, F., Scott, M. H., Fenves, G. L., and et al. (2006). “OpenSees Command Language Manual,” Open System for Earthquake Engineering Simulation (OpenSees), http://opensees.berkeley.edu/

Miranda, E., Taghavi, S., and Aslani, H. (2003). ”Performance Based Earthquake Engineering for Nonstructural Components,” PEER Annual Meeting.

Tian, Y. (2011). “Progress Report of Sprinkler Piping Subsystems Dynamic Test on NCS”, Progress Report, NEESR-GC: Simulation of the Seismic Performance of Nonstructural Systems, April, 2011.

Ryu, Y. (2013). “Fragility of Piping Systems and Reliability of Piping Components,” Ph.D. dissertation, North Carolina State University, Raleigh, NC.

Wasilewski, R. J. (1998). “Seismic Restraints for piping System,” ASHRAE Transactions Part 1B, SF-98-14-1, 1273-1285.