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Seismic fragility of threaded Tee-joint connections in piping systems

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ABSTRACT

This paper proposes a methodology to evaluate seismic fragility of threaded Tee-joint connections found in typical hospital piping systems. Existing experimental data on threaded Tee-joints of various sizes subjected to monotonic and cyclic loading indicates that the "First Leak" damage state is observed predominantly due to excessive flexural deformations at the Tee-joint section. The results of the monotonic and cyclic loading tests help us evaluate the characteristics for a given pipe size and material. A non-linear finite element model for the Tee-joint system is formulated and validated with the experimental results. It is shown that the Tee-joint section can be satisfactorily modeled using non-linear rotational springs. The system-level fragility of the complete piping system corresponding to the "First Leak" damage state is determined from multiple time-history analyses using a Monte-Carlo simulation accounting for uncertainties in demand.

1. Introduction

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 the non-structural systems in hospitals comprise a significant proportion of the total economic loss incurred 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 the 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, injuries or loss of life in many seismic events.

In recent years, engineers have recognized the need to address the problem in the design stages such that the nonstructural components remain operational or functional after an earthquake. Antaki and Guzy [5] conducted static and dynamic tests of the fire protection piping systems designed in accordance with National Fire Protection Association guidelines [6]. The objective of tests was to identify the stiffness, failure modes, and limit states for leakage of threaded pipe joints and grooved coupling systems that are commonly used in the piping systems. ATC-58 [7] has highlighted the need for a performance-based design based on statistical approaches in nonstructural systems. Consequently, probabilistic seismic fragility studies for these systems can be vital in mitigating risk and achieving reliable designs. A fragility curve describes the relationship between a ground motion intensity parameter like Peak Ground Acceleration (PGA) and the corresponding probability of failure as characterized by a specified limit-state or exceedence criteria. The concept of fragility has been used extensively for over more than a decade in the seismic probabilistic risk assessment of nuclear power plant structural and nonstructural systems. In the nuclear power plant industry, the most commonly used approach to evaluate structural fragilities is the lognormal model based on design factors of safety which assumes a lognormal distribution for the acceleration capacity of the structure [8,9]. The "acceleration capacity" of a structure is defined by the level of PGA that the structure can safely withstand without any damage and is equal to the Design Basis Earthquake (DBE) level of PGA multiplied by a Capacity Factor (F_c). The median and the logarithmic standard deviations of F_c are based on design code equations, past studies, experience data and to quite an extent in expert judgment.

The widely used lognormal model of structural fragility cannot be directly extended to the piping and secondary systems due to the lack of sufficient existing fragility data. Furthermore, characterization of the structural performance in terms of an "acceleration capacity" is quite simplistic and in many cases far from the "true

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performance" especially as the higher mode effects and mass interaction with the supporting structure tends to be significant in piping systems. Many researchers have evaluated seismic fragilities using experimental data either independently or in conjunction with experimentally validated finite element models [10]. Consideration of experimental data is essential in a fragility assessment primarily for the purpose of characterizing the structural performance in terms of an appropriate "limit-state". Almost all the studies have focused on evaluating the seismic fragilities of structural components or sub-systems. Limitations in conducting large-scale experiments are a key obstacle in the evaluation of system-level fragilities. This is particularly true in the case of piping-systems.

In this paper, we present the results of a detailed study that focuses on:

- Characterizing the performance "limit-state" of threaded Tee-joints in a fire sprinkler piping system using experimental results from monotonic and cyclic testing of Tee-joint components.
- Developing an equivalent non-linear finite element model of the Tee-joint component such that the results reconcile with the experimentally observed behavior.
- Incorporating the non-linear Tee-joint model in an actual hospital piping system model for the purpose of conducting a system level analysis and evaluate system level fragilities.
- Evaluating system-level fragilities for failure at different locations of the same Tee-joint component within the piping system.

Often, it is suggested that the excessive computational effort needed in a non-linear system-level analysis can be reduced by using linear analysis of the piping system to evaluate earthquake input at the location of the Tee-joint [11]. Then, conduct a separate (decoupled) non-linear analysis of the Tee-joint to determine the fragility. In this study, we compare the fragility evaluated from a system-level analysis with that evaluated from the corresponding decoupled analysis of the non-linear Tee-joint.

2. Experimental tests of threaded Tee-joint

Many assemblies and sub-assemblies in piping systems like connections and linkages often exhibit complex nonlinear behavior that is quite difficult to model or predict using simple finite element models. An accurate FE model for a connection like a threaded piping joint often requires dense meshing using special contact elements thus making the problem computationally ineffective for fragility estimations. In such cases, simple monotonic and cyclic tests can provide valuable insights into the behavior of these connections and their typical damage states. Data from such tests can also help us formulate simpler but experimentally validated nonlinear finite element models that describe the seismic response of the connections with sufficient accuracy.

Laboratory tests were conducted by University at Buffalo, State University of New York (UB) on various kinds of Tee-joint component of sprinkler piping systems [12]. Both, monotonic as well as cyclic loading were considered. Two types of piping material, Black Iron and CPVC, were considered. A total of three different diameter pipe components, 50 mm (2 inch), 25 mm (1 inch) and 20 mm (¾ inch), were included. In this paper, a detailed discussion is provided on the experimental setup and results for only the 50 mm (2 inch) diameter Black Iron threaded piping Tee-joint because the particular piping system considered in this study from an actual hospital consists of branch lines that are 50 mm in diameter. This piping system does not consist of any 25 mm and 20 mm diameter pipes and therefore we did not consider these components further in the fragility assessment of this actual piping system [12]. The 50 mm diameter pipe used in this study is the standard Black Iron schedule 40 50 mm diameter pipe and the corresponding Tee-joint that are typically used in fire-sprinkler piping systems. The outer diameter of such a schedule 40 50 mm diameter pipe is 60.325 mm and the inner diameter is 52.501 mm with a wall thickness of 3.912 mm. Therefore, the diameter to thickness ratio for this pipe is fairly large thereby rendering it as a thin walled pipe.

Fig. 1 shows the actual test set-up for determining the force-displacement and moment–rotation relationships of the threaded Tee-joint connection under monotonic and cyclic loading conditions. As seen in this figure, the loading was applied as an in-plane force loading at the bottom of the Tee-joint. The test-setup was built in such a way that the Tee-joint can be displaced in both forward and reverse directions along the "bottom of the T", an axis perpendicular to the center of the Tee-joint, as shown in Fig. 1. Also, the ends of the pipes connected to the flange of the Tee-joint were simply supported. The failure was characterized in terms of "first-leakage" and if observed in terms of "pipe-fracture." To detect the "first-leakage" point, the piping component arrangement was connected to a water hose that carried water at standard city pressure which is 276 kPa (40 psi) measured pressure. Also, ten potentiometers were used to record the data. One monotonic test and three cyclic tests were conducted for each type of piping component [12]. Fig. 2 gives the force-displacement curve as measured in the case of monotonic loading test. The "first-leakage" point is depicted by the vertical line at 38.58 mm displacement. As seen in this figure, a leakage caused a vertical drop in the force-displacement curve at this value of displacement. The moment–rotation curves as measured at the two flanges, right and left ends, are shown in Fig. 3 and Fig. 4. As in the case of force-displacement curve, the moment–rotation curve at the right-end of the Tee-joint flange also exhibits a vertical drop at the first-leakage, corresponding to a rotation of 0.0814 radians. However, the moment–rotation curve at the left-end of the Tee-joint flange does not exhibit a similar vertical drop. The rotation corresponding to the first-leakage point is identified in this curve by a vertical line. This difference between the left-end and the right-end behavior exists because the first-leakage occurred at the right-end as shown in Fig. 5. The reasons for the first-leakage are identified as bending of pipe ends and the corresponding slippage and rupture of pipe threads. Complex phenomena such as these vary with different specimen and with the location within a given specimen due to difference in manufacturing as well as variation in localized degradation. The particular approach followed in this study and

Fig. 1. Test setup for experiments on threaded Tee-joints conducted at UB.