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A NEW APPROACH TO CHARACTERIZING THE PEFORMANCE FUNCTION FOR T-JOINTS IN PIPING SYSTEMS

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ABSTRACT

Fragility assessment requires characterization of a component or system's performance through a performance function/limit-state equation. The exceedance of limit-state is representative of failure or damage state. For the purposes of evaluating piping fragility, characterizing the behavior of T-joints through an appropriate performance function is critical, as failures in piping are generally localized at the location of T-joints and elbows. Past studies have utilized a monotonic rotation based performance function. However, the existing criteria does not account for the cyclic behavior of T-joint. As observed during prior experimental studies, the T-joint behavior under cyclic loading is different from that under monotonic loading, and therefore it is important to include the effects of cyclic behavior while characterizing a performance function. Moreover, the monotonic rotation based performance function could not replicate all the leakage locations observed during experimental studies on a full-scale piping. Therefore, it is important to develop a new limit-state state for accurate piping fragility assessment. This paper presents a new approach for the development of such a limit state which considers the cyclic behavior of a T-joint.

INTRODUCTION

The safety of non-structural components like equipment and piping is vital for the operation and emergency management of critical facilities like hospitals and nuclear power plants. Moreover, the economic losses incurred due to a failure in these systems can be significant (Horne & Burton, 2003). The 1994 Northridge earthquake caused the Olive View Hospital to be shut down due to internal flooding caused by pipe break at a single location (Reitherman & Sabol, 1995). In recent years, researchers have recognized the importance of assessing and improving the performance of piping systems which form an integral part of these facilities (Antaki and Guzy, 1998; Tian et al. 2014; Ju et al, 2015). Applied Technology Council-58 (Bachman et al. 2003) has highlighted the need for a performance-based design of nonstructural piping systems. Seismic fragility studies for piping systems can provide meaningful insights for mitigating the risks and achieving reliable designs.

The concept of fragility assessment requires characterization of a component or system's performance through a performance function/limit-state equation. The limit-state is representative of a formal criterion corresponding to the observed failure/damage. Studies have shown that the failures in the piping systems are localized, i.e. at the location of the threaded T-joint connections and elbows (Ryu et al. 2011). Therefore, understanding the behavior of piping systems at such locations and characterizing their performance through an appropriate limit-state, is essential. The outcome of these studies, represented by fragility curves, is highly dependent on the definition of an appropriate performance function.

In this paper, the state of the art approach to characterize failure in T-joints and its limitations discussed and a new approach presented for the development of a new performance function that can be a significant improvement over the currently used limit-states.

BACKGROUND

In order to characterize failure in threaded T-joints, Ju et al. (2015) used a modified version of the ASME's (ASME, 2013) "Twice the elastic slope" criteria. ASME Boiler Pressure Vessel and Piping Code (ASME, 2013) characterizes the performance of a piping component such as a pipe-bend (elbow) or a T-joint in terms of a "Plastic Collapse" moment. Ju et al. (2015) analyzed the experimental test data given in Tian et al. (2014) to observe that the rotation corresponding to the ASME's definition of collapse moment gives a good prediction of the occurrence of the "first leak" at the T-joint. Although this a good approximation representing the first leakage in a T-joint, defining the performance function of the T-joint in terms of only the rotation is too simplistic as it doesn't take into account the cyclic nature of loading. Moreover, this limit state could not replicate all the leakage locations observed during large-scale experimental studies on a full-scale piping (Ryu et al. 2016).

Experimental data from existing studies (Tian et al. 2014) indicates that the T-joints leak after 11 to 20 loading cycles. The number of cycles vary with the specimen type and the size of T-joint. This is a characteristic of large-strain low-cycle conditions, typical of earthquake induced failures. Cyclic loading due to earthquakes involve very few cycles before failure. In the next section, we use a new approach to analyze the existing experimental test data in order to develop the new limit state.

INVESTIGATION OF EXPERIMENTAL DATA: ACCUMULATION OF PLASTIC ROTATIONS

Component level experimental data on Moment versus Rotation is examined to identify the governing mechanism causing leakage at the location of threaded T-joint. Test data from both monotonic and cyclic tests is analyzed. As shown in Figure 1, the total rotation at first leak during the monotonic test, denoted by $\theta_{leak,}$, consists of elastic (θ_e) and plastic (θ_p) parts. The value of the plastic rotation at first leak during the monotonic test of 1 inch T-joint is 0.067 radians. As the T-joint cycles back and forth during the loading sequence, it accumulates plastic rotations in each elastoplastic cycle. Therefore, it is essential to consider the number of cycles up to failure/leakage, while characterizing the performance function of T-joints. Next, the experimental data of the cyclic test is investigated. It is observed that the leakage during the cyclic test occurs during the loading cycle in which the total accumulated plastic rotation accumulated over all the cycles exceeds the plastic rotation during the monotonic test at leakage. Table 1 shows the progressive accumulation of plastic rotations during each loading cycle after yielding. The plastic rotation of the monotonic test is exceeded during the ninth loading cycle of the cyclic test. It is during this loading cycle in which the first leak was observed during the cyclic test. Therefore, the accumulation of plastic rotations is identified as the primary reason governing leakage at the threaded T-joints.

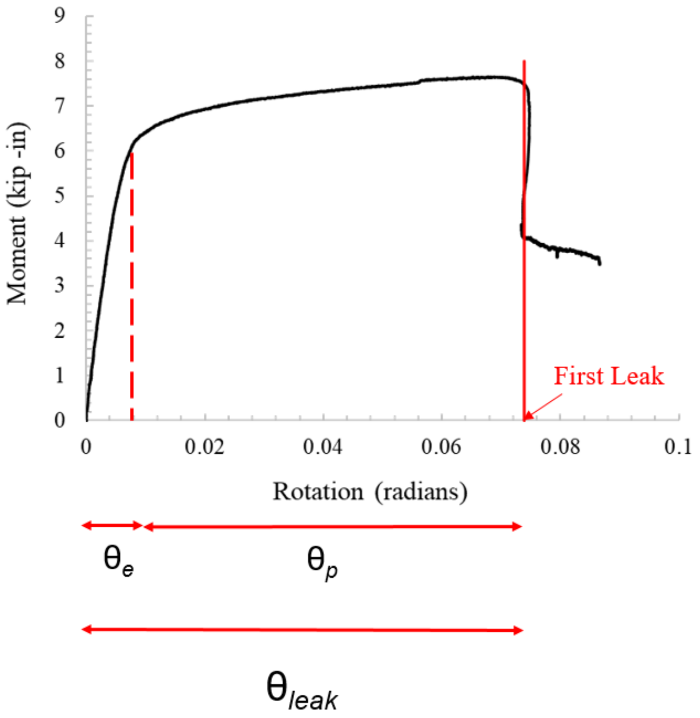

Figure 1. Elastic and Plastic Rotation during monotonic test

Table 1. Accumulation of Plastic Rotations during Cyclic Test

Loading Cycle	$\Sigma\theta_p^{cyclic}$
5	0.0215
6	0.0334
7	0.0483
8	0.0655
9	0.0750

Based on the above observation, any new limit state should account for the fact that the T-joint will leak during the loading cycle in which it has accumulated a plastic rotation value exceeding the plastic rotation observed during the monotonic test.

After the identification of the governing mechanism causing leakage at the T-joint, a literature survey is conducted to identify a suitable form of a limit state capable of handling such large strain and low cycle conditions. In order to characterize performance functions for such scenarios, researchers (Usami et al. 2011, Tateishi et al. 2006, and Zhou et al. 2010) have utilized experimental results to obtain relationships between the range of a quantity of structural response (drifts, strains etc.) and the number of cycles up to failure/prescribed performance level. The range of rotation at the T-joint (Figure 2) and the number of cycles to failure are identified as two suitable parameters to develop the new limit state.

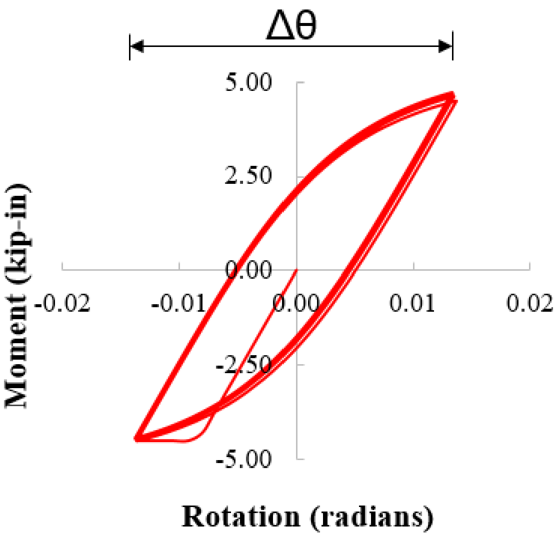

Figure 2. Range of rotation, Δθ, at T-joint

PROPOSED APPROACH TO DEVELOP THE NEW LIMIT STATE

Experimentally validated component level simulation models of the T-joints can be utilized to conduct a numerical study which in turn can be used to develop a new limit state. The choice of a suitable loading protocol is vital for the purpose of this numerical study.

The choice of a loading protocol for seismic testing of structural and non-structural components is governed by regulations of FEMA 461 standard (FEMA, 2007). The regulations specify progressively increasing amplitude of the loading, with a prescribed number of loading cycles below, at, and above the yield point of the material under study. The intent behind this loading protocol is to trigger and observe all possible damage states during a test and do so efficiently without having to conduct a large of experiments. Such a limitation does not exist in a numerical study. Therefore, we choose a loading protocol with a constant amplitude as shown in Figure 3. The loading amplitude of the initial test is chosen so that it induces yielding at the location of threaded T-joint, since we are interesting in quantifying the number of cycles after yielding, to reach the first leak instance. The constant amplitude of the displacement controlled loading can then be progressively increased during different simulations in the numerical study to induce failure at a range of different cycles and rotations.

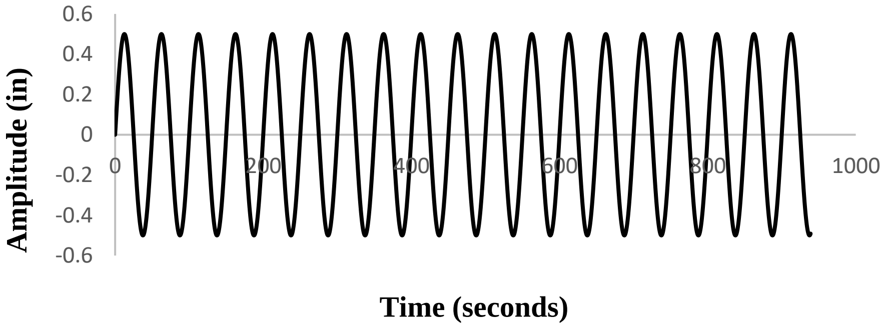

Figure 3. Loading Protocol for Numerical Study

An extensive numerical study can be conducted by utilizing the simulation model of the T-joint (Ju et al. 2015) and the loading protocol described above. The range of rotation at the T-joint ($\Delta\theta$) and the number of cycles till first leak (N_f) can then be recorded during each simulation (corresponding to each amplitude level of loading) of the numerical study. Next, the relationship between these quantities can be investigated to develop the new limit state. This framework is summarized in Figure 4.

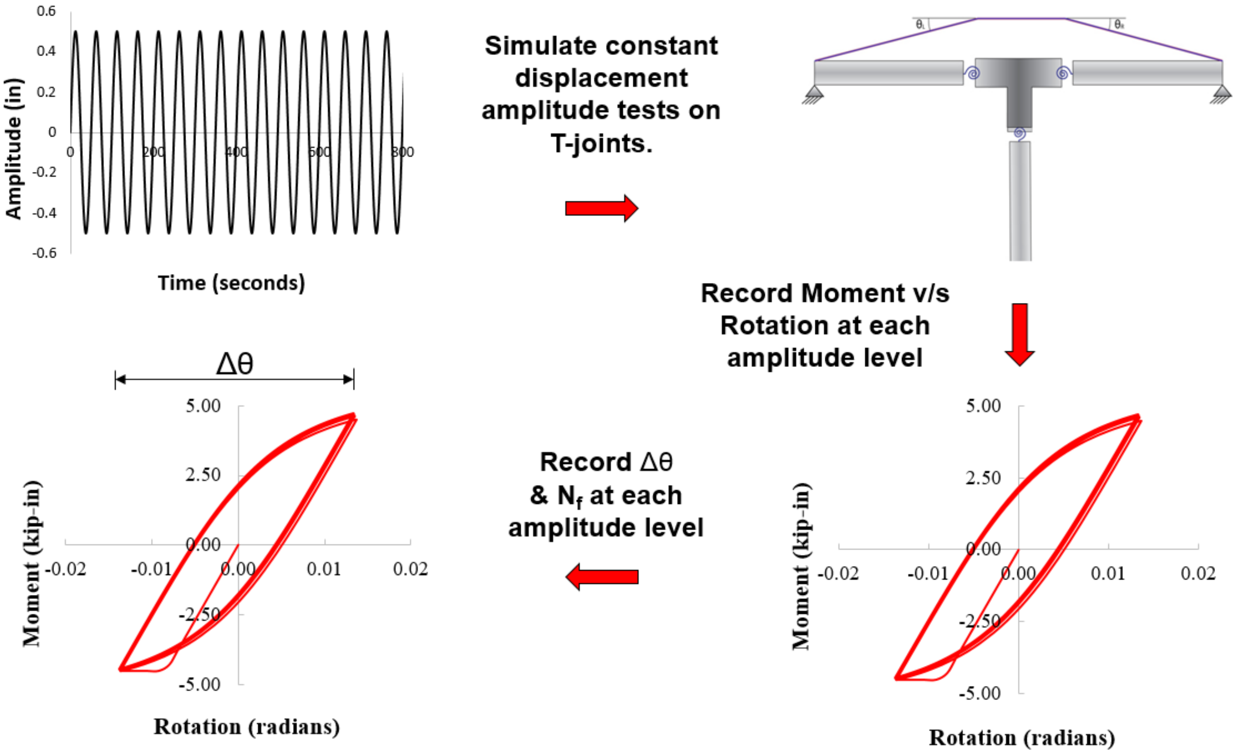

Figure 4. Framework for developing the new limit state

As per the previous studies on such large strain-low cycle conditions (Usami et al. 2011, Tateishi et al. 2006, and Zhou et al. 2010), it is expected that the limit state equation will follow a negative exponential form as expressed in Equation 1:

$$\Delta\theta = a\left(N_f\right)^{-b} \tag{1}$$

Where $\Delta\theta$ is the range of rotation at the T-joint in radians, N_f is the allowable number of cycles after yielding, to reach the first leak instance, a & b are positive constants. We plan to test the suitability of this limit state to predict leakage locations on a full scale piping utilizing the experimental test data on a two-story piping as reported in Ryu et al. (2016). This limit-state equation is expected to overcome the fundamental drawback of the current rotation based limit state, as it takes into account the effect of cyclic loading. A range of rotation at the T-joint can be recorded relatively easily for a particular loading/earthquake scenario.

CONCLUSIONS

In recent years, there has been an increased emphasis on understanding the behavior of piping components in the context of evaluating piping fragilities. Characterization of failure state through an appropriate limit-state is a key step towards generating accurate piping fragilities. Currently, a rotation based limit state is used to characterize failure at the threaded T-joints in piping systems. This limit state has a fundamental drawback that it is based on monotonic loading and it does not consider the cyclic behavior of T-joint. This paper presents a new approach for the development of a limit state which overcomes the fundamental drawbacks of the limit state used in the existing studies.

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