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The nonlinear behavior of threaded piping connections: Application using a modified Ramberg-Osgood model

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ABSTRACT

Damage to nonstructural components such as piping systems and mechanical and electrical equipment can result in major economic loss, injuries, and loss of life in critical facilities like offshore structures, nuclear power plants, and hospitals. Failures in piping systems especially due to water leakage can lead to shut-down of a facility, and connections in the pipelines are particularly important since failures often occur at these locations. This paper presents a technique for modeling threaded connections as rotational springs, either linear or nonlinear. Laboratory tests were conducted on 1 and 2-in. diameter specimens of black iron Schedule 40 pipe in a cantilever configuration where the support is a threaded piping flange. The specimens were loaded monotonically into the inelastic region. The piping system was modeled as a straight pipe using Euler-Bernoulli beam theory with a support modeled as the proposed rotational spring. The correlation between test results and analytical predictions was quite good. A modified Ramberg-Osgood equation (1943) was used to model the nonlinear moment-rotational behavior of the support spring, and the criterion specified by ASME Boiler & Pressure Vessel Code (ASME, 2007) was used to determine the rotational limit for the threaded piping connection.

1. Introduction

A wide variety of joint connections for piping systems has been used in industrial applications, and research on such piping systems has been both experimental and analytical. Clinedinst (1965) studied the strength of threaded joints for steel pipes with tensile tests and evaluated the strength corresponding to joint fracture and joint jump-out. Fabian (1981) focused on the nonlinear behavior of a piping type element subjected to both bending and pressure loads with respect to the influence of geometrical imperfections. Four-point bending tests have been conducted using three types of joints - grooved mechanical couplings, brazed copper, and threaded joints (Antaki, 2004). His experimental results showed that threaded joints were the most reliable type of connection in terms of repeatability and predictive ability. Kershenbaum et al. (2000) investigated the dynamic response of pipelines under seismic excitation. The characterization of system failure in terms of first leakage at the threaded T-joint connection has been established from observed monotonic and cyclic test data (Ju et al., 2011). They defined the maximum rotation to prevent first leakage in a piping component by the moment corresponding to the intersection of the moment-rotation curve and a collapse limit line with twice the slope of the elastic slope from the monotonic test data. The twice-elastic-slope (TES) method was originally proposed to determine a 'limit load' from a load–displacement plot based on results of experimental tests (Rodabaugh and Moore, 1978). They also indicated that the limit load could be used to define the limit moment. Chattopadhyay et al. (2004) and Kim and Oh (2006) proposed a closed form equation for the limit moment solution based on their FEA results in which a collapse moment load was defined by the TES method in simulations. This TES method forms the basis of design guidelines specified in the ASME Boiler & Pressure Vessel Code (ASME, 2007).

Understanding the monotonic behavior of piping connections can be fundamental in defining the performance criterion in critical facilities since they often use threaded connections. The case study described in this paper involved the quasi-static monotonic response of a cantilever pipe threaded into a flanged support. Loads, strains, and displacements were recorded during the test. The mathematical model of this specimen consisted of a beam element for the pipe and a rotational spring for the pipe to flange interface representing the exposed threaded section. The test data were used to verify the modulus of elasticity E and to calculate the parameters associated with the spring model, which was represented by a Ramberg-Osgood equation (1943). This model is widely used to characterize the non-linear relationship between stress and strain for numerical simulations

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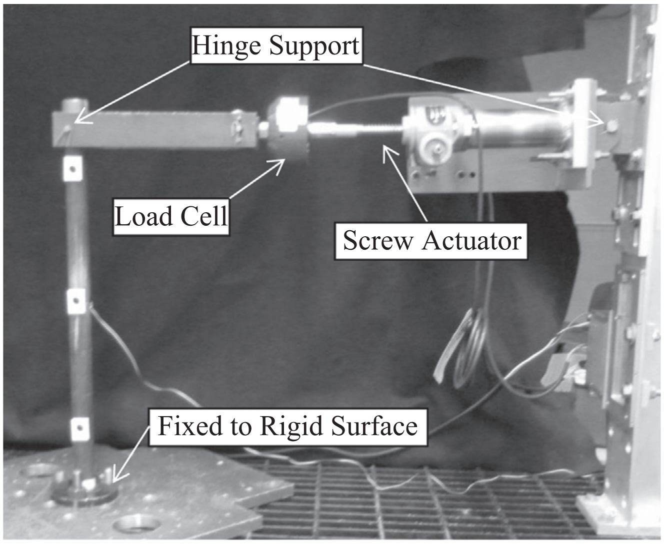

Fig. 1. Monotonic test of a pipe to threaded flange connection.

(Ruocco, 2015) and to validate analytical results compared to the experimental results for steel materials (Gardner et al., 2016). The damage state in this study was defined by the TES method.

2. Laboratory test

Laboratory tests were performed on 1 and 2-in. diameter Schedule 40 black iron pipes and forged steel threaded flanges (Ryu et al., 2011). The cantilever pipe was screwed into the threaded flange, and the flange was then fixed to a rigid surface as shown in Fig. 1. The specimens were fabricated in-house to achieve the desired thread engagement length. A maximum torque of approximately 71*kN-mm* and 112*kN-mm* were measured for 1 and 2-in. pipes, respectively, when the pipes were threaded into the flange. The test schedule consisted of multiple threaded pipe specimens that were loaded to levels appropriate for examining the elastic and inelastic behaviors.

2.1. Experimental test on 1-in. Pipe

Loads were measured using an Interface load cell and applied by a screw actuator at a distance of Lp=565.9 *mm* from the flange as shown in Fig. 2. A strain gage was attached at Ls=304.8 *mm*, and displacements were measured using a digital camera with optical measurement software with targets at distances of L_1=508.0 *mm*, L_2=304.8 *mm*, and L_3=101.6 *mm*. All lengths were measured from the flange-pipe interface. The threaded region of the pipe was between 7 and 7.7 full threads, and the pipe was screwed into the flange 4 full turns in accordance with the specifications for American national standard taper threads, NPT, leaving an exposed threaded region of 3–3.7 full threads. Additionally, six measurements of outside diameter (OD) and thickness (t) measurements were taken at locations around the pipe circumference as shown in Fig. 3 using a micrometer, and the calculated mean values from Table 1 were used to determine the moment of inertia I. Following a series of elastic tests, the specimen was loaded into the inelastic region. Load control was used in the elastic range and, in the inelastic region, a displacement control loading strategy was followed. Measured forces, strains, and displacements are plotted in Figs. 4 and 5. In Fig. 4 we observed that the force-stain behavior was essentially linear for the entire test whereas in Fig. 5 we observed that the force-displacement behavior was linear in the early part of the loading but then became noticeably nonlinear. In a later section of this paper we argue that the yielding is restricted to the very small region right at the pipe-flange interface.

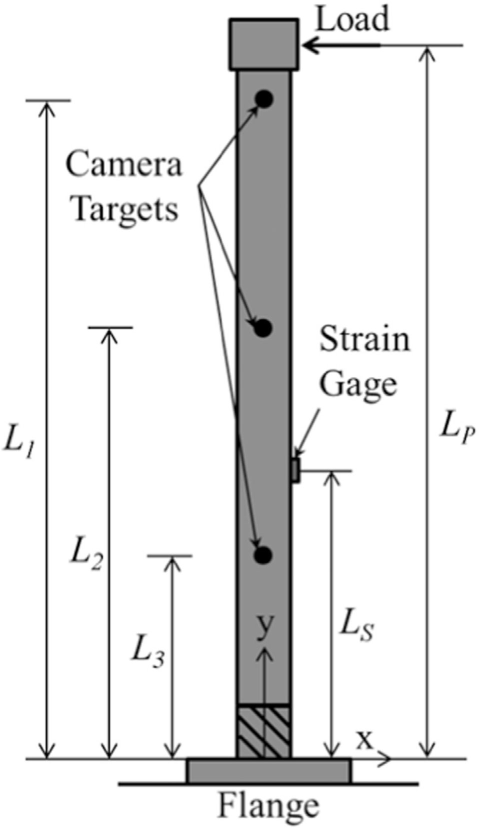

Fig. 2. Test-setup (not drawn to scale).

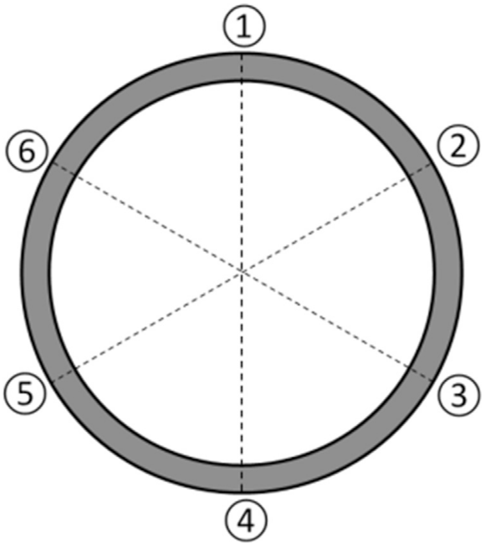

Fig. 3. Measurement points and directions of cross section.

2.2. Experimental test on 2-in. pipe

The test configuration of the 2-in. specimen was the same as that of the 1-in. specimen – see Fig. 2 – with the exception that the loads were applied at a distance of 577.6 *mm* from the flange. The threaded region of this pipe was between 8 and 8.5 full threads, and the pipe was screwed into the flange 5 full turns. The moment of inertia I was calculated as before. The results for this test are given in Figs. 6 and 7. As before, the force-strain behavior remains essentially linear, whereas the force-displacement behavior is linear followed by nonlinear.