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DESIGN OF WELDED SLIP JOINTS IN PIPELINES FOR COMPRESSIVE LOADING

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SUMMARY

Steel pipelines, which are used in many high-pressure water distribution systems in regions of high seismicity, are susceptible to large strains, buckling, and fracture as a result of large ground deformations experienced during earthquakes. A common method of joining segments is the welded slip joint, in which a circumferential fillet weld is applied where the bell end of one pipe overlaps the straight end of an adjacent one. These joints are susceptible to local buckling when subjected to compressive loading. In fact, welded slip joints can buckle locally at as little as 50% of the theoretical yield strength of the straight pipe. This paper describes a detailed investigation into the strength and ductility characteristics of welded slip joints in steel pipelines under compressive loading. A series of analyses for various geometric configurations of these joints and on straight sections of pipe was performed using the finite element software package ABAQUS. In all models, geometric and material nonlinearities were included to model both yielding and buckling response. The analytical results compare favorably with experimental results. Finally, plots of compressive strength, normalized with theoretical yield strength of the straight pipe, versus diameter-to-thickness ratio are presented and discussed.

INTRODUCTION

The 1994 Northridge earthquake resulted in the most extensive damage to a U.S. water supply system since the 1906 San Francisco earthquake. The Los Angeles Department of Water and Power (LADWP) and Metropolitan Water District (MWD) trunk lines (nominal pipe diameter greater than 600 mm) were damaged at 74 locations, and the LADWP distribution system required repairs at 1013 locations. An analysis of the Northridge earthquake performance shows that approximately 60% of critical trunk line damage in the LADWP system occurred because of compressive failure at welded slip joints [1].

Figure 1a shows a compressive failure at a welded slip joint on the Granada Trunk Line—a 1245-mm diameter steel pipeline with 6.4-mm wall thickness—that failed during the Northridge earthquake because of lateral ground movement triggered by liquefaction near the intersection of Balboa Boulevard and Rinaldi Street in the San Fernando Valley. Similar compressive failures were observed in trunk lines during the 1971 San Fernando earthquake and in the adjacent 1727-mm diameter (9.5-mm wall thickness)

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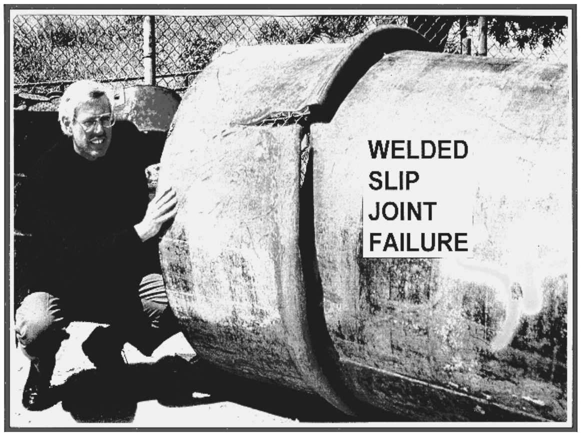
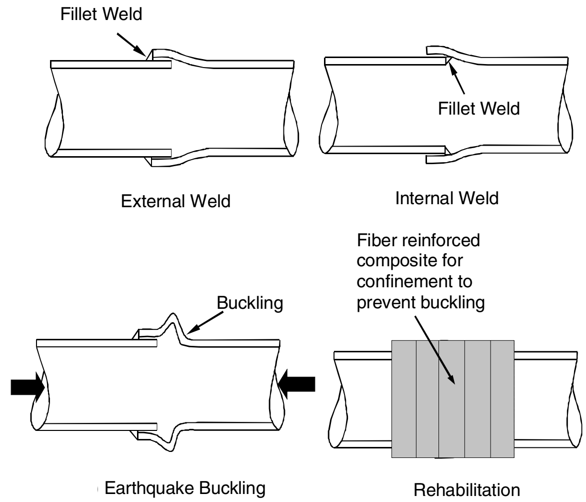


(a)



(b)

Figure 1. a) Compressive Failure of the 1245-mm Granada Trunk Line. b) Diagrams of a Welded Slip Joint in a Steel Pipeline.

Rinaldi Trunk Line during the Northridge earthquake. Loss of both the Granada and Rinaldi Trunk Lines cut off water to tens of thousands of customers in the San Fernando Valley for several days.

A welded slip joint is fabricated by inserting the straight end of one pipe into the bell end of another and joining the two sections with a circumferential fillet weld. Figure 1b shows diagrams of welded slip joints with internal and external welds. The bell end is created by the pipe manufacturer by inserting a mandrel in one end of a straight pipe section and expanding the steel into a flared, or bell casing. Large diameter pipelines can be constructed rapidly and economically in the field by joining the bell and spigot (straight) ends of connecting pipe segments.

As illustrated in Figure 1b, failure of a welded slip joint may be initiated by compressive forces that induce buckling and outward deformation at the location of maximum curvature in the bell casing. These compressive forces can be substantially lower than those required to buckle and fail a straight pipe section [2]. One method to strengthen a welded slip joint is to wrap the joint with fiber reinforced composites that provide additional confinement against buckling (also shown in Figure 1b). Research is in progress at Cornell University to determine the increase in strength gained by wrapping the welded slip joints with fiber reinforced composites.

One goal of the research is to develop predictive capabilities to aid in the design of welded slip joints with and without fiber wrap reinforcement. To that end, this paper presents finite element modeling techniques for characterizing the compressive strength of unreinforced welded slip joints.

FINITE ELEMENT MODELING

A series of finite element models were developed to investigate the compressive capacity of steel pipelines with welded slip joints. First a set of finite element models was developed to validate the modeling approach and select a model type for a parametric study. The finite element models were developed to create a design curve for the compressive strength of welded slip joints in some commonly used steel pipe sections.

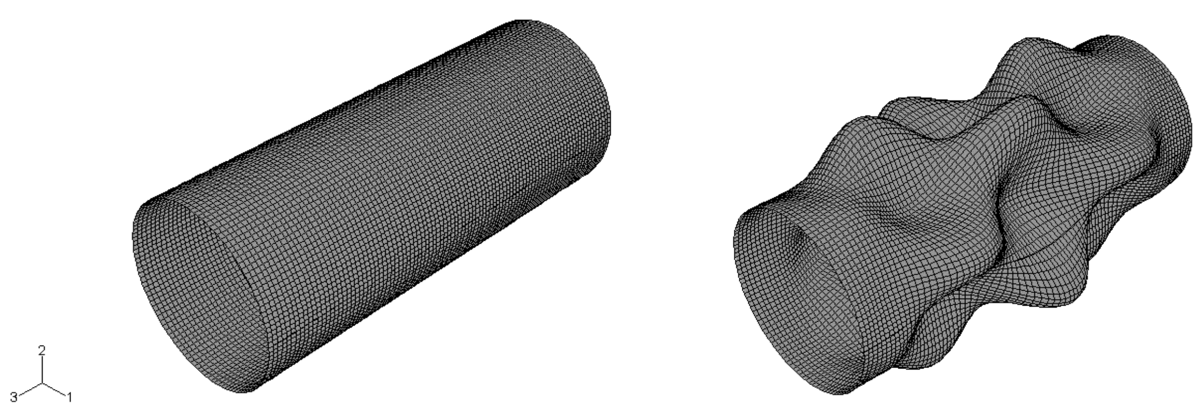
Validation Models

Following methods similar to those described by Tutuncu [3], the finite element models of welded slip joints were developed. First the straight pipe was modeled, and its buckling capacity was compared to the theoretical yield strength (product of cross sectional area and material yield stress) of the pipe. Then the welded slip joint was modeled in two ways, and the results from these models were compared with experimental results for welded slip joint test specimens. The models and corresponding results are described under the following subheadings.

Straight Pipe

All straight pipe models were developed in 3D, using shell elements to account for the possibility of 3D buckling response. Because of the relatively small wall thicknesses, the models were created with reduced integration 4-noded shell elements (S4R in ABAQUS) with a characteristic size of approximately 25 mm. The element size was selected on the basis of preliminary convergence studies performed by Tutuncu [3]. Figure 2a shows an undeformed mesh of a 915-mm diameter pipe finite element model created using ABAQUS [4]. To model compressive loading of the pipe, all degrees of freedom were constrained to zero on all nodes at both free ends of the pipe with the exception of an applied displacement of 25 mm in compression (in the 3 direction in Figure 2a) on one free end.

A straight pipe model absent of geometric imperfections will not simulate buckling but will deform in axisymetric compression according to the stress-strain behavior of the material. To accommodate buckling, an imperfection pattern was generated based on the first mode shape of the straight pipe predicted by a modal analysis. The exaggerated imperfection pattern shown in Figure 2b follows the first mode shape with a maximum deflection of 10 percent of the pipe wall thickness—for this case 0.67 mm. Once the geometry hase been defined, the analysis is run using ABAQUS Standard with the nonlinear geometry option (NLGEOM) activated.



(a) (b)

Figure 2. (a) 3D Shell Undeformed Finite Element Mesh Used to Model 915-mm Diameter Straight Pipe Sections. (b) The First Mode Shape Resulting from a Modal Analysis of the Straight Pipe.

Welded Slip Joints
The welded slip joints were modeled first in 3D using shell elements for direct comparison with straight pipe models. They were also simulated with 2D axisymmetric solid elements to better characterize the effect of weld geometry and reduce the model processing time. As is described in more detail below, the shell elements used in the 3D model have difficulty representing constrained conditions at the end of the pipe. In contrast, the 2D models with axisymmetric solid elements allow for explicit simulation of the weld and its interaction with the pipe ends. The 2D models are also especially useful for the performance of parametric studies because the time to develop and run this type of model is considerably less than that required for a 3D model.

The 3D models of the welded slip joints using shell elements are created in a fashion similar to that for the straight pipe models, with the exception that two independent pipe segments are created with one overlapping the other. The conditions at the free ends of the pipe segments are identical to the straight pipe models with the exception of the ends that overlap one another. The overlap is accommodated by the flare at the end of one pipe segment (see Figure 3) which is consistent with the flare observed in the experimental specimen that is used for comparison of results below. The weld is then modeled by tying together all degrees of freedom for each tied pair of nodes. For an externally welded pipe, a tied pair of nodes consists of one node at the end of the bell and a corresponding node (along the same radial line) near the end of the adjoining pipe. The tied pair of nodes for an internally welded pipe is activated in a similar manner by connecting the end of the straight pipe to the bell. Using tied pairs of nodes in this manner essentially treats the weld as a rigid body.

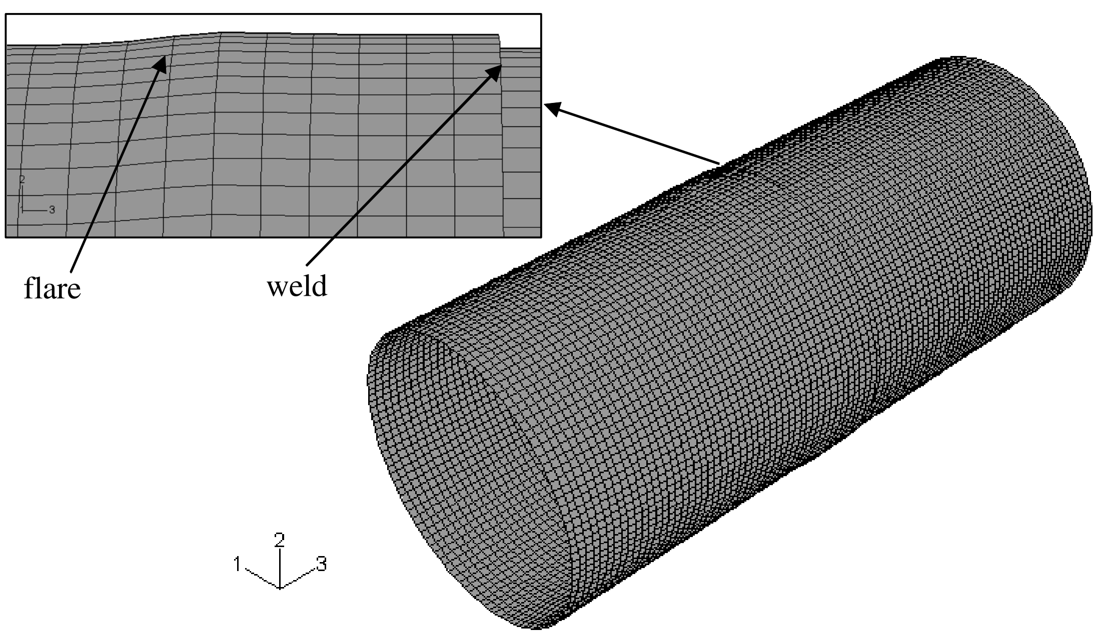
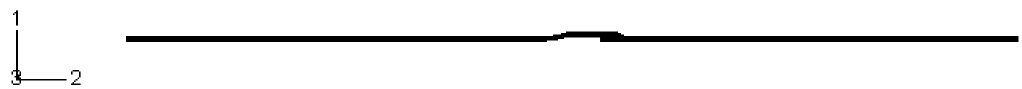
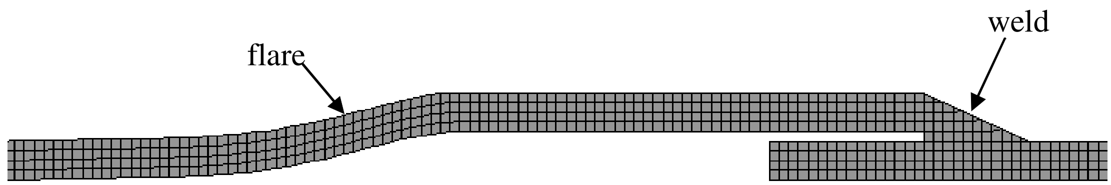


Figure 3. 3D Shell Finite Element Mesh Used to Model 915-mm Diameter Welded Slip Joint Pipe Sections. The Inset Shows a Close-up of the Flared Bell End of One Pipe and the Weld Location.



(a) Entire model



(b) Close-up of flare and weld

Figure 4. Axisymmetric Solid Finite Element Model Used to Analyze 915-mm Diameter Welded Slip Joint Pipe Sections.

The 2D model using axisymmetric solid elements was created to address the flexibility of the welds and for decreasing the time required per run. The axisymmetric model geometry is created by taking a 2D cut along a radial plane through the wall of the pipe (Figure 4a). The model is then meshed in ABAQUS using linear quadrilateral and triangular axisymmetric solid elements (CAX4R and CAX3 in ABAQUS), with the triangular elements being used only to accommodate the triangular shape of the weld (Figure 4b). The boundary conditions at the free ends of the pipe are similar to those of 3D models with the displacement constrained in the 1 and 2 directions (zero everywhere with an applied displacement in the 2 direction at one end).

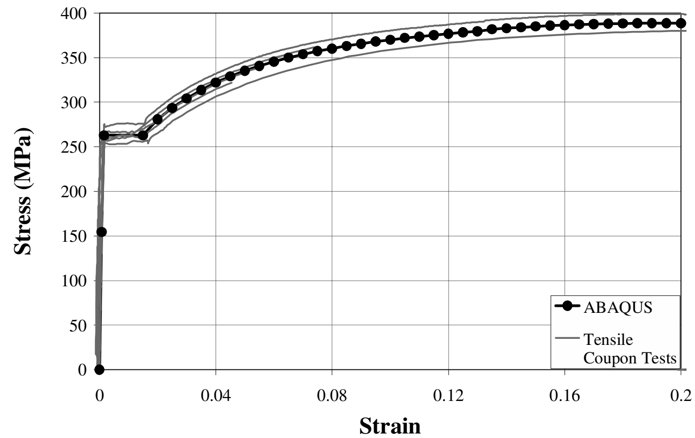
As with the straight pipe models, all finite element models of the welded slip joint were run using ABAQUS Standard with the nonlinear geometry option (NLGEOM) activated. The applied displacement at the free end of the welded slip joint models was also 25 mm.

Material Properties

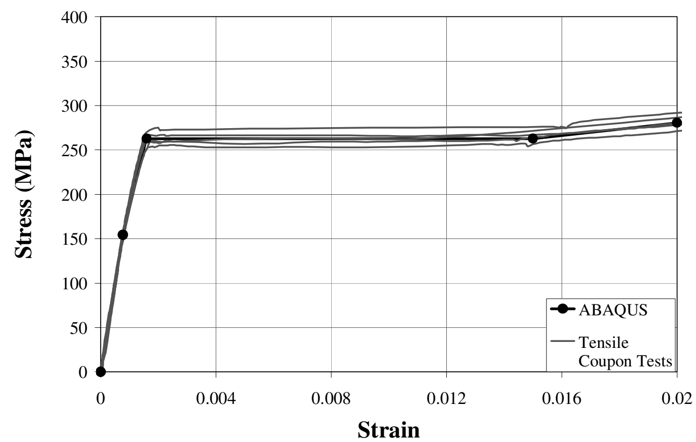
A set of tensile tests was performed on standard dogbone specimens in order to determine the material properties of the steel and generate a stress-strain curve to input to the finite element models. Five specimens were cut from unused portions of the 915-mm diameter pipes and tested according to ASTM standards [5]. The stress and strain results were then averaged to generate input for the finite element models. The results of the material testing and the corresponding curve used for the finite element models are shown in Figures 5a and 5b. The input lines used in ABAQUS to represent this curve are shown in Figure 5c.

Results of Validation Models

All finite element models were run to a maximum displacement of 25 mm at one free end of the welded slip joint, and the results were compared with results from full-scale experiments on 915-mm diameter welded slip joint specimens. Figure 6 shows the final deformed shape of the finite element meshes for the 3D shell and 2D axisymmetric solid models. Note the similarities between the buckled shape predicted by analyses and the buckled shape of the pipe in Figure 1. Figure 7 compares the load-displacement response predicted by the 3D shell models of the straight pipe with the welded slip joint response for clearances (to accommodate the overlap) of 0.8 mm and 2.3 mm, corresponding with the average and maximum measured clearances for the experimental specimens. The results show that the welded slip joint has 65% of the capacity of the straight pipe section.



(a) Entire stress-strain curve



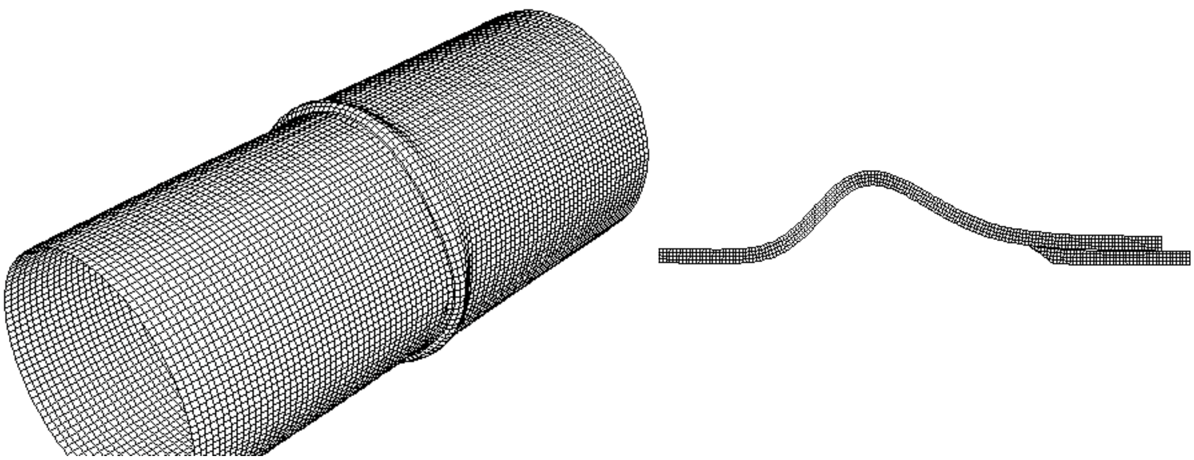
(b) Elastic range and yield plateau

*PLASTIC	
154.5,	0.00000
263.3,	0.00027
266.8,	0.01355
286.3,	0.01837
324.5,	0.03278
351.9,	0.04703
372.7,	0.06111
388.7,	0.07502
402.8,	0.08874
414.4,	0.10229
425.5,	0.11566
436.6,	0.12884
445.6,	0.14187
453.4,	0.15474
460.4,	0.16744
466.0,	0.17999
471.8,	0.19238
477.6,	0.20463
485.4,	0.22072

(c) ABAQUS Input (units are MPA and mm)

Figure 5. Comparison of ABAQUS Material Model to Tensile Coupon Test Data.

Figure 8 shows the load-displacement curves predicted by the 3D shell and 2D axisymmetric models of the welded slip joint for the average and maximum measured clearance. The load verses displacement data from an experiment on a 915-mm diameter welded slip joint specimen [5] are also shown. The experimental specimen was fabricated by LADWP crews using the same procedures they use in the field. The results for all finite element models agree quite well with the experimental results before and immediately following the onset of buckling. The largest difference between the predicted and measured peak loads is 10% for the 3D model with average clearance at the overlap. The best agreement between analytical and experimental results of approximately 0.3% occurs with the 3D model, using the maximum offset. The 2D model of the pipe using the maximum offset also shows excellent agreement with the experimental results with a maximum percentage difference of 1%. Note that the 2D model using maximum offset follows the curve for the experimental results more closely than any of the other models for pre-buckling and briefly during post-buckling response of the pipe.



(a) 3D model using shell elements **(b) 2D model using axisymmetric solid elements**

Figure 6. Deformed Meshes from Finite Element Models of a 915-mm Diameter Pipe.

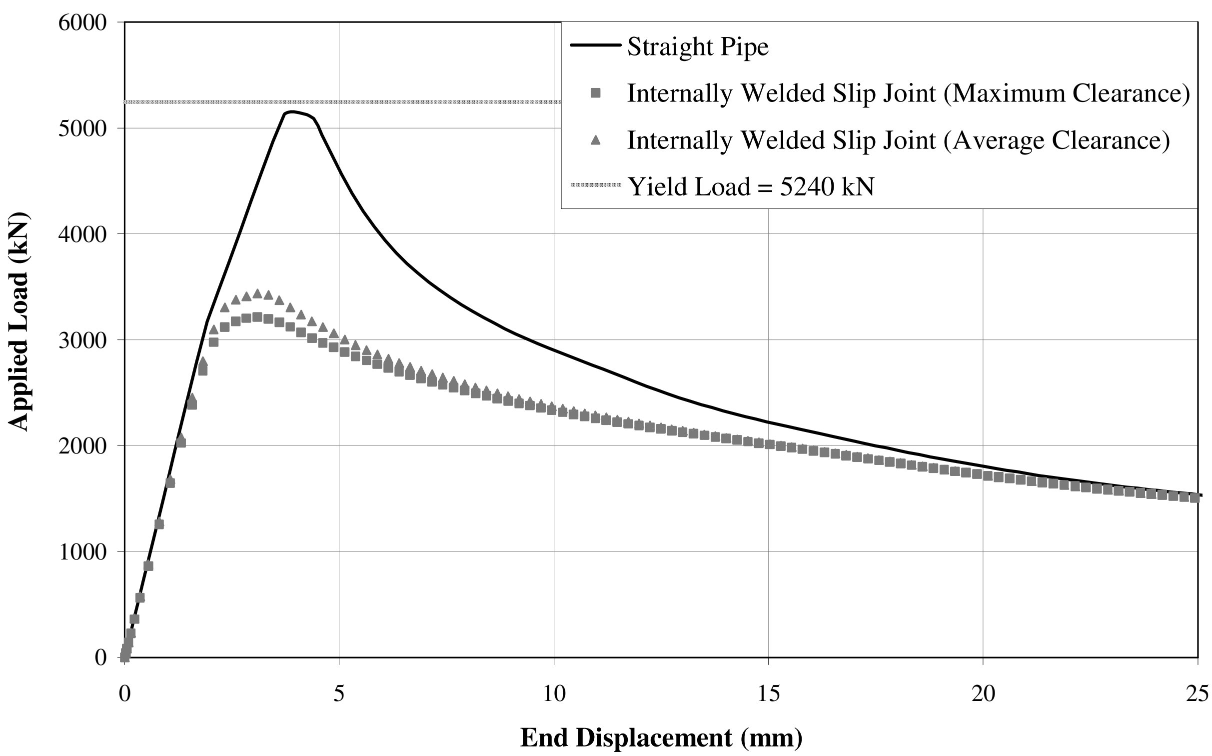


Figure 7. Load-displacement Response Predicted by 3D-shell Finite Element Models of a 915-mm Diameter Welded Slip Joint and a 915-mm Diameter Straight Pipe.

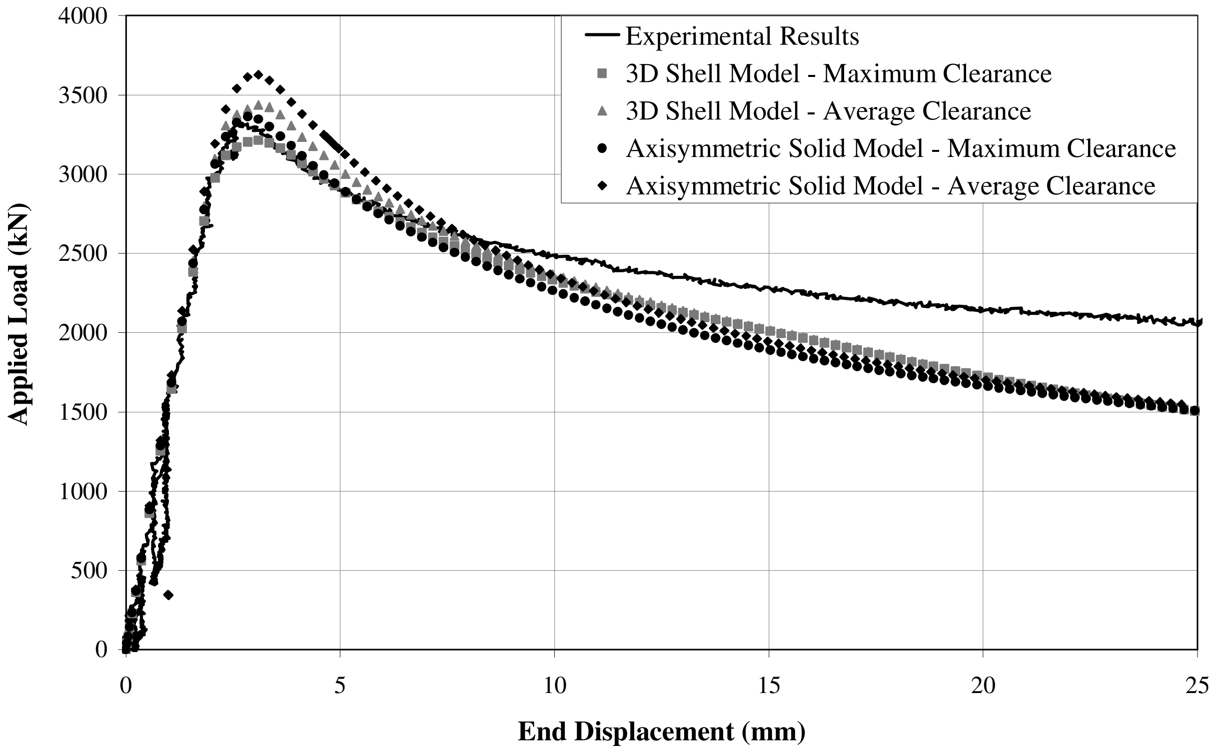


Figure 8. Load-displacement Response predicted by 3D Shell and Axisymmetric Solid Finite Element Models of a 915-mm Diameter Welded Slip Joint Compared with Results from a Corresponding Experiment.

Parametric Study

To develop a design curve for various sizes of pipe, a parametric study was performed. To streamline the process, a short program was written using FORTRAN to create the input files for 2D models in ABAQUS. All models had a minimum of 3 elements through the thickness of the pipe wall with an aspect ratio for the elements of approximately 1:1.

Several assumptions were made about the geometry, material properties, and boundary conditions that apply to the models in the parametric study. First, the boundary conditions used in the validation studies above were assumed to be adequate for determining compressive strength of welded slip joints. Second, the clearance at the weld was assumed to be 3.2 mm for all pipe geometries to simulate a worst case scenario. This variable is clearly not a constant, and variation of the clearance will affect the strength of the slip joint as is illustrated in Figures 7 and 8. Third, the overlap length for all pipes was assumed to be 50 mm based on the experimental specimens. The overlap length may affect the buckling strength for internally welded pipes because the weld location is controlled by the overlap. Fourth, the material properties used in the validation study were used for all finite element models. Finally, the shape of the bell was determined by fitting a curve to bell shape data from specimens tested at Cornell University [5]. From the real data, the following normalized curve was created to describe the y-coordinate (1-axis in Figure 4) of the pipe wall nodes:

$$y = \begin{cases} \dfrac{D}{2} & z \le 0 \\ \dfrac{D}{2} + (t_w + c)\left(10.89z^2 - 103.01z^3 + 361.39z^4 - 365.85z^5\right) & 0 \le z \le 0.5 \\ \dfrac{D}{2} + t_w + c & z \ge 0.5 \end{cases} \tag{1}$$

where D is pipe diameter, t_w is pipe wall thickness, c is the clearance between the bell and straight end of the adjoining pipe, and z is the normalized length—defined as x/L, where x is measured from the beginning of the bell and L is the distance from the beginning to the end of the bell. The origin of the local coordinate system for this calculation is the beginning of the bell in the x-direction (2-axis in Figure 4) and the center of the pipe in the y-direction. The distance, L was assumed to be 305 mm, which is consistent with the corresponding dimension of the experimental specimens.

The parametric study was performed by running finite element analyses of dozens of commonly used pipe geometries. Table 1 shows the diameter-to-wall thickness ratios for all geometries considered. All combinations of diameter and wall thickness were taken from Table 4-2 of the AWWA Manual M11 [6]. Normalized parameters are used here in the interest of comparing the response of different size pipes to identical loading patterns.

Figure 9 shows the results of the parametric study. The theoretical yield strength, P_y, is determined by multiplying the cross-sectional area of the straight pipe by the yield stress of the steel (~265 Mpa in this study). Note the similar shapes of the curves for the different diameter pipe with approximately constant strength for a range of diameter-to-wall thickness ratios. The drop in normalized strength is especially apparent in smaller diameter pipes.

Table 1. Diameter to Wall Thickness Ratios for the Pipes Modeled in the Parametric Study.

	Pipe Diameter (mm)				
Wall Thickness (mm)	**305**	**610**	**915**	**1220**	**2134**
2.6	114	228	345		
3.4	88.2	177	269		
4.0	75.8	152	231		
4.6	65.9	133	202		
5.6	53.8	109	166		
6.4	47.0	95.0	145	193	337
7.9		75.8	116	155	270
9.5		63.0	97.0	129	225
11.1		53.8	83.3	111	193
12.7		47.0	73.0	97.0	169
14.3				86.3	150
15.9				77.8	135
17.5				70.8	123
19.0				65.0	113
20.6					104
22.2					97.0
23.8					90.6
25.4					85.0

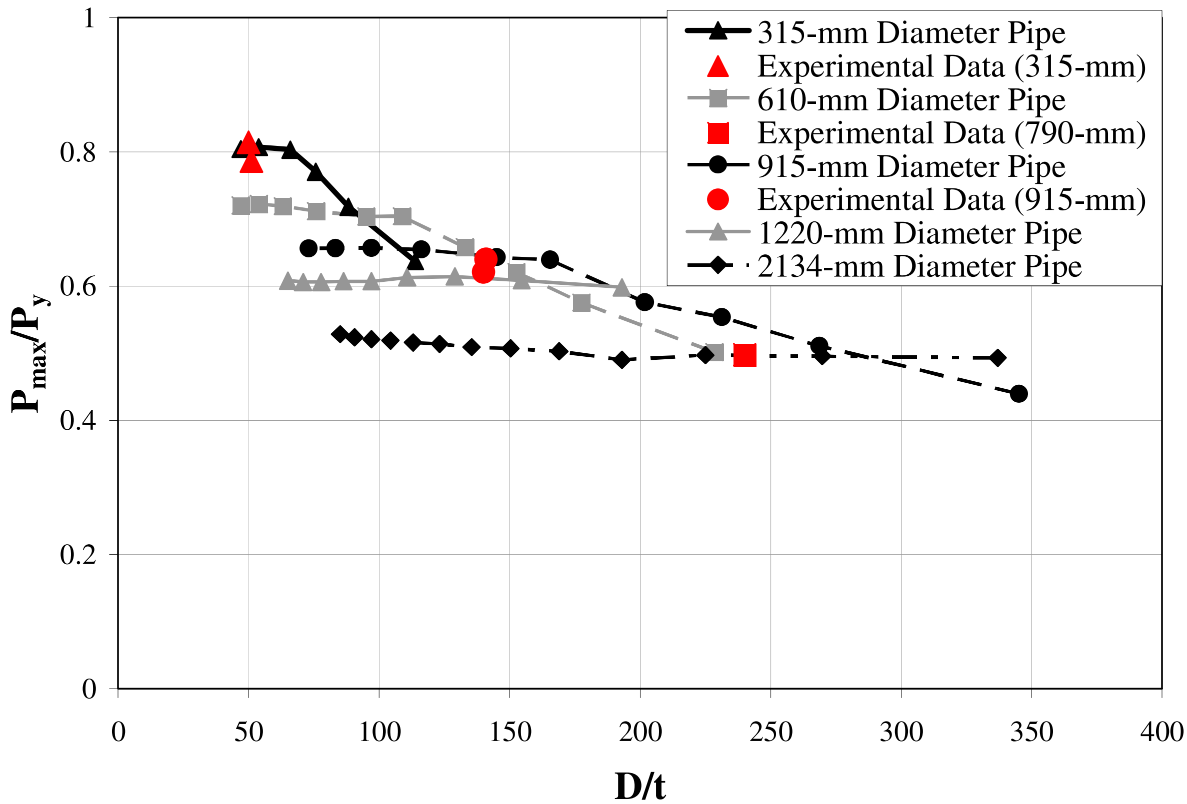


Figure 9. Normalized Compressive Capacity vs. Diameter to Wall Thickness Ratio for Some Commonly Used Steel Pipe Sections.

Also shown in Figure 9 are the results of laboratory tests on full-scale specimens of water trunk and distribution pipelines with welded slip joints. The specimens were fabricated by LADWP field personnel to be consistent with the type of welding and construction of facilities in service. The 305-mm specimens were tested in the Winter Laboratory at Cornell University with an MTS load frame having a capacity of 2700 kN [3]. The wall thickness of these specimens was 6.4 mm. Additional tests on larger diameter pipe specimens were performed at Taylor Devices, Inc. in North Tonawanda, NY using a load frame with a capacity of 6700 kN [5]. These specimens were 915 mm in diameter with a wall thickness of 6.4 mm and 790 mm with a wall thickness of 3.3 mm and hence, the experimental investigations provide results for D/t ratios ranging from 50 to 250. There is very good agreement between the trend of the analytical results and that of the experimental results.

Another important result of this study is that the time to complete a series of 10 or so models (pre-processing, running, and post-processing) is on the order of hours using a standard PC with a 2.0 GHz Pentium 4 processor and 512 Mb of RAM. Each model takes between 5 and 20 minutes to run. Research is ongoing to develop simple equations to describe the buckling capacity of slip joints and thus further reduce the time required to perform these analyses.

DISCUSSION OF RESULTS

The results presented above show that 1) finite element modeling accurately predicts the buckling capacity of welded slip joints and 2) the methods presented above can be used to develop curves for the design of new welded slip joints and the evaluation of existing ones. The implications of these results are discussed in the paragraphs below.

Having the capability to quickly generate load verses displacement curves is especially valuable for evaluating the effects of material properties, clearance between the bell and straight pipe, and overlap of the bell and adjoining straight pipe. The designer often has limited control over these variables—the steel manufacturer typically produces steel according to minimum yield strength and overlap and clearance are often specified but modified to accommodate details in the field. With the tools presented in this paper, engineers can quickly predict the compressive strength of a welded slip joint based on measured properties and/or assumptions about the worst case properties.

Research is currently underway at Cornell University to use the methods described above to determine the sensitivity of the welded slip joint compressive strength to material properties and overlap geometric variables and to extend these methods to welded slip joints wrapped with fiber reinforced composites.

CONCLUSIONS

This study was organized to develop predictive models for use in the design and evaluation of welded slip joints in seismic zones. Using the commercially available finite element package ABAQUS, the authors demonstrate modeling techniques that may be used in this respect. The following conclusions are made based on the results of this study:

- Comparison of the validation models with the experimental results shows that finite element modeling using ABAQUS accurately predicts the compressive strength of unreinforced welded slip joints. Research is underway to extend these modeling techniques to welded slip joints wrapped with a fiber reinforced composite.

- Analytical and experimental results show substantial reductions in the axial compressive capacity of pipelines with welded slip joints that can be as large as 50 percent for 2100-mm-diameter pipe at D/t used commonly in practice.

- The analytical results show significant reductions in axial compressive capacity as D/t increases for 50 to approximately 150 in pipelines with diameters less than 900 mm.

- The trends demonstrated analytically compare very favorably with experimental data for pipelines with welded slip joints having D/t ranging from 50 to 250. This comparison indicates that the analytical modeling procedures provide a sound basis for predicting the compressive capacity of welded slip joints in the field.

- The modeling techniques presented herein allow for the assessment of various parameters on the axial load capacity of welded slip joints. These parameters include pipe diameter, wall thickness, clearance between the interior face of the bell and the exterior face of the adjoining straight pipe, the length bell overlap with the adjoining straight pipe, and material properties. This study presents the results of a parametric study where the pipe radius and pipe wall thickness (easily controlled variables in design) are varied.

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