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# Effects of Weld Zone Properties on Burst Pressures and Failure Locations

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**Abstract**

The effects of weld zone properties on the burst pressures and burst failure locations of DOT-39 nonrefillable refrigerant cylinders were examined using the finite element analysis (FEA) approach. In order to do this, the weld zone properties were specified from the manufactured cylinders. In the computer modeling process, these cylinders were subjected to an incremental internal pressure within the material nonlinear field. The results, compared with corresponding experimental results, show that weld zone properties play an important role in determining the burst pressures and the failure locations of these cylinders.

**Key words:** Weld zone effects, DOT-39 refrigerant cylinders, Nonlinear FEA analysis, Burst pressures, Failure analysis.

## Introduction

Department of Transportation (DOT) cylinders, generally containing hazardous materials, have been designed and manufactured based on the requirements of the Hazardous Material Regulations to meet the specifications of the DOT Codes in the USA. DOT-39 cylinders, approved by the DOT as nonrefillable / nonreusable, are specifically designed for refrigerant gas shipping and storage applications. They are equipped with a one-way hermetic leak-stop valve to prevent refilling, which is unsafe and illegal. These cylinders usually contain refrigerant gases such as R22, R134A, R404A, R500 and R502. These are low-pressure cylinders (service pressure < 500-psi (3.45-Mpa)), having capacities ranging from 15 lbs (6.8 kg) to 50 lbs (22.7 kg).

Weld joints are used in the assembly of the DOT-39 nonrefillable refrigerant cylinders during the manufacturing process. They are produced within 2 bottomed cylindrical shell components and assembled together using a weld joint circumferentially as shown in Figure1. Because of the welding process and weld properties, the strength of the cylinder is enhanced locally at the welded zone under the assumption of no local residual stresses. This enhancement affects the load capacity that increases the burst-failure strength of the refrigerant cylinders (Kisioglu, 2000).

Many researchers have developed analytical and experimental methods to predict the effects of weld joints on structural behavior. However, advances in computer-aided modeling such as the finite element method (FEM) help in analyzing structural behavior in welded components enhancement even further. The effects of welding conditions on residual stress during one-pass arc welding in a steel plate were developed using ANSYS FEM techniques (Teng and Lin, 1998). The influence of pipe wall thickness on welding residual stresses was examined by Teng and Chang (1998), and a procedure was proposed by Brickstad and Josefson (1998) for determining the temperature and residual stress field in multi-pass butt-welds in piping systems. The effect of mechanical heterogeneity of a weld joint on the J-integral assessment curve was examined by Lei *et al.*

(1998), the reliability of pressure piping with welded joints containing defects was examined by Zhou and Shen (1998), and the local mechanical properties of pipeline steels and welded joints were estimated by Zhang and Dorn (1998).

In a preliminary study (Kisioglu *et al.* 2001) the burst pressures of DOT-39 nonrefillable refrigerant cylinders were predicted and examined under internal pressure without considering weld zone effects in detail. However, in this study, the effects of weld zone properties, including thickness variations, are discussed with regard to the burst pressures (BP) and the burst failure locations (BFL) of DOT-39 refrigerant cylinders. The properties of the weld zone were investigated and used to analyze the BP and BFL within 2 different computer models, homogeneous and nonhomogeneous.

**Structures of DOT-39 Non-Refillable Refrigerant Cylinders**

DOT-39 nonrefillable refrigerant cylinders are usually designed to be thin-walled and are manufactured in 3 different groups. These are classified by their inner diameters (*ID*), 7.5 in (190.5 mm), 9.5 in (241.3 mm), and 12 in (304.8 mm) and associated variable wall thicknesses ($t$), so they are manufactured within different ratios of $0.0017 < t/ID < 0.013$. In general, these cylinders are called *ID*-7.5, *ID*-9.5 and *ID*-12 in industrial applications. In addition, these refrigerant cylinders mainly consist of 2 shell components, top and bottom shells, and are manufactured by a deep drawing process. These 2 shell components are welded together at the middle circumferentially about their axes of rotation to form a cylinder as shown in Figure 1.

The material properties of DOT-39 nonrefillable refrigerant cylinders including the weld zone were specified to determine the BP and BFL of these cylinders. These material values were used in the computer modeling, since the cylinder properties were changed from initial steel to drawn shells. These cylinders were manufactured from SAE-1008, cold-rolled low-carbon (0.06% C) steel, which has relatively low tensile strength values of 30∼35 Ksi (∼205 to 240 MPa). Therefore, during the burst testing of these cylinders using computer modeling, the BPs of these cylinders were predicted about 16.5% lower than the corresponding experimental results without regard to the weld zone properties and nonuniform shell geometries (Kisioglu *et al.* 2001).

**Investigation of Weld Zone Properties**

From the general design viewpoint, the weld joints must implement functionality of the required strength. In order to avoid the affects of stress concentrations as well as discontinuity stresses, the geometrical discontinuity at the welded place must be applied smoothly considering the welding procedures. In the case of the weld joints of these cylinders, the weld zone geometries were generally generated quite uniformly. Therefore, the average values of the nominal dimensions of the weld joints were gauged as shown in Figure 1.

The well known tensile test technique was applied to identify the weld zone material properties of the cylinders. A few tensile test specimens were taken from the weld zones of several sample cylinders. These specimens were cut out circumferentially from about the axis of rotation as indicated with dashed lines on the weld zone in Figure 1. From the tests, the engineering stress-strain data (ESS) and associated curves were obtained. It was observed that the ESS data and related curves obtained from each test behaved approximately in the same ranges and slopes. The conversion method (Mielnik, 1991) was used to explore the weld zone properties that were converted from ESS to True Stress Strain (TSS) curves as well as drawn shell properties (Kisioglu *et al.* 2001), which are illustrated as TSS curves in Figure 2. Therefore, the mechanical properties of the weld zone material were investigated using the tensile test technique, and the following results were obtained: *Ultimate Tensile Strength (UTS)*: 84,900 psi (585.4 MPa), *Tensile Yield Strength (TYS)*: 70,900 psi (488.8 MPa), *Modulus of Elasticity (E)*: 176 ksi (1.2 GPa), and *Elongation*: 26.25%.

**Computer Modeling**

Two different types of computer model, homogeneous and nonhomogeneous, were generated as uniform geometry using the ANSYS finite element computer code. The homogeneous model was developed under the assumption of no changes in the material properties of the cylindrical shells during the cup drawing process, so that the initial steel (SAE-1008) properties for the entire cylindrical shells were conducted in the computer modeling. In contrast, the nonhomogeneous model was generated considering the actual drawn shell material properties obtained from the drawn shells and constant wall thickness conditions as seen in Figure 3. The drawn shell material properties of 3 different drawn shell zones were taken into account for this modeling process. In order to define these models, the weld zone material properties were utilized in both modeling types.

These models, created to be 2D axisymmetric with respect to the main axes and internal loadings, were simulated in the material nonlinear field. In order to develop a suitable model, a 2D axisymmetric finite shell element with a 2-node selected from the ANSYS element library (ANSYS User Manual) and a fine mesh structure were generated. In these modeling processes, a 212-node was created in the FEA mesh generation. However, it was necessary to define the welded place geometry in these models accurately because the weld zone thickness was nonuniform points from "a" to "c" as shown in Figure 3.

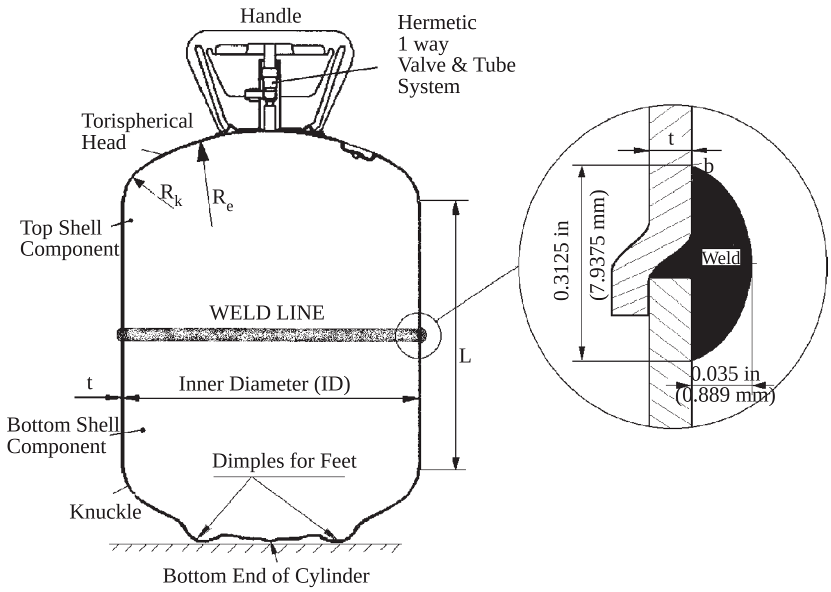


**Figure 1.** The geometry of the DOT-39 refrigerant cylinder and its weld zone.

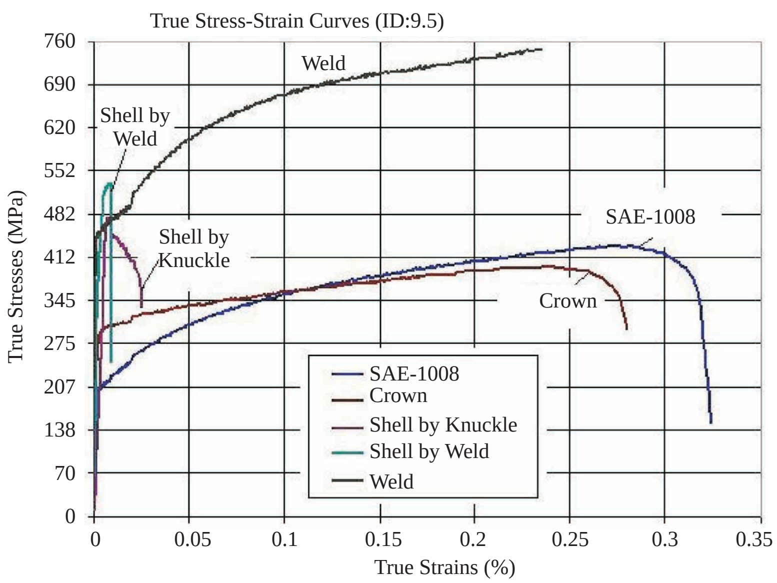


**Figure 2.** Evaluations of the weld zone, SAE-1008, and drawn shell material properties.

## Loading Conditions

Graphical views of the loading process as a function of loading times for both homogeneous and nonhomogeneous models are shown based upon the modeling types in Figures. 4 and 5, respectively. Two loading curves for the homogeneous models, named “Orij95-32” and “OrijW95-32”, were obtained using SAE-1008 steel without and with weld zone properties, respectively, as illustrated in Figure 4. The material properties are ductile in this modeling process. Similarly, for the nonhomogeneous models, the loading curves named “She95-32” and “SheW95-32” were determined using the drawn cylindrical shell without and with weld zone properties, respectively, as shown in Figure 5. The material properties in this modeling are more brittle than those in the homogeneous modeling.

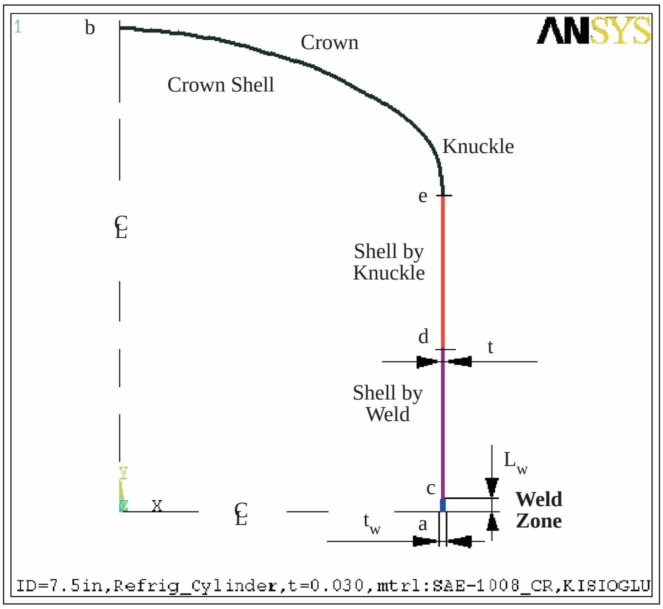


**Figure 3.** Nonhomogeneous computer 2D model.

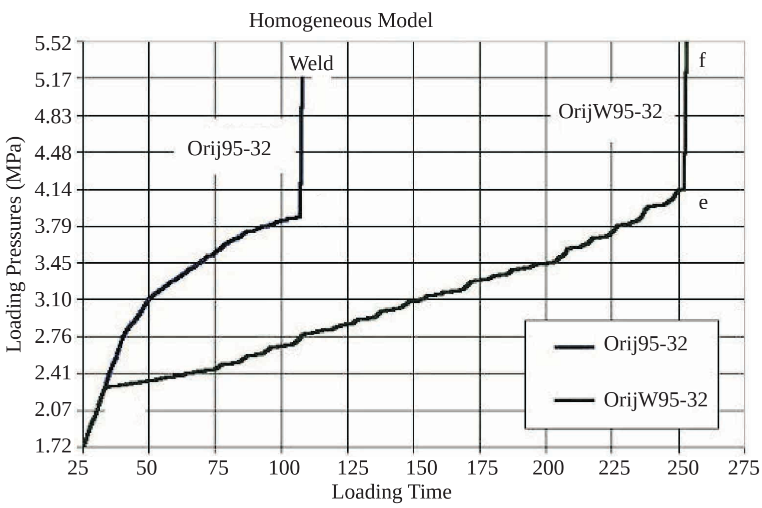


**Figure 4.** Homogeneous model’s loading conditions.

At the initiation of these loadings, the loads were increased proportionally, 10-psi ($68.95 \times 10^{-3}$ kPa) per step up to points "a" and "d" based upon the modeling types as depicted in Figures. 4 and 5. When the linear loadings reach these points, the cylinder material enters the fully plastic range and changes to nonlinear behavior. Therefore, these points, "a" and "d", can be called "break-down points" for elastic-plastic conditions. After the break-down points, nonlinear loading increases gradually since full strain plasticity conditions take place. When the loads reach "bursting points" "b" and "e" the loads shift suddenly to points "c" and "f" in one loading step. Finally, the loads reach points "c" and "f", which represent the initial estimations for the magnitudes of the BP loadings at the beginning of the simulations.

### Effects of Weld Zone Properties on BP and BFL

Resistance of the model to burst failure primarily depends on the strength of its material. When the DOT-39 nonrefillable cylinders are subjected to internal pressure incrementally, the pressure, "$p$", exceeds some critical value, "$p > p_c$", and the system

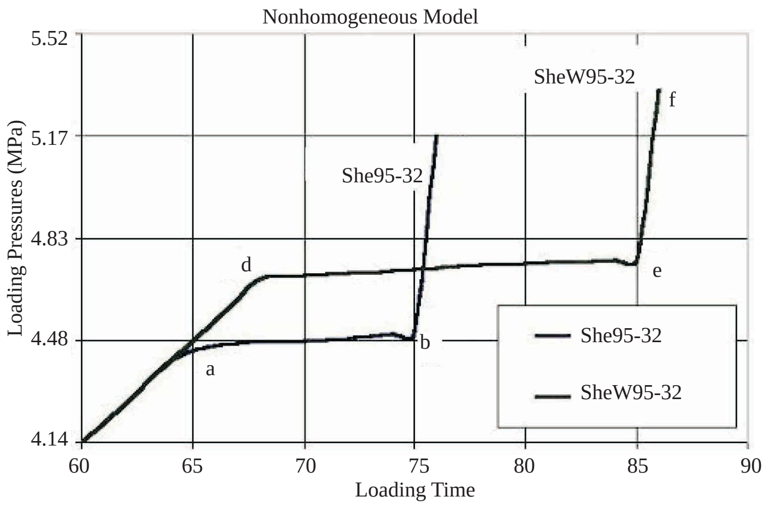


**Figure 5.** Nonhomogeneous model's loading conditions.

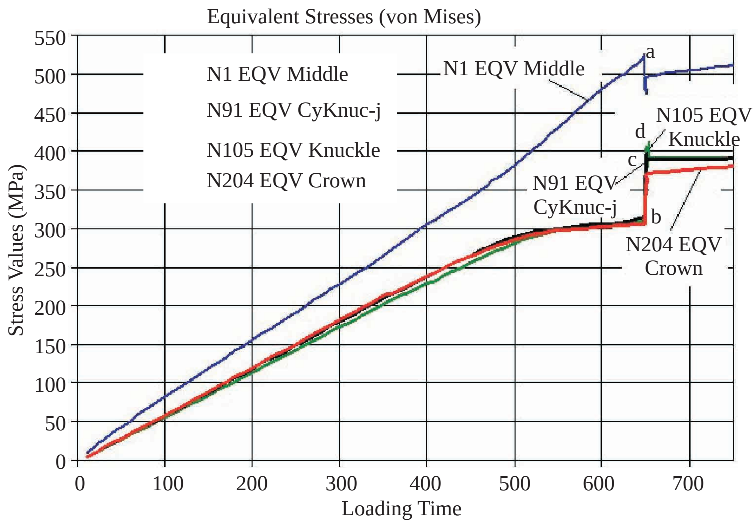


**Figure 6.** Equivalent stresses at selected nodes of the nonhomogeneous model.

exhibits an unstable behavior. As "$p$" increases from the zero stage through "$p_c$", at the instant of "$p = p_c$", a bifurcation state takes place in such a way that the maximum stress of the model reaches the corresponding material property (defined by the UTS) as shown in Figure 6. In this case, the maximum stress tends to tear the wall of the cylinder so that the bursting phenomenon begins to occur. Therefore, the equivalent stress (von Mises) values for some selected nodes of the model were plotted as a function of loading time as depicted in Figure 6. The max-equivalent stress value, 76,885 psi (530.1 Mpa), was higher than the corresponding material properties, (UTS), 76,700 psi (529 Mpa).

The BFLs of the DOT-39 refrigerant cylinders were investigated by the experimental burst tests, and failure occurs at the junction of the cylindrical shell and knuckle regions. This point, at N98 in Figure 7 is defined as the failure location of these refrigerant cylinders. In the burst experiment, cylinder specimens fracture starts at this point in such a way that the burst tearing continues longitudinally through the weld zone (Kisioglu *et al.* 2001).

In the case of computer modeling for burst tests of the DOT-39 refrigerant cylinders, the BFLs were obtained in different places as illustrated in Figure 7, based upon the nonlinear modeling types. A computer model from post simulation, seen in Figure 7, is shown with inside and outside lines, which represent the undeformed and deformed models, respectively. The BFL was obtained at point "N1" when the weld zone properties were not considered in both types of uniform modeling process. In the uniform modeling process, the shell thickness was considered uniform. However, when the weld zone properties were taken into account in both uniform computer models, the BFLs were found in the "shell-by-weld" region between the points "N16" and "N25". The exact BFL from the computer modeling was obtained in the "shell-by-knuckle" region at point "N98", when the non-uniform FEA model was considered in the simulation processes as shown in Figure 7. This location was confirmed by the experimental results in such a way that the BFL was determined using the computer modeling approaches.

The BP results of the DOT-39 refrigerant cylinders from both homogeneous and nonhomogeneous models were plotted as a function of $t/ID$ ratios as illustrated in Figures 8 and 9, respectively. Figure 8 shows BP results with 2 curves, named "SAE-1008" and "SAE1008WELD", which were obtained using SAE-1008 steel without and with the weld zone properties in the homogeneous models. Similarly, Figure 9 portrays the BP result curves of the nonhomogeneous models. These 2 curves, named "Drawn Shell" and "D-Shell + WELD", were obtained using a drawn shell without and with weld zone properties

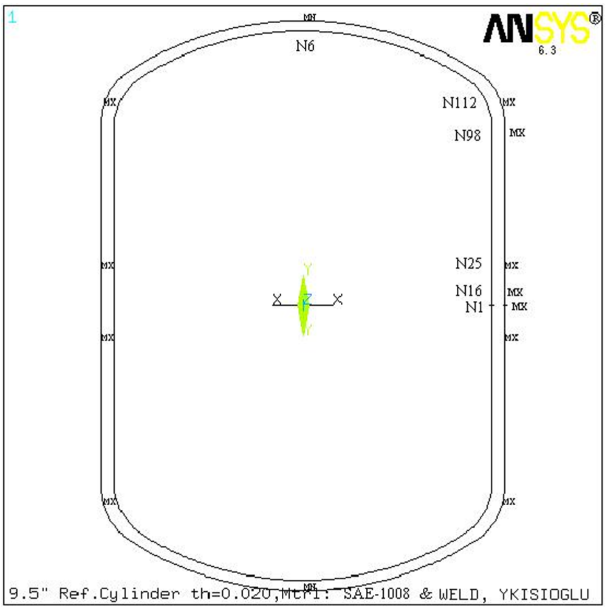


**Figure 7.** The BFLs of the DOT-39 nonrefillable refrigerant cylinders.

in the nonhomogeneous models. In addition to these results, Figure 10 shows the effects of the weld zone properties on the BP of the cylinders as a function of the material types used in the computer simulations including nonuniform models. The nonuniform model was created using the drawn shell thickness variation obtained from the drawn shells. Therefore, for 3 different groups described above, the ranges of the BP curves as a function of the material types are affected and increased by involving the weld zone properties for both computer models.

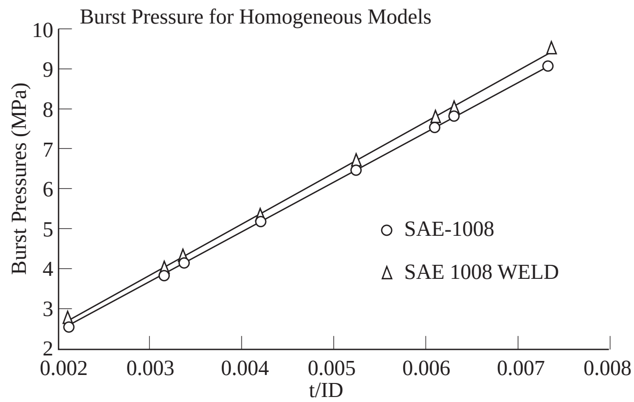


**Figure 8.** The BP values of the homogenous models.

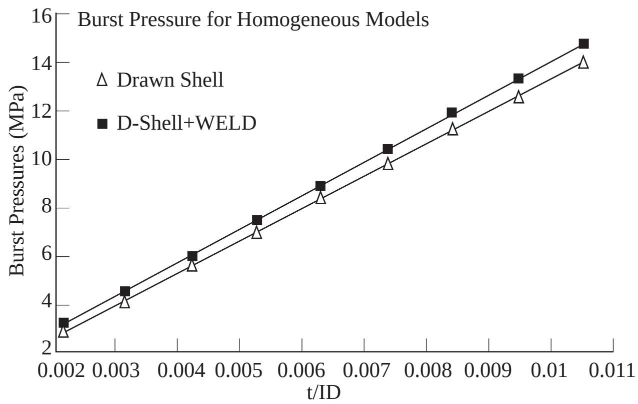


**Figure 9.** The BP values of the nonhomogenous models.

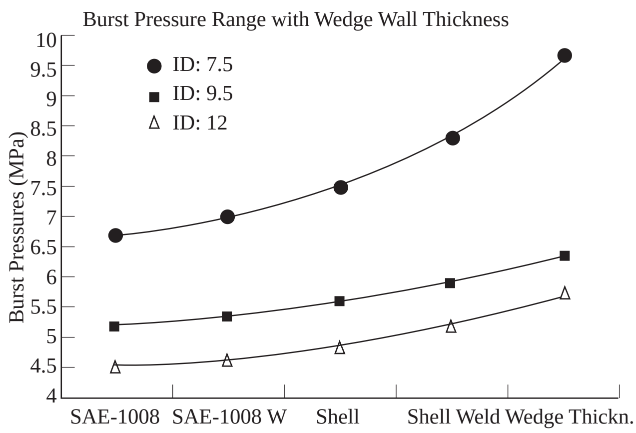


**Figure 10.** The effects of the weld zone properties on the BP of the DOT-39 nonrefillable refrigerant cylinders.

## Conclusions

The effects of weld zone material properties on both BP and BFL of DOT-39 nonrefillable refrigerant cylinders were investigated using nonlinear axisymmetric computer modeling approaches. Based on the generated results, the outcomes can be summarized as follows:

It was observed that the SAE-1008 material and the actual drawn cylindrical shell properties were not sufficient to investigate the BP and BFL of the DOT-39 refrigerant cylinders using computer modeling. As can be seen, however, from the results in Figures 8-10, the weld zone properties played an important role in both the homogeneous and nonhomogeneous modeling cases.

The BPs of these cylinders were predicted about 16.5% lower than the corresponding experimental results using the uniform-homogeneous models. However, when the weld zone properties were involved in the uniform nonhomogeneous modeling, the BP results were 5.55% less than the actual BP obtained from the experimental modeling.

The properties of the weld zone located in the middle of these cylinders including its thickness variations, were specified and well represented in the computer modeling. Based on the UTS values, the weld zone was found to be about 44%, 20% and 10% stronger than the crown, shell-by-knuckle and shell-by-weld regions, respectively. In addition, in the computer models, the behavior of incremental loading regarding the model types remains linear up to pressure levels of about 88-95% of the failure load.

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