Burst Pressure Determination of Vehicle Toroidal Oval Cross-Section LPG Fuel Tanks

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This study addresses the prediction of the burst pressures and burst failure locations of the vehicle toroidal liquefied petroleum gas (LPG) fuel tanks using both experimental and finite element analysis (FEA) approaches. The experimental burst test investigations were carried out hydrostatically in which the cylinders were internally pressurized with water. The FEA modeling processes of these LPG fuel tanks subjected to incremental internal uniform pressure were performed in the nonlinear field. Two different types of nonlinear models, plane and shell, were developed and evaluated under nonuniform and axisymmetric boundary conditions. The required actual shell properties including weld zone and shell thickness variations were also investigated and used in the computerized modeling processes. Therefore, the results of the burst pressures and their failure locations were predicted and compared with experimental ones. [DOI: 10.1115/1.4002863]

Keywords: burst pressures, toroidal shells, LPG fuel tank, nonlinear failure analysis, nonuniform FEA model

1 Introduction

Liquefied petroleum gas (LPG) is commonly used as an alternative fuel for the internal combustion engines of the vehicles in Turkey and Europe. The LPG is stored and transported based on Turkish Standards (TS) [1] in Turkey and Economic Commission for Europe Regulation (ECE-R) [2] in Europe. The pressure cylinders known as LPG fuel tanks and approved by these regulations are commonly used to store the LPG in vehicles. The toroidal oval cross-section LPG tanks are designed and manufactured about 25,000 annually by a manufacturer, in Turkey, based on ECE-R67 and TS 12095 to be used in Europe and Turkey, respectively. These LPG tanks, called low-pressure cylinders since their service pressures (SPs) are lower than 3.45 MPa (500 psi) [3], can be filled and used commercially in the automobile industry. They, equipped with a refillable two-way hermetic valve, were produced as LPG containers and used in vehicles having 45 l water capacities.

The primary problem of the manufacturer is to determine the burst pressures (BPs) and their failure locations of the toroidal LPG tanks whose service and test pressures (TPs) are known by the definitions of the ECE-R and TS rules. The SP is the working (operating) pressure, where the tanks are filled and used in industrial applications. The TP is a given pressure that is applied and released after which the permanent volume expansion of the tanks must exceed at least 10% of the initial volume. Finally, the BP is the maximum pressure a toroidal tank can hold without bursting. Therefore, by the definitions of the regulations, the BP of these tanks has to be determined by the manufacturer to confirm the minimum code requirements.

Although the toroidal shell is one of the lesser used shell components, a number of studies have recently been published in literature, which highlights new applications. Kisioglu et al. [3] studied and determined the BP and their failure locations for the DOT-39 refrigerant cylinders, Kisioglu [4] studied volume expansions during the burst of the vehicle toroidal LPG fuel tanks, and Kaptan and Kisioglu [5] determined the BP of the cylindrical LPG fuel tanks using both experimental and finite element method (FEM) approaches. Xue et al. [6] determined the influence of geometrical parameters on the burst pressure of a cylindrical shell intersection using analytical method. Wang et al. [7] had determined the burst pressure of the cylinder with hillside nozzle by the use of both finite element analysis (FEA) and experimental approaches. Galletly [8] had studied the buckling analysis of a complete toroidal shell having elliptical cross-section using the shell buckling programs BOSOR and INCA. Aksoley et al. [9] compared the BP of the LPG tank, used for home-kitchen applications, employing the experimental and FEM techniques. Blachut [10] had studied the static stability and buckling failure of externally pressurized toroidal shells using numerical analysis technique. Mirzaei analyzed the failure of the exploded cylinders containing and transporting the hydrogen gas using the analytical methods [11]. Redekop et al. had studied the stability of fluid-containing toroidal shell and derived some numerical results using both FEM and DQM methods [12]. Kisioglu designed an alternative end-closure for the DOT-4BA propane cylinders to prevent their buckling failure [13]. Therefore, no similar body of knowledge appears to be available in current literature for BP and its failure location investigations of the vehicle toroidal oval cross-sectional LPG fuel tanks.

The purpose of this study is to investigate the BP and its failure location of the vehicle toroidal oval cross-section LPG fuel tanks using both experimental burst tests and computerized numerical analysis. The experimental burst tests were studied using the research and development laboratory facilities of the manufacturer. The actual shell and weld zone material properties (MPs) including thickness variations of the tanks were investigated to predict the BP and failure location using numerical approach. These properties were used nonlinearly in the numerical modeling process to approximate the BP values obtained by the experimental tests. Besides, these tanks were subjected to incremental internal uniform pressure depending on loading time. Therefore, two different types of 2D nonlinear computerized finite element models, *plane* and *shell*, were developed under axisymmetric boundary and nonlinear material conditions.

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Fig. 1 Toroidal oval cross-section LPG Fuel tank and its components

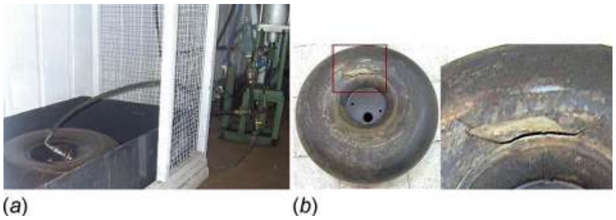


Fig. 3 (*a*) The experimental setup and equipments and (*b*) a burst toroidal LPG tank

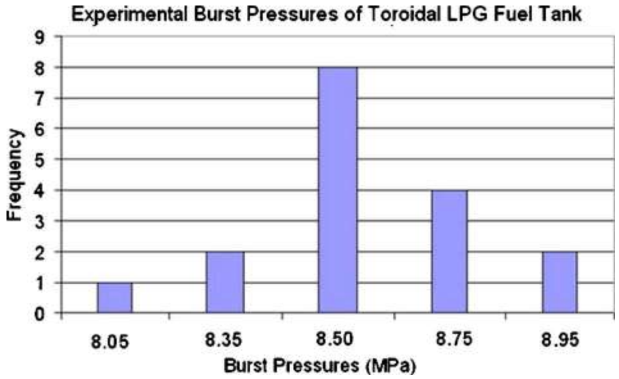


Fig. 4 The BP results of toroidal oval cross-sectional LPG fuel tanks

2 Design of Toroidal Oval Cross-Section LPG Fuel Tanks

The toroidal LPG fuel tanks are designed and manufactured according to the restrictions of the ECE-R and TS codes considering the SP and TP values. According to these rules, the SP and TP of the toroidal tank are given as 1.75 MPa and 3.00 MPa, respectively. The minimum BP of a toroidal tank must be 9/4 times of the TP based on the regulations. These fuel tanks are usually called by their water capacities as 45 l tank, and designed in oval cross-section having 600 mm toroidal diameter and 3 mm of wall thickness. The tanks are constructed from Erdemir-6842 hot rolled steel [14], which is produced by Erdemir Steel Company in Turkey. It is 0.18% carbon content steel and a ductile material suitable for cold forming process used to construct them.

The toroidal LPG tanks consist of three main parts: one internal ring and two semitoroidal shells, as seen in Fig. 1. Both internal ring and two semitoroidal shells are manufactured using the spinning process. After the spinning process, these parts are welded circumferentially to form the toroidal LPG tanks in Fig. 1. The design parameter definitions of the tank are given in Fig. 2, such as toroidal radius (R), the radii of oval cross-sectional curvatures (R_1 and R_2), and height of the oval shell (h). The oval cross-section of the toroidal shell is designed with the radii of curvatures R_1 and R_2, which are slightly different from each other.

3 The Experimental Burst Tests

The experimental burst investigations of the toroidal LPG fuel tanks were carried out at the research and development laboratory of the manufacturer, in Turkey. In order to burst these tanks, the experimental setup was established, as shown in Fig. 3(*a*). Tanks were burst using the hydrostatic burst test technique at room temperature. The specimens carefully placed horizontally in the experimental equipments were completely filled with water to burst. The pressure was controlled by means of a single acting hydraulic pump and the air was vented during the filling, as seen in Fig. 3(*a*).

In the burst experiments, 17 toroidal LPG tanks randomly selected from the manufactured stacks were tested at different times. One of the burst tanks and the view of its burst location are enlarged, as shown in Fig. 3(*b*). The BP distribution of a total of 17 toroidal LPG tanks is shown in a function of test frequency histogram, in Fig. 4, where the frequency refers to the number of occurrences of each BP value in the overall test process. Since the wall thickness of the Erdemir 6842 blank steel sheet was variable due to the thickness tolerances, the BP values ranged from a minimum of 8.05 MPa to a maximum of 8.95 MPa. Therefore, the mean BP values obtained were about 8.50 MPa for the 45 l toroidal LPG fuel tank with a standard deviation of around 0.220.

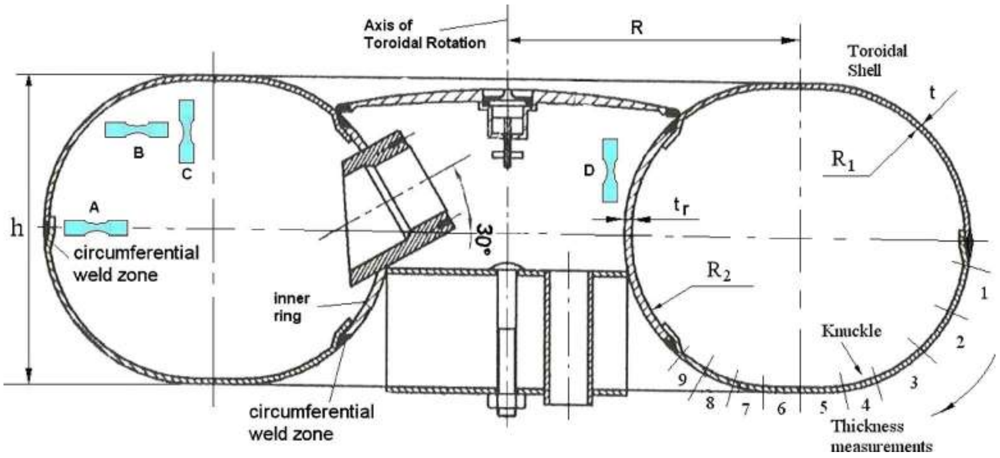


Fig. 2 Design of the toroidal oval cross-section LPG fuel tank and its design parameters

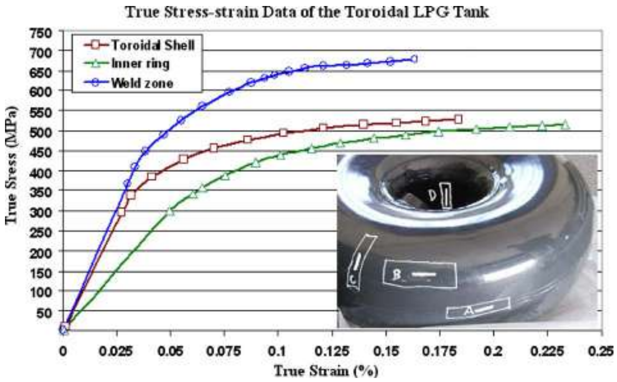


Fig. 5 Orientations of tensile test specimens and their true stress-strain curves

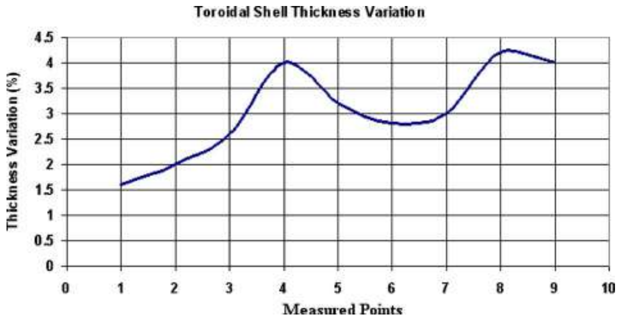


Fig. 6 Thickness variation of the toroidal LPG fuel tanks

4 Computer-Aided FEA Modeling and Burst

Computer-aided investigations were carried out using ANSYS, finite element based computer code to predict the BP and its failure location of the toroidal LPG tanks. To do this, two different types of nonlinear finite element models, plane and shell, were developed using 2D axisymmetric finite plane and shell elements, respectively. Due to spinning processes, the shell MPs and thickness variations of the LPG tanks were investigated and inputted to create these models and simulate the experimental bursts. Additionally, the nonlinear axisymmetric 2D FEA models were generated and simulated in nonuniform and nonhomogeneous conditions after selecting the loading and boundary conditions.

4.1 Investigation of Material Properties. The tensile test technique was used to investigate the MPs of the tank, which is divided into three regions: toroidal shell, weld, and inner ring (see Fig. 2). From each region, tensile test specimens A, B, C, and D were cut out in the directions (see Fig. 2) drawn by a chalk shown in Fig. 5, and the corresponding engineering stress-strain (ESS) data were obtained. The orientations of the tensile test specimens for each region are also shown in Fig. 2. These data were converted to relevant true stress-strain data using well-known empirical equations, illustrated in Fig. 5. The mechanical properties of these three specimens A, C, and D are given in Table 1.

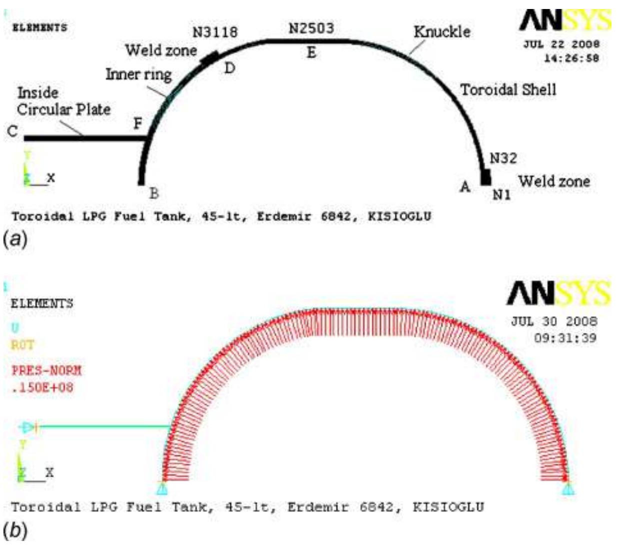
4.2 Thickness Variations. The toroidal shell thickness varies due to the spinning process mentioned above so that the thickness variations were also investigated by measuring from the full cross-sectional geometry of the tank, as shown in Fig. 2. The measurements were done using a micrometer having a precision of 0.001 mm in both "point-by-point" and "by-sliding" on the surfaces. A total of nine different thicknesses were measured from nine different points of the toroidal tanks (see Fig. 2). The measured thicknesses were obtained slightly higher than the nominal thickness of Erdemir 6842 blank steel sheet [14] (see Fig. 6). In fact, the steel is manufactured within the thickness tolerances of the sheet as well. Therefore, the thickness variation in percentage of the nominal tank thickness is revealed as a function of shell regions, as illustrated in Fig. 6. On the other hand, the weld deposits were generally formed quite uniform to assemble the tank. From the full cross-sections, the average thickness value of the weld deposit was measured about 6.35 mm with the micrometer.

4.3 Development of the Nonuniform Nonhomogeneous Model. Nonuniform FEA model was constructed using the thickness variation and applying to relevant zones, as illustrated in Fig. 7. To apply nonuniform wall thickness concepts in the modeling, the wedge function technique [3] was applied. On the other hand, different types of the MPs were applied nonhomogeneously to relevant shell regions on the model. Therefore, the nonhomogeneous FEA models consist of three different types of MP, toroidal shells including knuckle region, weld zone, and inner ring, which are applied on both plane and shell models, as seen in Figs. 7(*a*) and 7(*b*), respectively. The nonhomogeneous plane FEA model has 2764 elements and 6413 nodes. Similarly, the shell model has 89 elements and 90 nodes, respectively.

The midsurface of the wall thickness is considered to create the 2D FEA shell model of the toroidal LPG tank (see Fig. 7(*b*)). Preliminary investigations were carried out to select the most suitable shell element from the ANSYS element library, and the SHELL51 element was used. The element has two nodes and four degrees of freedom at each node: three nodal translations are in the x-, y-, and z-axes and one nodal rotation is in the z-axis [15]. Similarly, to create the 2D FEA plane model, the LPG tank is generated as full section of the tank using its half symmetry, as seen in Fig. 7. A suitable 2D plane element, PLANE2, was selected to create the plane model. The element has six nodes and

Table 1 Mechanical properties of tensile test specimens of the torus tank material

Specimen	Tensile yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
Mechanical properties of torispherical LPG fuel tanks			
A	408	690	18
C	296	410	20
D	301	413	25



(*a*)

(*b*)

Fig. 7 Nonuniform nonhomogeneous axisymmetric FEA: (*a*) plane and (*b*) shell models

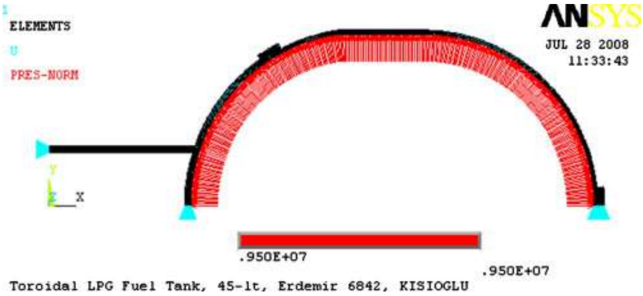


Fig. 8 The axisymmetric boundary and loading conditions

two degrees of freedom at each node, which are nodal translations in x- and y-axes [15].

4.4 Selection of Boundary and Loading Conditions. The structure of the toroidal LPG tank considered here was axisymmetric with respect to both main axes of the torus geometry and with respect to applied load. The 2D axisymmetric FEA model was developed by using half symmetry without valve slot (see Fig. 2). Initially, it was assumed that the valve hole located at the inside body of the torus have no affects on the BP values. The axisymmetric boundary conditions were applied to the nodes located on both x- and y-axes of the FEA models, as shown in Fig. 8.

The LPG tanks were subjected to incremental internal uniform pressure to determine the BP and define the behavior of the shell structures in the simulations. Initially, the internal pressure was applied incrementally and linearly increased 0.1 MPa per step. The loading incremental internal pressure was applied as a function of loading time and gradually increased up to critical pressure value. When the loading time reaches a critical pressure value, the bifurcation state takes place and then the structure of the tank achieves maximum deformation. As the incremental loading step increases, the internal pressure decreases to a value lower than 0.1 MPa per step, such as 0.001 MPa, then the loading time reaches bursting so that the point is called burst time of the tanks.

4.5 Burst Failure Analysis and Failure Locations. To determine the BP and its failure location predicted by the FEA simulations, the values of some variables, such as loading conditions, deflections, and equivalent stresses, can be considered. The loading conditions explained above are defined during the simulations. Additionally, the structural behavior of the tank model was observed using the maximum deflections, as illustrated in Fig. 9. To illustrate this, two nodes were selected from critical places of the model (see Fig. 7). The nodal displacements of the selected points of the plane model were plotted as a function of loading time, as shown in Fig. 10. The nodal displacement shows the nonlinear behavior during the loading time from beginning to point "a" and then the behavior converts suddenly from nonlinear to linear (between points a and "b"). Therefore, the structural behavior is changing rapidly from nonlinear to linear at the loading time of 8.77 MPa at which the toroidal LPG tank is burst. In addition, to predict the BP in the simulation, it was noted that the FEA simulation process does not converge after the loading time of 8.77 MPa while the simulation flow is running as a function of loading time.

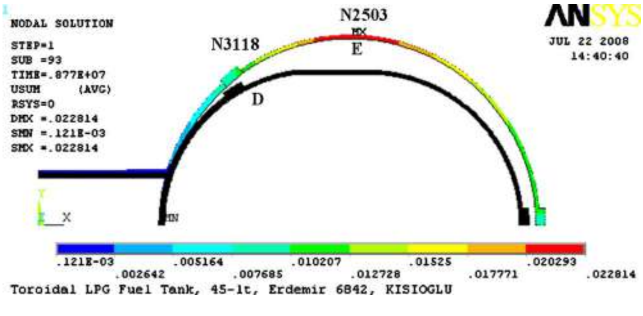


Fig. 9 Max deflections (burst deflection) of the LPG tanks

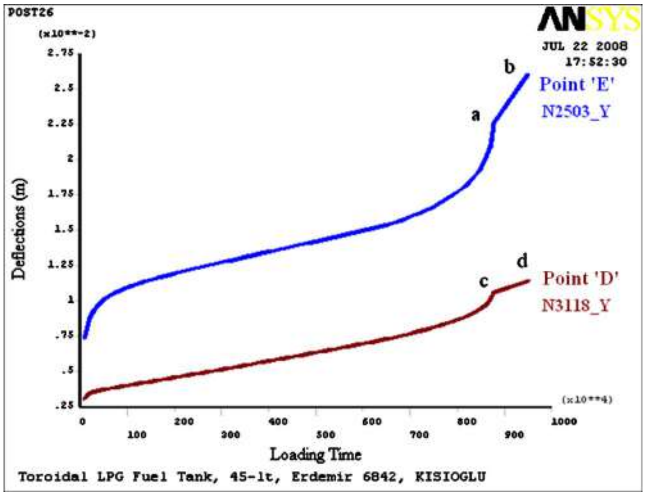


Fig. 10 Nodal deflection of selected nodes of the LPG tanks

The equivalent stress (von Mises stress) results were considered to evaluate the burst failure of the tank using the FEA plane model, as seen in Fig. 11(*a*). The maximum stress value was obtained at the junction of the toroidal shell and inner ring at point "D" and compared with the tank MPs, as shown in Fig. 11(*a*). Similarly, the maximum equivalent stress values were also obtained from the FEA shell model, as illustrated in Fig. 11(*b*). Based on the maximum equivalent stress value found at the same failure location at point D defined with a node number of N49 on the shell model (Fig. 11(*b*)), the burst failure location is complied with the plane model and experimental results. Therefore, the maximum stress value of 412 MPa on the plane model (Fig. 11(*a*)) and 1150 MPa on the shell model (Fig. 11(*b*)) were found

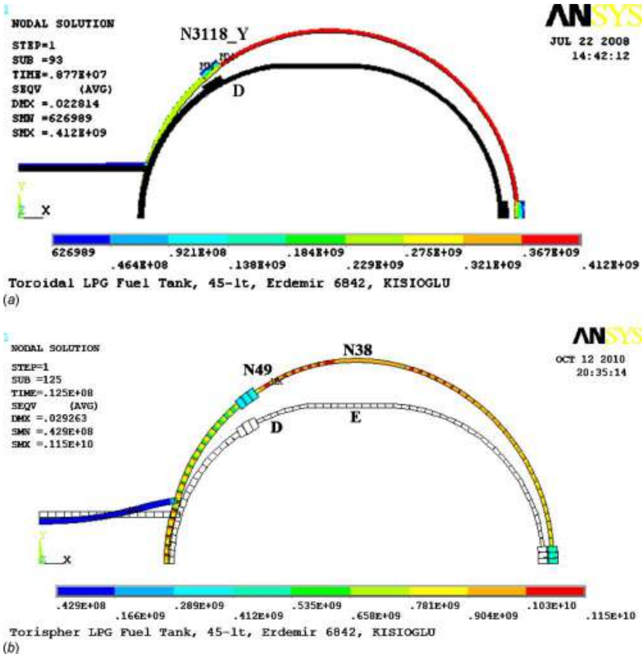


Fig. 11 The maximum equivalent stress of the toroidal LPG tanks: (*a*) plane and (*b*) shell models

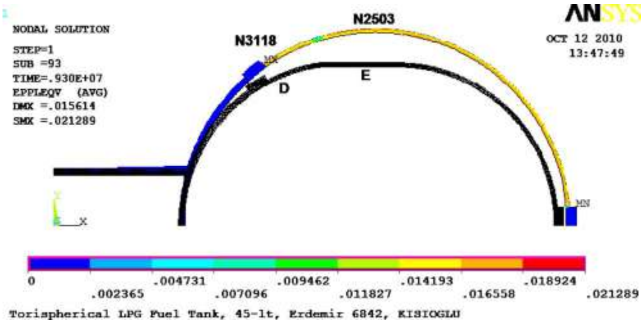


Fig. 12 The maximum nonlinear equivalent plastic strain of the toroidal LPG tanks

greater than the given ultimate tensile stress of 410 MPa of the actual shell material (see Table 1). Besides, to analyze the burst failure of the tank, the nonlinear equivalent plastic strain results, as seen in Fig. 12, were also used and compared with corresponding MPs. The maximum plastic strain was obtained about 21.289% at the instant of burst (Fig. 12), and this was higher than the given elongation of the actual shell material, which was about 20% (see Table 1).

The burst location of the LPG cylinders is well-known by the experimental burst tests (see Fig. 3(*b*)). Burst fracture occurs at the junction of the toroidal shell and weld zone shown with point D, as shown in Fig. 7, that can be defined as the burst failure location of the toroidal LPG fuel tanks since the maximum equivalent stress and strain occur at this point based on the failure criteria [16]. This point is also shown by the node number "N3118" of the FEA plane model and "N49" of the FEA shell model, as seen in Figs. 11(*a*) and 11(*b*), respectively. In the experimental studies, the tank specimens were also fractured at the same location in such a way that the burst crack continues circumferentially about the toroidal axis, as illustrated in Fig. 3(*b*).

5 The BP Results

The BP values were obtained from the FEA simulations for toroidal LPG tanks having the design parameters aforementioned and compared to corresponding experimental values (see Fig. 4) for validation. The BP values from both plane and shell FEA models were obtained very close to the experimental results. Therefore, the BP values of the toroidal LPG tank were obtained about 8.77 MPa (see Figs. 10, 11(*a*), and 11(*b*)), which was close to the mean BP value (8.50 MPa) of the experimental studies (see Fig. 4). These results are higher than the 9/4 times the TP value of the tank and comply with the code requirements.

6 Conclusions

The case of thin-walled vehicle toroidal oval cross-section LPG fuel tanks subjected to an incremental internal pressure to determine the exact BP and burst failure location were studied using both experimental and computer-aided FEA approaches. The axisymmetric 2D FE models having nonuniform geometries and nonhomogeneous MPs were developed and simulated in the nonlinear field. Based on the generated results, the following conclusions can be made.

- Good agreement between the experimental burst and the corresponding nonlinear axisymmetric FEA simulations was found about the BP values and their failure locations. The BP values of the toroidal oval-section LPG fuel tank were obtained about 8.77 MPa (Figs. 9, 11(*a*), and 11(*b*)), which is close to the mean BP value, 8.50 MPa, of the experimental ones (Fig. 4). These values were obtained higher than the 9/4 times the TP value of the torus tank and also confirmed the code regulations.
- The actual toroidal shell and weld zone MPs including wall thickness variations were well specified in this study and successfully adapted into the ANSYS computer code. Additionally, the behavior of incremental internal pressure loading was applied successfully and remained linear about 95% of the loading time. This shows that the simulation process was performed completely in the nonlinear field as mentioned above.

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