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Strength performance evaluations of vehicle cylindrical lpg tanks

Taşıt silindirik lpg tanklarının mukavemet performans değerlendirmeleri

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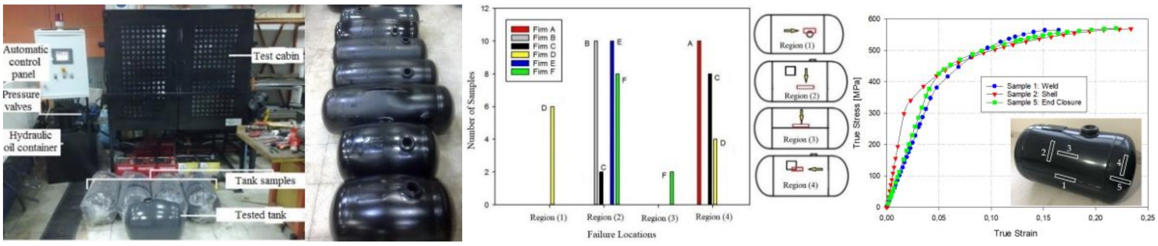
Strength Performance Evaluations of Vehicle Cylindrical LPG Tanks

Highlights

- *The safety strengths of all brand vehicle cylindrical LPG tanks were investigated.*
- *Validated use of a new universal test bench developed for burst and fatigue tests.*
- *This study showed that some manufacturers must review their design processes in terms of safe strength.*
- *The results of study can be used as a guide for manufacturers and customers to select the safety product.*

Graphical Abstract

Vehicle cylindrical LPG tanks were evaluated in terms of burst and fatigue performance. Burst pressures, fatigue cycle numbers and failure regions were investigated comparatively.



(a) (b) (c) (d)

Figure. (a) Test bench (b) Burst tank specimens (c) Tank failure locations (d) Material properties

Aim

This study aims to examine and compare the strength performances of vehicle cylindrical liquefied petroleum gas (LPG) tanks produced and used in Turkey, taking into account European and Turkish Standards.

Design & Methodology

The LPG tanks were subjected to burst and fatigue tests to explore their burst pressures and fatigue performances using both experimental and computer aided techniques.

Originality

To investigate the strength of the tanks, a universal test bench was developed and calibrated for use in both burst and fatigue tests. The obtained experimental results in terms of burst and fatigue failure locations for each brand of tank are compared with the results obtained using finite element based simulations. Visual solid models in 3D were drawn in SolidWorks and then ANSYS software was used to perform FEA simulations on those LPG cylinders to obtain the results, such as stresses, deformations, burst and fatigue failure locations.

Findings

As a result of this comparison, it has been observed that some brands of cylindrical LPG tanks are more durable and safe for use in vehicles. Since the same standard requirements and the same commercial material are used in LPG tank production, it is revealed that some companies need to reconsider their design, manufacturing and especially welding processes.

Conclusion

The results of this independent and objective study can also be used as a warning for LPG tank manufacturers and a guide for their customers in choosing safe products.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Strength Performance Evaluations of Vehicle Cylindrical LPG Tanks

Research Article

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ABSTRACT

This study aims to examine and compare the strength performances of vehicle cylindrical liquefied petroleum gas (LPG) tanks produced and used in Turkey, taking into account European and Turkish Standards. The LPG tanks were subjected to burst and fatigue tests to explore their burst pressures and fatigue performances using both experimental and computer aided techniques. To investigate the strength of the tanks, a universal test bench was developed and calibrated for use in both burst and fatigue tests. The obtained experimental results in terms of burst and fatigue failure locations for each brand of tank are compared with the results obtained using finite element based simulations. Visual solid models in 3D were drawn in SolidWorks and then ANSYS software was used to perform Finite Element Analysis (FEA) simulations on those LPG cylinders to obtain the results, such as stresses, deformations, burst and fatigue failure locations. As a result of this comparison, it has been observed that some brands of cylindrical LPG tanks are more durable and safe for use in vehicles. Since the same standard requirements and the same commercial material are used in LPG tank production, it is revealed that some companies need to reconsider their design, manufacturing and especially welding processes. The results of this independent and objective study can also be used as a warning for LPG tank manufacturers and as a guide for their customers in choosing a safe product.

Keywords: Vehicle cylindrical lpg tank, burst test, fatigue performance test, finite element analysis, nonlinear failure analysis.

Taşıt Silindirik LPG Tanklarının Mukavemet Performans Değerlendirmeleri

ÖZ

Bu çalışma, Türkiye'de üretilen ve kullanılan araç silindirik sıvılaştırılmış petrol gazı (LPG) tanklarının dayanım performanslarının Avrupa ve Türk Standartları dikkate alınarak incelenmesi ve karşılaştırılmasını amaçlamaktadır. LPG tankları, hem deneysel hem de bilgisayar destekli teknikler kullanılarak patlama basınçlarını ve yorulma performanslarını belirlemek için patlama ve yorulma testlerine tabi tutulmuştur. Tankların mukavemetini araştırmak için üniversal bir test tezgahı geliştirilmiş ve hem patlama hem de yorulma testlerinde kullanılmak üzere kalibre edilmiştir. Her bir tank markası için patlama ve yorulma hasar konumları açısından elde edilen deneysel sonuçlar, sonlu elemanlar tabanlı simülasyonlar kullanılarak elde edilen sonuçlarla karşılaştırılmıştır. SolidWorks'te 3B olarak görsel katı modeller çizilmiş ve ardından gerilimler, deformasyonlar, patlama ve yorulma hasar konumları gibi sonuçları elde etmek için bu LPG silindirleri üzerinde Sonlu Elemanlar Anallizi (FEA) simülasyonları gerçekleştirmek için ANSYS yazılımı kullanılmıştır. Bu karşılaştırma sonucunda bazı marka silindirik LPG tanklarının araçlarda kullanım için daha dayanıklı ve güvenli olduğu gözlemlenmiştir. LPG tankı üretiminde aynı standart gereklilikleri ve aynı ticari malzeme kullanıldığından, bazı firmaların tasarım, imalat ve özellikle kaynak proseslerini yeniden gözden geçirmeleri gerektiği ortaya çıkmaktadır. Bu bağımsız ve objektif çalışmanın sonuçları, LPG tank üreticileri için bir uyarı ve müşterileri için de güvenli ürün seçiminde bir rehber olarak da kullanılabilir.

Anahtar Kelimeler: Taşıt silindirik lpg tankı, patlama testi, yorulma performans testi, sonlu elemanlar analizi, nonlineer hasar analizi.

1. INTRODUCTION

Although high emission rates, harmful to the environment and human health and causing a heavy burden to the economy due to high oil prices, vehicles are widely used in passenger and freight transportation all over the world [1]. Liquefied petroleum gas (LPG), a hazardous materials, is widely used as an alternative fuel for vehicles with internal combustion engines in Europe, Turkey and many other countries. Pressurized containers (tanks) are designed and manufactured in two different geometries, cylindrical and torispherical (rarely spherical), to store and/or transport the LPG material and used in vehicles for storage. The safe performance of pressure cylinders is crucial, especially when they carry or store hazardous materials. The magnitude of the working (service) pressure of the cylinders is supported by an additional safety factor which can vary in different applications. Those tanks

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are designed and manufactured by six different manufacturers over 75,000 tanks annually and put in service based on Economic Commission for European Regulation (ECE-R67 or EN 12805) [2] in Europe and Turkish Standards (TS 12095-1) [3] in Turkey. In Turkey and many other nations, it has been translated into related languages and is employed in production as being exactly the same as the European standard. Thus vehicle LPG tanks produced in Turkey according to the same European standard can be exported to many countries of the world and used in vehicles. They come in different sizes ranging from capacities of 30 liters (l) of water to 80 liters (l). The nominal design parameters of these cylindrical tanks can be defined as internal diameter, ID, shell thickness, t, and in different cylinder lengths, L. They are used repeatedly by being filled under a pressure of 3.44 MPa (34.4 bar) with the help of a two-way hermetic valve.

There is no study in the current literature about strength performance evaluations of the vehicle cylindrical LPG tanks of all brands designed and manufactured in Turkey considering the relevant standards. The burst pressures (BP) and burst failure zones of the cylindrical LPG tanks produced by one company [4] and cylindrical shell intersections [5] were determined using experimental and simulation techniques. Numerical predictions were made for the pressure vessels' deformation features [6], elastic behavior of a long tube [7] burst pressures [8, 9], dynamic burst pressures, and average shear stresses [10]. Metallurgical failures of the pressure vessels [11, 12], the BP values of torispherical LPG tanks [13, 14], and household 2 l volume of LPG cylinders [15] were studied using both experimental and simulation techniques. The BP values of shallow spherical and torispherical caps [16], steel toriconical shells [17], and large diameter-to-thickness ratio thin-walled steel cylinders [18] were computed using both experimental and numerical studies. The BP of pipelines [19], strain distributions and the BP [20], and explosion burst tests [21, 22] of the pressure cylinders were calculated analytically. The BP [23] and fracture failures [24] of the LPG cylinders were studied. Fault detection [25] and the wall thickness reductions [26] for the LPG cylinders were calculated. Metallographic crack propagations [27] and design analysis [28] of the LPG cylinders were studied using computer aided calculations. Fatigue strength performances of both cylindrical and torispherical [29, 30] and the BP along with volume changes [31] of the LPG tanks were investigated.

It should be primarily noted that this research project was carried out for academic research purposes only with the support of Kocaeli University, without involving any commercial LPG tank manufacturer. This study aims to investigate the strength performances of the vehicle cylindrical LPG tanks of all brands manufactured by six different manufacturers. The LPG tanks were produced completely and ready for use and purchased from the domestic commercial markets for tests. The strength performances of the tanks were analyzed using both experimental and computer aided calculations. A PLC (programmable logic control) controlled universal test bench was developed to perform the burst and fatigue tests of the tanks. The obtained results were compared amongst themselves to evaluate their manufacturing qualities and strength for safe operating.

2. MATERIALS and METHODS

2.1. Design Parameters of the Vehicle Cylindrical LPG Tanks

All brand vehicle cylindrical LPG tanks are designed and produced according to ECE-R67 (EN 12805) standards in Europe and TS 12095-1 standards in Turkey. As briefly mentioned above, the cylindrical LPG tanks as depicted in Figure 1 are designed and produced currently by six different manufacturers (all brands). Three different pressures (service, test, and burst) of the tanks are ruled by those standards and used in the design processes. The service pressure (SP) is the working (operating) pressure where the tanks are filled and used in vehicles. The test pressure (TP) is a given design pressure by the codes that is pressure applied and released, after which the permanent volume expansion of the cylinder must not exceed 10% of the original measured volume. Also, the TP is the design pressure (or limit load) that determines the post-production sealing control pressure on which the calculations are based. Finally, the burst pressure (BP) represents the maximum allowable pressure where the LPG tanks can hold internal pressure loading without bursting. On the other hand, the fatigue strength performance of the tanks refers to the number of loading-unloading cycles that can be performed without any crack, failure, or leakage under the SP. Therefore, the BP is specified as at least (9/4) × TP which is set at between (1.2 ~ 2) × SP based on the regulations [2, 3]. As mentioned above, those tanks are the low-pressure cylinders since their SP or operating pressure is lower than 3.44 MPa (500 psi, 34.40 bar) [2-4].

Figure 1. Design components of the vehicle cylindrical LPG tank

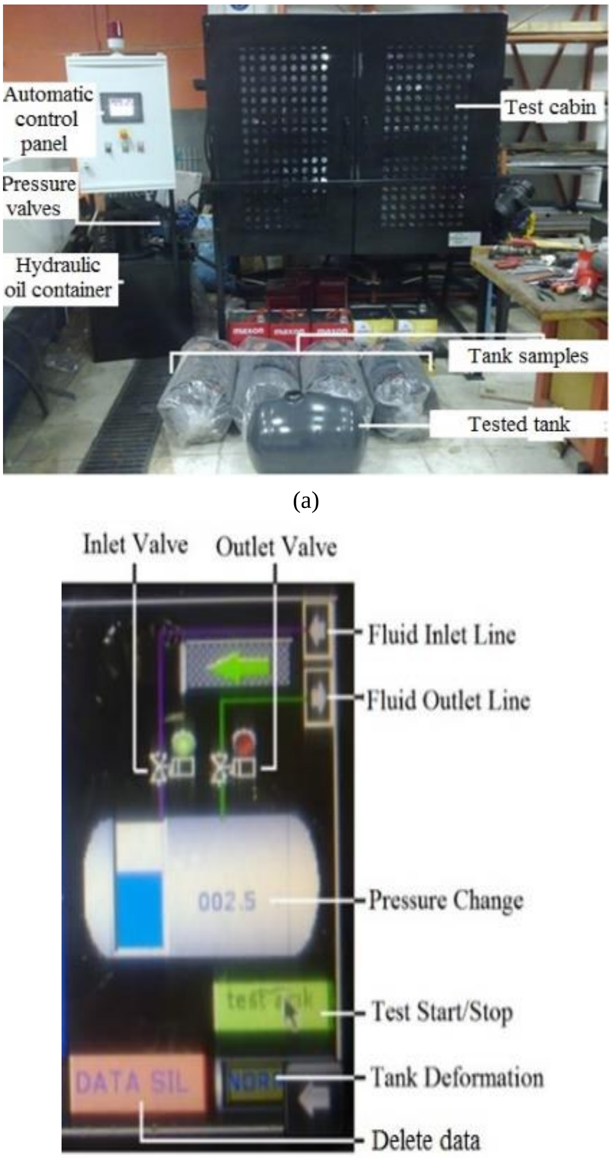
The nominal dimensions of the cylindrical LPG tanks were generally designed with the volume capacity of 40 *l* and 60 *l* including design parameters of inner diameter

(ID) of 315 mm, shell thickness (t) of 2.5 mm and different length (L) ranges from 470 mm to 1135 mm. The cylindrical tanks are consisting of five main components; a cylindrical shell (body), two end-closures, a use/refill nozzle and a tank identity label (see Figure 1). They are generally produced from Erdemir 6842 coded (EN 10120) hot rolled steel sheets with a coming thickness of 2~3 mm [32, 33]. All manufacturers are using the Erdemir 6842 (EN 10120) low carbon (0.18% C) alloy steel material to produce the LPG cylindrical tanks to comply with the Regulations. The average sheet thickness of caming sheet was measured as 2.5 mm at cross-sections of the cylindrical shell (body). The cylindrical shell is produced by bending a rectangular sheet and welded at the ends in axial direction (see Figure 1). The cylindrical shell is closed by two end-closures that are produced by deep drawing (or spinning) process [34] using circumferential arc weld seams at both ends. They are also equipped with an inlet nozzle including a two-way hermetic valve to fill and a tank identity label welded to the body as illustrated in Figure 1. All tanks are subjected to heat treatment process to relieve the residual stresses after all manufacturing processes are finished.

2.2. Experimental Studies

Tank specimens from all brands for the tests were purchased directly from the commercial assembly or authorized installation services with no involving the relevant manufacturers for the independent research purposes and reliable results. Purchasing process of the samples was performed randomly at intervals of several months considering the manufacturer’s production batches. In this study, 120 tank samples from 6 different manufacturers were purchased for both burst and fatigue tests.

To perform the burst and fatigue tests in the same experimental equipment, a servo-hydraulic controlled universal test bench was designed and manufactured as seen in Figure 2.a. The test bench was calibrated and validated by a professional test lab company and it can be pressurized either water or hydraulic oil and managed with a developed PLC interface. The user interface screen (control panel) was designed as seen in Figure 2.b [35]. As seen, one tank can be connected for the burst test and 4-tank can also be connected in parallel simultaneously for the accelerated fatigue tests. That is, both tests can be able to executed hydrostatically using the bench. The burst tests, as well known, can be performed in shorter time than the accelerated fatigue tests. In case of any tank bursting or fatigue failure during test operations, it can be replaced with a new sample without stopping the test operation. The hydrostatic internal pressure was applied with hydraulic oil and recorded tank behaviors depending on the time.



(a)

(b)

Figure 2. (a) PLC controlled servo-hydraulic universal test bench and (b) control panel (user interface)

3. RESULTS

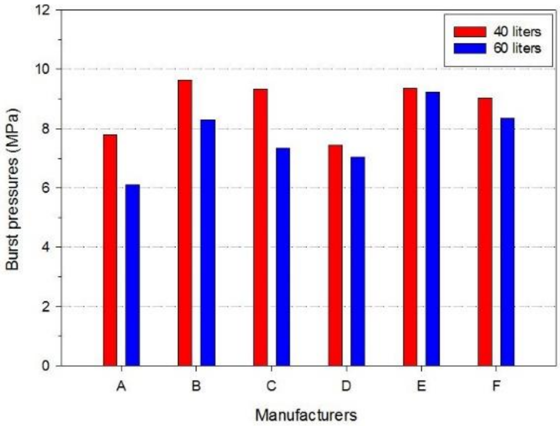
3.1. Experimental Burst Pressures and Failure Locations

In this study, 10 LPG tanks from each manufacturer's products (5 tanks each for 40 *l* and 60 *l*, totally 60 samples) were used for the burst tests only. The specimens were initially loaded by quasi-static internal pressure until they collapsed and subsequently internally pressurized until burst. Figure 3.b shows tanks with a volume of 40 *l* and 60 *l*, which were burst by volumetric expansion (like a barrel) at the end of the experimental study.

The BP values for all tanks were found from the tests and the results are plotted as function of manufacturer names as seen in Figure 3.b. Code names such as A, B, C, etc. were used for each manufacturer instead of the companies' real names and all the results were presented by categorizing them according to those codes. The results were calculated as average values of each 5-test. Letters A, B, C, D, E, and F were used as code labels for the manufacturers. As seen, the highest and the lowest BP values of 9.64 MPa and 7.44 MPa were found for the 40 *l* tanks produced by the firms B and D, respectively. Similarly, the highest and the lowest BP values of 9.22 MPa and 6.10 MPa were calculated for the 60 *l* tanks produced by the firms E and A, respectively.

(a)

Figure 3. (a) Burst tank specimens



(b)

Figure 3(continue). (b) burst pressure values of the 40 *l* and 60 *l* cylindrical LPG tanks

Burst failure locations (BFL) were also obtained generally in four different regions as shown in Figure 4. As seen, the regions where the BFL appeared on the tanks can be defined as; nozzle weld zone (1), cylindrical shell (2), cylindrical shell-weld seam (3), and identity label weld zone (4). That is; The region (1) is the cylindrical shell by nozzle weld seam, the region (2) is the cylindrical shell (body) where the failure crack occurs in axial direction, the region (3) is the cylindrical shell by longitudinal weld seam, and finally, the region (4) is the cylindrical shell by identity label plate weld seam (see Figure 1). The identity plate is designed as a rectangular plate having 2.5 mm thickness that contains info about the tank and producer, such as production date, tank volume, company name, etc. Therefore, most burst failures occurred as ruptured in cylindrical shell region (2) and torn in the axial direction of the cylinder body. Additionally, the majority of the BFL were appeared at regions of (2) and (4). The BFL were also obtained at the weakened areas influenced by welding processes called as heat-affected zone that complied with the BFL criteria defined by [2, 3]. However, two tanks that failed at the region (3) were considered as out of code specifications [2, 3] that indicate the weld seam defects as depicted in Figure 4.

Distribution of the BFL of 30, 22, 6, and 2 specimens after the burst tests were observed at the regions of (2), (4), (1), and (3), respectively, as illustrated in Figure 4. As seen, all tanks produced by the companies of A, B, and E were burst at the regions of (4), (2), and (2), respectively. In addition, 8 tanks produced by each firm of C and F were burst at the regions of (4) and (2), respectively. Also, 6 tanks produced by firm D were burst at the region of (1) and the rest of the tanks were burst at different regions. As can be seen from distributions, the BFL were happened generally at the regions of (2) and (4) that the hoop stress plays an important role as defined in EN 12805 standards and literature [2-4, 9,12].

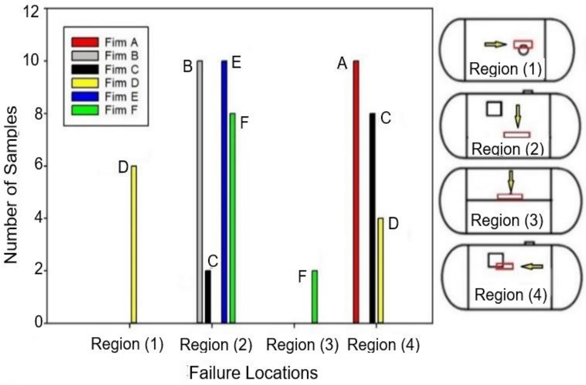


Figure 4. The BFL distributions for the LPG tanks produced by all firms

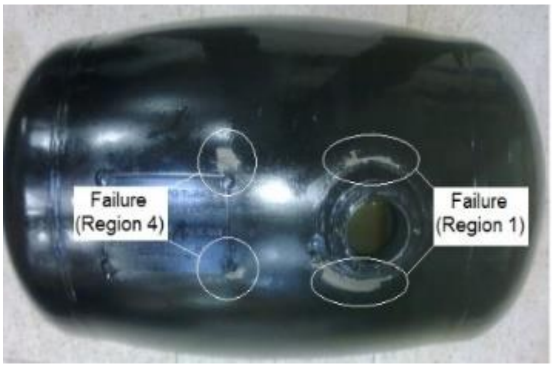


Figure 4(continue). The BFL distributions for the LPG tanks produced by all firms

3.2. Experimental Fatigue Tests and Failure Locations

Similarly, 10 LPG tanks from each manufacturer's products (5 tanks each for 40 *l* and 60 *l*, so totally 60 samples) were used for the accelerated fatigue performance tests. The universal test bench was operated continuously in the lab. and the tanks were subjected to cyclic internal pressure. Variable internal pressure (zero-based cyclic load) was applied to 4 specimens connected in parallel at the same time. When one of the tanks is failed during the cyclic loading processes, it can be replaced with a new specimen without stopping test operation. The fatigue tests were applied at a frequency of 0.25 Hz. and zero-based pressure cyclic load ranging from 0 MPa to 1.75 MPa (0 - 17.5 bar) [2, 3]. As well known, the cyclic loading process was carried out in three phases as fill-and-empty. That is; the tanks are internally pressurized fully in 2-sec. and hold the pressure for 1-sec. and then make the tank fully pressure free (empty) in 1-sec. Therefore, the cyclic loading process was continued until the fatigue failure being happened with hydraulic oil leakage. The fatigue failure locations (FFL) and the number of loading cycles can be decided and marked when the fatigue cracks and oil leakage are happened. Based on these definitions for all brands, the fatigue test results in terms of number of loading cycles for each 40 *l* and 60 *l* tank are given as a function of manufacturers as illustrated in Figure 5.

The 40 *l* tanks produced by the firms of A, B, C, D, E, and F were showed an average endurance loads of 25231, 367694, 68290, 330085, 93910, and 81105 cycles, respectively (see Figure 5). Similarly, the 60 *l* tanks manufactured by the A, B, C, D, E, and F companies were indicated strength loads of 33339, 256383, 16407, 121129, 19394, and 68458 cycles, respectively. From the results, the tanks produced by company B showed the highest strength performance with an average of 367694 cycles in 14 and 17 days for the 40 *l* and 60 *l* tanks, respectively. However, the lowest loading cycles of 25231 and 16407 were found in a day and in half a day for 40 *l* and 60 *l* specimens produced by A and C companies, respectively.

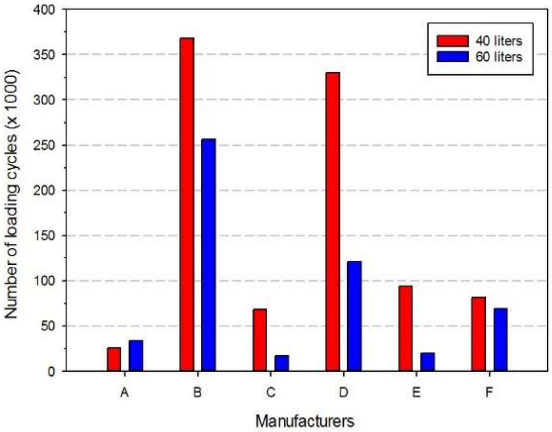


Figure 5. Fatigue loading cycles for the 40 *l* and 60 *l* cylindrical LPG tanks

The fatigue failures are usually happened in a small zone due to repeated loading and begin with small cracks which start the pressurized oil ejection suddenly as shown in Figure 6. That is; The pressurized oil is ejecting from those cracks, e.g. in region (2) where the pressurized tank is failed. The fatigue failure cracks are usually occurred shell by weld seams and continue in parallel to the weld seam. Therefore, fatigue cracks for all tanks are happened shell by weld seams that comply with the relevant standard criteria and engineering based knowledge.

Distributions of the fatigue failures that occurred in four main regions of the tanks are depicted as a function of failure locations in Figure 6. As seen in the diagram, the FFL can be named as; nozzle weld region (1), end-closure weld region (2), cylinder body weld region (3), and tank identity-plate weld region (4). Those regions may be described as slightly different than the regions where the BFL occurred, defined above. That is; the regions (1), (3), and (4) are on the cylindrical shell by weld seams, but the region (2) is on the cylindrical shell by circumferential weld seam of the end-closures (see Figures 1 and 6). Therefore, it was observed that the fatigue damages occur generally at the junctions of the weld seam and the cylindrical shell that also complied with the relevant standard criteria. Because those areas are the weakest zones of the tanks in terms of thickness and material properties since those regions can be called as heat-affected zones due to welding processes.

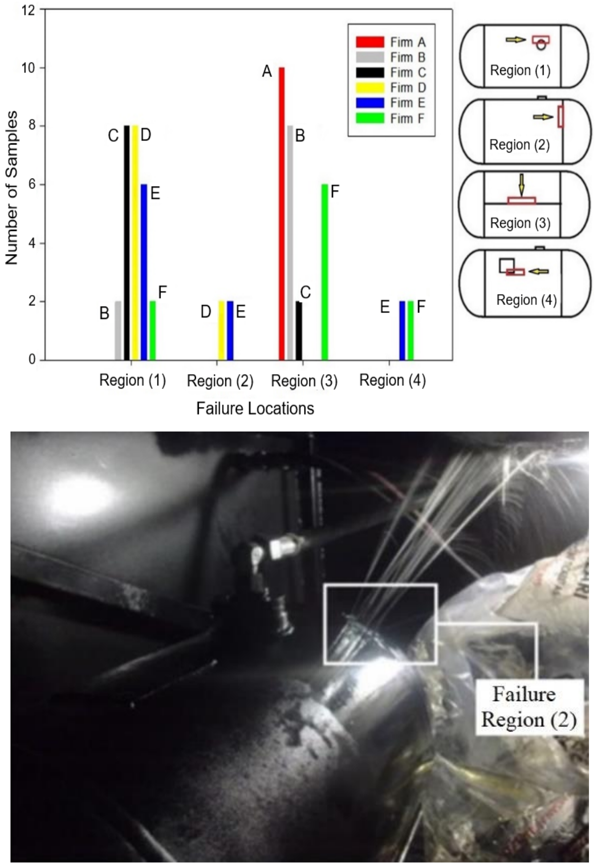


Figure 6. Failed location and distributions of failed zones of the tanks

3.3. Finite Element-based Analysis

Two different forces, limit and plastic, can serve as an important part of tank structural integrity during internal pressurizing under anticipated design conditions. The limit load is the maximum load satisfying equilibrium between external and internal forces when assuming the small deformation theory. The plastic load is the load requiring more complex analysis when including large deflection effects and material strain hardening. The tanks may exhibit geometrical strengthening and/or weakening when considering the large deflections, but plastically deformed tanks can support stresses greater than yield stress when including strain hardening conditions [17].

Both 40 *l* and 60 *l* tanks were also subjected to hydrostatic burst and fatigue failure tests using the computer aided finite element analysis (FEA) to compare with the experimental results. To simulate the LPG tanks, the mechanical properties of EN 10120 hot-rolled steel material, Erdemir Co., Turkey, were adapted into ANSYS Workbench for the FEA processes. The geometric modeling of the tank was prepared using SolidWorks software and then transferred into the ANSYS Workbench to create the FEA models. Yield and ultimate stresses of the EN 10120 material were given as 265 MPa and 410 MPa, respectively, by Erdemir Co. considering the ASTM A730 standard. Six manufacturers of the LPG tanks are using the EN 10120 material to produce the tanks that is compatible with the ECE-R and TS rules [2, 3, 32, 33].

Tensile tests were used to determine the characteristic properties of the LPG tank material. Tensile test samples were taken from 5 different critical locations of the LPG tanks, ready for service as shown in Figure 7. As seen, the test samples were taken in different directions to determine more accurate material properties of the tanks. The obtained tensile test data for the samples taken in the places of 1, 2, and 3 were converted to the true stress-strain data to be used in the simulations [35].

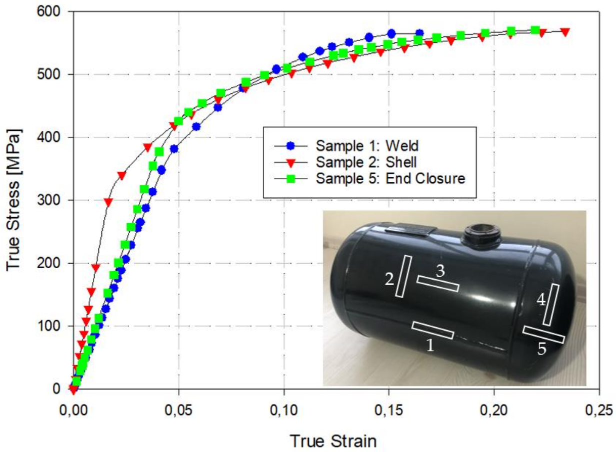
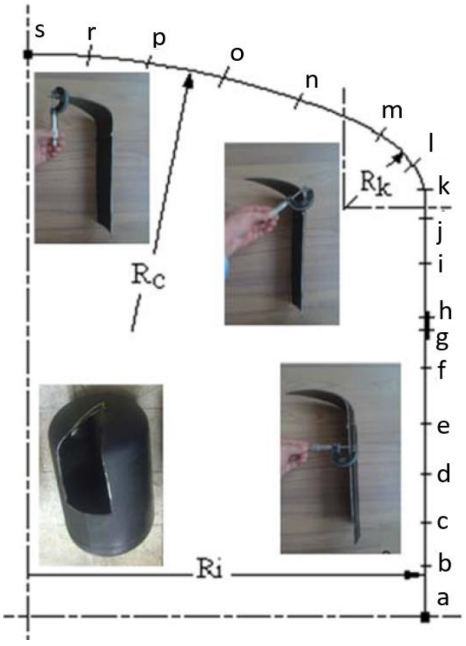


Figure 7. Test sample locations and the obtained true stress-true strain curves

In order to measure the wall thickness of the cylindrical tanks exactly, the cylindrical shell body was cut out to represent the torispherical cap and the knuckle zone (1/16 of the whole tank), as shown in Figure 8.a. These sections were measured accurately point from “a” to “s” with a micrometer to consider in the simulations (Figure 8.b).

(a)

Figure 8. (a) Cross-section of the cylindrical tanks



(b)

Figure 8(continue). (b) determination of thickness by micrometer along the cross section of the LPG tank. *Ri: tank radius, Rc: end-closure radius, Rk: knuckle radius).*

As known, structural discontinuity of the shells especially in the weld zones will cause inaccurate results from the experimental studies. For this reason, test samples were cut out from the LPG tanks including the welding areas in Figure 8a. The cleaner was applied to the surface of the sample at an angle of 45° to clean the weld zones and then the penetrant liquid was applied for 30 minutes to penetrate the cracks (Figure 9). After the penetrant was removed, a developer was used to reveal the penetration-caused discontinuities. Therefore, no discontinuities were found in the weld zones.

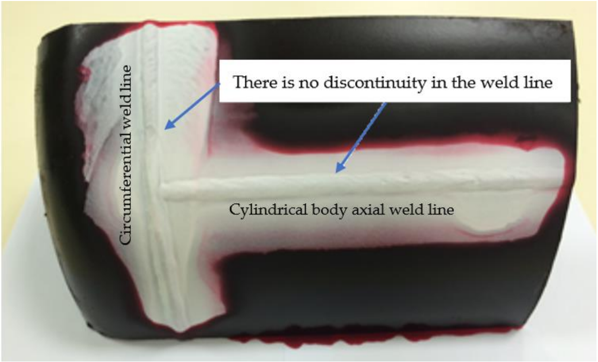


Figure 9. Welding zone sample to measure the discontinuities using penetrant liquid.

3.3.1. The burst pressures and failure locations

The experimental burst tests were also performed in the computer based simulations to validate the results as explained above. Both axisymmetric and whole cylindrical geometrical models were created and used in the simulations. The internal pressure was applied incrementally with 0.01 MPa (0.1 bar) per loading step until the burst failure occurs. Material properties defined by stress-strain data calculated by tensile test techniques were used as input (See Figure 7). The end-closures' estimated thickness variations caused by spinning operations and weld seams were also taken into consideration. Therefore, nonuniform and nonhomogeneous FEA models were created applying the thickness variations and nonlinear material properties, respectively, to achieve the expected results.

Shape changes or volume expansions in both 40 *l* and 60 *l* tanks in response to the applied load were observed and recorded. The obtained burst results from the simulations were given in Figure 10 and compared with relevant experimental burst tests. As seen, the BP limit value of 6.75 MPa (67.5 bar) for both 40 *l* and 60 *l* LPG cylindrical tanks is shown with the horizontal line labelled as EN defined by EN 12805. The calculated BP values in the simulations were also shown with the horizontal lines labelled as “FEA-40 *l*” and “FEA-60 *l*” for both volumes of 40 *l* and 60 *l* tanks, respectively. The BP values from the FEA simulations for all 40 *l* tanks produced by six brands were showed and exceeded the limit value of EN. However, it was observed that the test values of all 60 *l* tanks produced by company A failed considering the EN limit.

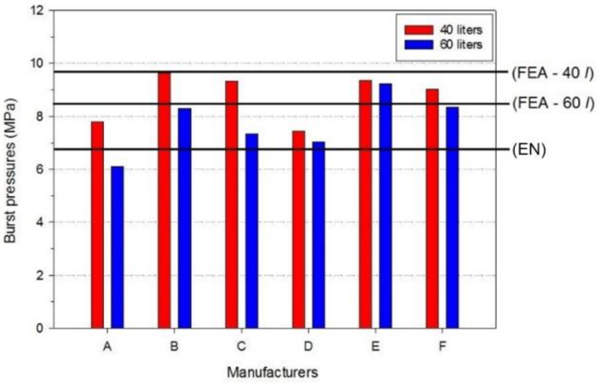
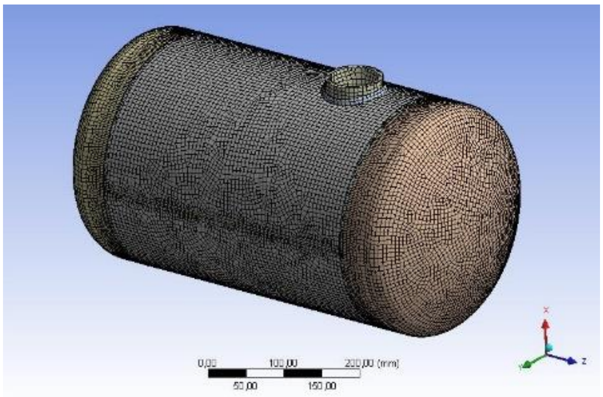


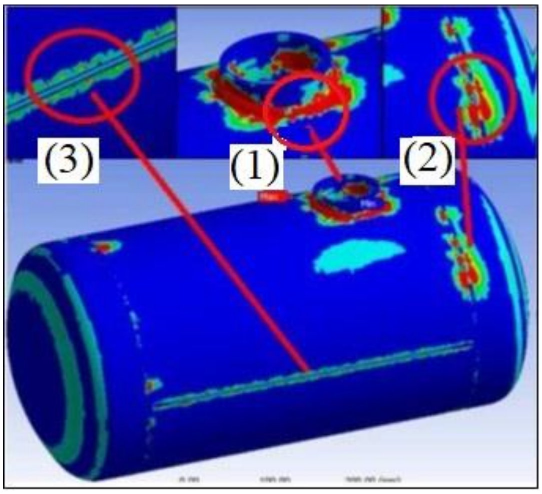
Figure 10. Comparisons of both experimental and FEA simulation BP results considering the EN limit.

3.3.2. The fatigue performances and failure locations

Similarly, all cylindrical LPG tanks were subjected to accelerated fatigue tests to examine their fatigue performances using computer aided simulations. The simulations were performed considering the zero-based dynamic loading conditions to obtain the fatigue failure locations (FFL) and number of loading cycles. The geometrical and material properties of the models were imported into ANSYS Workbench and the S-N data of the structural steel was selected from the ANSYS material library which is close to the EN 10120 steel material. The developed FEA models have consisted of 237727 nodes, 66500 elements (Figure 11.a) and were subjected to zero-based internal pressure loads of 0 ~ 1.75 MPa (0 ~ 17.5 bar). The created finite element models and obtained the FFL from the simulations were illustrated in Figure 11.b. As seen, the FFL generally occurred at the junctions of cylindrical shell weld region (3), nozzle weld region (1), and end-closure weld region (2). The obtained FFL complied with the experimental results given in Figures 6 and 11 as well as EN requirements [2, 3]. As seen, it is seen that the weld seam areas failed first considering the fatigue safety factor distributions on the cylindrical shell weld. It has also been observed that the FFL generally occurred at the junctions of the weld seams and cylindrical shells where the region (3).



(a)



(b)

Figure 11. (a) The finite element model of the cylindrical LPG tank and (b) the failure regions.

The fatigue performance results of both 40 *l* and 60 *l* tank models were obtained and evaluated considering the endurance limits calculated as 366530 cycles and 258120 cycles, respectively. It is realized that those cycles are exceeding the minimum limit of 60000 cycles, required by the EN 12805 rules, shown with the horizontal line labeled as EN illustrated in Figure 12. Considering the limit (EN line), all 40 *l* and 60 *l* tanks produced by the firm A have shown lower fatigue performance than 60.000 cycles. It is seen that the experimental results of the 40 *l* tanks produced by the company B are quite compatible with the FEA results. Thus, boundary conditions (material properties, wall thickness change, tensile tests, application of internal pressure, etc.) for simulation applications were successfully determined and it was confirmed that they were defined as input to the ANSYS program. The fatigue performances of the tanks produced by company D was found close to the experimental fatigue results. However, it was observed that the fatigue strength results of tanks produced by the rest companies were unsuccessful.

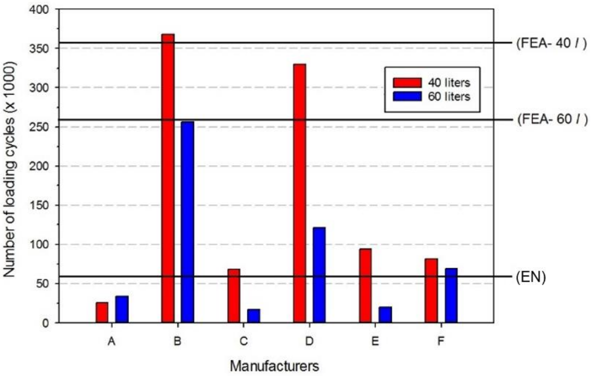


Figure 12. Fatigue performance values (40 *l* and 60 *l*)

The fatigue load cycles were also given in Figure 12 to compare with the required limit for the 60 *l* tanks from the FEA simulations. As seen, the tanks with a volume of 60 *l* produced by company B are also quite compatible with FEA results. The tanks produced by the firms B, D, and F are consistent with the experimental results. However, it was realized that the experimental fatigue performances of tanks produced by the companies A, C, and E could not meet the minimum required limit.

4. DISCUSSIONS

Considering the experimental results in terms of BFLs, 30 tanks were failed from region (2) and 22 tanks were failed from region (4), 6 and 2 tanks were failed from the zones (1) and (3), respectively, (see Figure 4). Most of the BFLs had been observed in regions (2) and (4) due to higher circumferential stresses that comply with the EN 12805 standards. Therefore, the obtained experimental BFL distributions of all tanks are given as a function of regions (see Figure 4). Most of the tested tanks produced by different companies meet the EN 12805 regulations in terms of the BFLs. From the BFL distributions, all tanks produced by the company A burst at the region of (4), and all tanks produced by the companies B and E were burst at region of (2). The rest of the tanks produced by the companies C, D and F were burst at different regions as given in Table 1 and Figure 4.

The BPs of 40 *l* and 60 *l* tanks are listed and compared considering the manufacturers' nicknames as shown in

Tables 1 and 2. As seen, the BP values of all tested 40 *l* tanks produced by all companies were obtained above the minimum BP limit of 67.5 MPa according to EN 12805 [2, 3]. As seen, the strongest and weakest 40 *l* LPG tanks in terms of BP values were produced by companies' B and D, that is; their BP values were found 1.42 and 1.11 times higher than the EN 12805 limit value, respectively. Similarly, the strongest and weakest 60 *l* LPG tanks in terms of BP values were produced by companies' E and D, that is; their BP values were found 1.36 and 1.05 times higher than the EN 12805 limit value, respectively. On the other hand, the BP values of all 60 *l* tanks of Company A remained below the EN 12805 limit value and these tanks did not meet the standard requirements.

When the obtained results in terms of FFL were examined, each of the 26 tanks were failed in regions (1) and (3) (see Figure 6). Similarly, it was also observed that each of the 4 tanks were failed in regions (2) and (4). The most of the FFL have been observed in regions (1) and (3) since the circumferential (hoop) stress is playing an important role for the fatigue failure occurs in axial direction [4, 9, 12, 15, 22]. Distributions of the FFL of all tanks were given as a function of failure regions (see Figure 6). As seen, the FFL of the tanks produced by the company A were occurred in region (3). Eight tanks produced by the firm B were failed in region (3) and the rest 2 of them were failed in region (1). Eight tanks produced by the firm C were failed in region (1) and the rest 2 tanks were failed in region (3). Eight of the tanks

Table 1. The BP and BFL results comparing the standard limit (EN) (40 *l*)

Manufacturers (Brands)	Average BP (MPa)	Failure Regions	Comparison with EN Codes
B	9.6	(2)	1.42
C	9.4	(4)	1.39
E	9.3	(2)	1.38
F	9.0	(2)	1.33
A	7.7	(4)	1.14
D	7.4	(1)	1.11
EN Limit	6.75	(3)	1

Table 2. The BP and BFL results comparing the standard limit (EN) (60 *l*)

Manufacturers (Brands)	Average BP (MPa)	Main Failure Regions	Comparison with EN Codes
E	9.2	(2)	1.36
B	8.3	(2)	1.23
F	8.2	(2)	1.21
C	7.4	(4)	1.1
D	7.1	(1)	1.05
EN limit	6.75	(3)	1
A	6.1	(4)	0.91

Table 3. The fatigue strength and FFL results comparing the standard limit (EN) (40 *l*)

Manufacturers (Brands)	Average number of load cycles	Main Failure Regions	Comparison with EN Codes
B	367694	(3)	6.1
D	330085	(1)	5.5
E	93910	(1)	1.5
F	81105	(3)	1.4
C	68290	(1)	1.1
EN Limit	60000	(3)	1
A	25231	(3)	0.4

Table 4. The fatigue strength and FFL results comparing the standard limit (EN) (60 *l*)

Manufacturers (Brands)	Average number of load cycles	Main Failure Regions	Comparison with EN Codes
B	256683	(3)	4.3
D	121129	(1)	2
F	68458	(3)	1.1
EN Limit	60000	(3)	1
A	33339	(3)	0.6
E	19394	(1)	0.3
C	16407	(1)	0.27

produced by the company D were failed in region (1) and the rest 2 tanks were damaged in region (2). Six tanks produced by the firm E were failed in zone (1) and the remaining 4 tanks were failed in zones (1) and (2), in twos. Finally, it was observed that six tanks produced by the firm F were failed in region (3) and the rest 4 tanks were failed in regions (4) and (1), in twos.

The fatigue strengths of the 40 *l* and 60 *l* tanks were listed and compared considering the brands as shown in Tables 3 and 4. As seen, the fatigue strength values were defined in terms of the loading cycle numbers and the most common FFL. The main FFL were given considering the average cycle numbers and brand names in Table 3. As seen, the minimum fatigue loading cycles for the 40 *l* tanks were reached the required limit in [2, 3]. Based on the results given in Table 3, the best and the weakest 40 *l* LPG tank were produced by the firms B and A, respectively. That is; it was observed that the 40 *l* tanks of the firms B and A were obtained 6.1 and 0.4 times more durable than the minimum required limit, respectively. Similarly, it also recognized that the 60 *l* tanks of the firms B and C were found to be 4.3 and 0.27 times strongest, respectively, considering the minimum required limit (Table 4) [2, 3].

5. CONCLUSION

The burst pressures (BP), fatigue strength performance values and failure locations of both 40 *l* and 60 *l* cylindrical LPG tanks produced by all firms in Turkey were calculated and compared each other considering the ECE-R67 (EN 12805) and TS 12095-1 rules [2, 3]. A universal experimental bench, related fixtures, and PLC interface were developed and validated successfully for both burst and fatigue tests to investigate the strength performances of the LPG tanks. Therefore, the results of the tanks were found employing both experimental tests and FEA simulations. Based on those performed studies, the results can be concluded briefly as follows:

1. By comparing the BP and fatigue performance values of the vehicle cylindrical LPG tanks with a volume of 40 *l* and 60 *l* produced by six companies, a safer product was determined according to the European and Turkish Standard criteria. However, a few companies must review their design and manufacturing processes for their LPG tanks in terms of burst and fatigue strengths (see Figures 4, 5, 10, and 12).
2. It can be stated that the LPG tanks from all companies has fulfilled the relevant standard criteria except brand A considering the BP values and BFL (see Figures 3 and 4). The companies A and C must re-evaluate their design processes used for the cylindrical LPG tanks in terms of both BFL and FFL.
3. The welding seams of the tank identity plate has negative effects on both BFL and FFL. An alternative design application must be recommended for all companies instead.
4. The obtained results can be used as a guide to select a safer LPG tank for customers.

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DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS’ CONTRIBUTIONS

Arslan KAPTAN: Performed the experiments and analyse the results. Wrote the manuscript.

Yasin KİŞİOĞLU: Performed the experiments and analyse the results. Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Doğan B. “Analysing the performance and working parameters of a CNG compressor prototype designed as a household type”, ***Journal of Polytechnic,*** 19(4): 427-431, (2016).

[2] EN 12805, “BS Automotive LPG Components. Containers”, ***British Standard Institution,*** (2002).

[3] TS 12095-1 EN 12805, “TSE Automotive-Liquefied Petroleum Gas (LPG) System Components-Fuel Tanks”, ***Turkish Standard Institute,*** (2004).

[4] Kaptan A. and Kisioglu Y. “Determination of burst pressures and failure locations of vehicle LPG cylinders”, ***International Journal of Pressure Vessels and Piping,*** 84: 451-459, (2007).

[5] Xue L., Widera G.E.O. and Sang Z. “Burst pressure prediction of cylindrical shell intersection, transactions”, ***SMIRT 19***, Toronto, (2007).

[6] Lee H.S., Yoon J.H., Park J.S. and Yi Y.M. “A study on failure characteristic of spherical pressure vessel”, ***Journal of Materials Processing Technology,*** 164: 882-888, (2005).

[7] Akış, T. and Eren Ö. “Yielding of radially pressurized functionally graded long Tubes based on Von Mises criterion”, ***Journal of Polytechnic,*** 18(2): 63-71, (2015).

[8] Brabin T.A., Christopher T. and Rao B.N. “Bursting pressure of mild steel cylindrical vessels”, International ***Journal of Pressure Vessels and Piping,*** 88(2-3): 119-122, (2011).

[9] Aksoley M. E., Ozcelik, B. and Bican, I. “Comparison of bursting pressure results of LPG tank using experimental and finite element method”. ***Journal of hazardous materials,*** 151(2-3): 699-709, (2008).

[10] Chen Z., Li X., Wang W., Yang H., Guo Z. and Zhu W. “Dynamic burst pressure analysis of cylindrical shells based on average shear stress yield criterion”, ***Thin-Walled Structures,*** 148: 106498, (2020).

[11] Jha A.K., Sreekumar K. and Sinha P. “Metallurgical failure analysis of the 560 mm dia 0.15 C–1.25 Cr–1Mo–0.25 V steel pressure vessel”, ***Engineering Failure Analysis,*** 17(4): 802-809, (2010).

[12] Lu Z., Cui Y., Xu H., Lin S. and Liang H. “Effect of the length-to-diameter ratio on the burst pressures of thin-walled pressure vessels”. ***Journal of Applied Mechanics and Technical Physics,*** 64(1): 10-17, (2023).

[13] Kisioglu Y. “Burst tests and volume expansions of vehicle toroidal LPG fuel tanks”, ***Turkish Journal of Engineering and Environmental Sciences,*** 33(2): 117-125, (2010).

[14] Kisioglu Y. “Burst pressure determination of vehicle toroidal oval cross-section LPG fuel tanks”, ***Journal of Pressure Vessel Technology,*** 133(3): (2011).

[15] Kartal F. “Evaluation of explosion pressure of portable small liquefied petroleum gas cylinder”, ***Process Safety Progress.*** (2019).

[16] Blachut J. and Vu V.T. “Burst pressures for torispheres and shallow spherical caps”, ***Strain,*** 43: 26-36, (2007).

[17] Błachut J. and Ifayefunmi O. “Burst pressures for toriconical shells: experimental and numerical approach”, ***Journal of Pressure Vessel Technology,*** ASME, 139: (2017).

[18] Wang H., Zheng T., Sang Z. and Krakauer B.W. “Burst pressures of thin-walled cylinders constructed of steel exhibiting a yield plateau”, ***Int. J. of Pressure Vessels and Piping,*** 193: 104483, (2021).

[19] Budhe S., Banea M. and de Barros S. “Prediction of the burst pressure for defective pipelines using different semi-empirical models”, ***Frattura ed Integrità Strutturale,*** 14: 137-147, (2020).

[20] Lohar H., Sarkar S. and Mondal S.C. “Stress analysis and burst pressure determination of two-layer compound pressure vessel”, ***International Journal of Engineering Science and Technology,*** 5: 349-353, (2013).

[21] Gajdoš Ľ. and Šperl M. “Determination of burst pressure of thin-walled pressure vessels”, ***18th International Conference Engineering Mechanics,*** Svratka, Czech Republic, May 14-17, paper # 67: 323-333, (2012).

[22] Wang H., Zheng T., Sang Z. and Krakauer B. W. “Burst pressures of thin-walled cylinders constructed of steel exhibiting a yield plateau”. ***International Journal of Pressure Vessels and Piping,*** 193: 104483, (2021).

[23] Kulkarni A.M. and Wankhade R.L. “Design by analysis of liquid petroleum gas cylinder using Twice Elastic Slope Criteria to calculate the burst pressure of cylinder”, ***International Journal of Engineering Research & Technology,*** 4(1): 561-568, (2015).

[24] Chondrou D., Chondrou I., Panteliou S. and Chondros T. “Household LPG cylinder fracture and a boiling liquid expanding vapor explosion”, ***Известия высших учебных заведений. Машиностроение,*** 9: 54-66, (2019).

[25] Peña S.P., Galvis C. and Quiroga J.E. “Failure detection in a pressure vessel using acoustic emissions technology”, ***Revista UIS Ingenierías,*** 18(4): 147-156, (2019).

[26] Reddy D.D. and Prasad T. “Finite element analysis of LPG cylinder”. ***Advanced Research Journals of Science and Technology,*** 3(1): 140-144, (2016).

[27] Kingklang S., Daodon W. and Uthaisangsuk V. “Failure investigation of liquefied petroleum gas cylinder using FAD and XFEM”, ***International Journal of Pressure Vessels and Piping,*** 171: 69-78, (2019).

[28] Kiran C.S. and Sruthi J. “Design and finite element analysis of domestic LPG cylinder using ANSYS Workbench”, ***CVR Journal of Science and Technology,*** 14: 97-101, (2018).

[29] Kartal F. and Kisioglu Y. “Determination of fatigue life and failure location of vehicle cylindrical LPG fuel tanks”, ***Practical Metallography,*** 53(6): 360-378, (2016).

[30] Kartal F. and Kisioglu, Y. “Fatigue performance evaluations of vehicle toroidal liquefied petroleum gas fuel tanks”, ***Journal of Pressure Vessel Technology,*** 139(4): 041402, (2017).

[31] Oosterkamp L.D. and Heurtaux, F. “New polymorph friction stir welded aluminium liquid petroleum gas tank”, ***Journal of Automobile Engineering,*** 220: 27-35, (2006).

[32] Eregli Iron and Steel Factory TR. Product Catalog. ***https://www.oyakmadenmetalurji.com.tr/sites/1/upload/files/Yassi_Urun_Katalogu_2020_subat-3734.pdf*** (accessed date: 3 February 2023).

[33] EN 10120 European Standard, Steel Sheet and Strip for Welded Gas Cylinders, CEN, ***European Committee for Standardization,*** Brussels, (2008).

[34] Özek C. and Taşdemir V. “Experimental and numerical investigation of the effect of temperature on deep drawing of Aluminum alloy”, ***Journal of Polytechnic,*** 21(1): 193-199, (2018).

[35] Kaptan A. “Examination of burst pressures and fatigue performances of vehicle LPG tanks”, ***Kocaeli University, Graduate School, Ph.D. Thesis.*** (2015).