

Finite Element Method for Creep Testing of High Density Polyethylene Lubricant Oil Bottles

Chakrit Suvanjumrat and Ekachai Chaichanasiri*

ABSTRACT

Stacking is one method for storing many lubricant oil bottles. Bottles on the lower storey may collapse after storage for a long time because of the creep behavior of bottle materials. To avoid bottle collapse, creep testing of the bottle is required to obtain the relation between deformation and the time a bottle is under creep load. This relation can be used to manage the storage time and to improve bottle shape. Unfortunately, the identification of creep resistance for lubricant oil bottles may take more than one month. This is not satisfactory considering the market competition for container products. Therefore, this study used the finite element method (FEM) to simulate the creep behavior of high density polyethylene (HDPE) lubricant oil bottles and compared the experimental results to validate the FEM. Sample 1 L and 6 L bottles with masses of 55 and 310 g, respectively, were tested and simulated. From the results, the overall difference of deformation between the FEM and experimental samples for the 1 L and 6 L bottles was 16.20 and 13.91%, respectively. However, the FEM was able to capture the trend of bottle deformation. The weak points of 1 L and 6 L bottles were the shoulder and the handle of the bottle, respectively. The FEM results can be applied to manage the storage time of lubricant oil with regard to stacking and to developing the design of the lubricant oil bottle as well.

Keywords: finite element method, creep testing, lubricant oil bottle, high density polyethylene (HDPE), stacking

INTRODUCTION

Stacking is one method for storing many lubricant oil bottles. The number of bottle storeys depends on the column crush properties that are determined according to ASTM D2659-95 (2001). However, this standard test method does not specify the top load that bottles must support over a long period. Consequently, the bottles in the lower storey may collapse because of the creep behavior of the bottle materials. This behavior changes the strain of materials under constant load over time. High density polyethylene (HDPE)

is a polymer which is favored in the production of lubricant oil bottles and has been identified as having creep behavior (Ezrin, 1996). The creep resistance of HDPE bottles is determined using test methods according to ASTM D4577-05 (2007). Unfortunately, the identification of creep resistance for lubricant oil bottles may take more than one month. This is not satisfactory considering the market competition for container products.

Analysis of the strength of lubricant oil bottles was made easier with the introduction of Computer Aided Engineering (CAE) software.

The finite element method (FEM) is a very good tool available in CAE software and can be used to specify the limits of endurance of lubricant oil bottles before manufacturing. For example, Thusneyapan and Suvanjumrat (2004) used static FEM to simulate the top load test of lubricant oil bottles. They specified an increase of 2 kg load on the top of HDPE bottles and investigated bottle deformations. The simulation and experimental results were compared to validate the FEM and a good comparison was reported. The top load test simulation of plastic bottles using CAE software has also been of interest to other researchers. Abbes *et al.* (2010) used the ABAQUS FEM software to simulate a cosmetic polypropylene bottle based on the column crush standard conditions. Dijk *et al.* (1999, 2000) simulated top load testing of polyethylene terephthalate (PET) bottles, which contained gas and liquid using the ABAQUS FEM software. The enclosed fluid can contribute significantly to the strength and stiffness of bottles; nevertheless, testing empty bottles is still the safest way to determine bottle design.

The research cited used the FEM to simulate various tests of bottles and did not apply the FEM to analyze creep resistance of lubricant oil bottles. The current study used the FEM to

simulate the creep behavior of HDPE lubricant oil bottles. The simulation results were compared with the experimental results to validate the FEM. The creep simulation accomplished in this study can be used to analyze the creep resistance of plastic bottles before manufacturing and prototyping.

MATERIALS AND METHODS

Creep testing of lubricant oil bottle

In this study, lubricant oil bottles with capacities of 1 L and 6 L were subjected to creep testing (Figure 1). The bottles were made of HDPE grade 6140 plastic and fabricated by the blow-molding method. The creep tests were conducted according to ASTM D4577-05 (2007) which is the recognized standard for determining the resistance of HDPE bottles to constant top loads. Figure 2 shows the apparatus developed for creep testing. The apparatus consisted of a top and bottom plate, steel columns, a known mass and a mass guider. An additional mass was used with the 6 L bottle because the available masses were not sufficient for the test procedure. Ball bearings were installed on the top plate to ensure that there was minimal friction between the top plate and the steel columns.

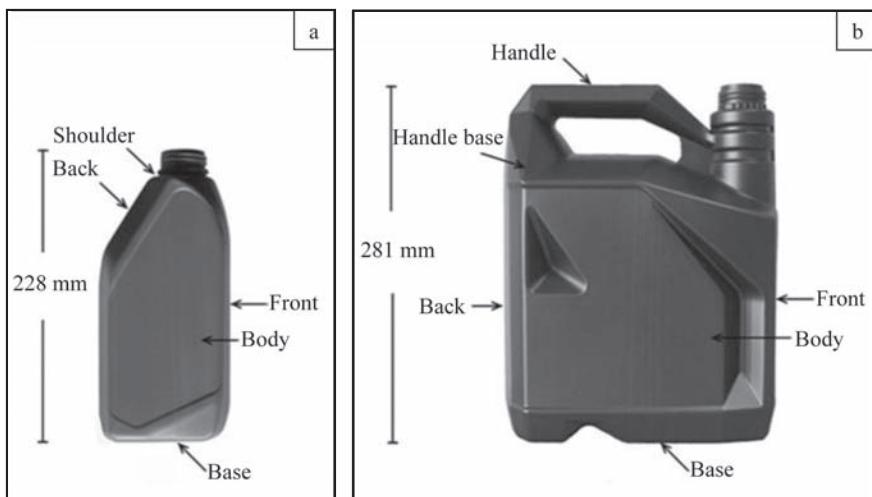


Figure 1 Lubricant oil bottles used for creep testing: (a) 1 L bottle; (b) 6 L bottle.

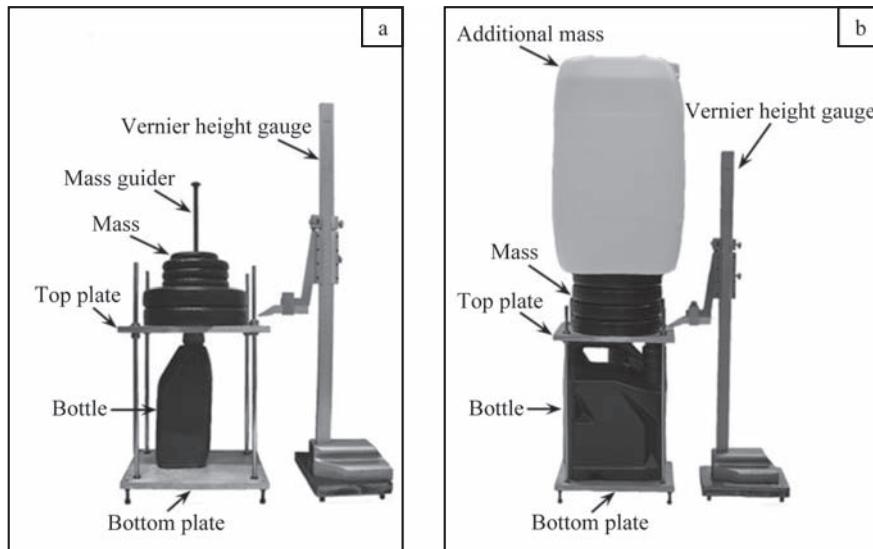


Figure 2 Apparatus constructed for lubricant oil bottle creep testing for: (a) 1 L bottle; (b) 6 L bottle.

The empty bottles with their caps on were inserted between the top and bottom plates. Constant loads were placed on the top plate to compress the bottles for 1 mth. For each bottle capacity, three levels of creep load testing were carried out and each test was repeated three times as shown in Table 1. The deformations of the bottles were measured using a vernier height gauge.

Numerical simulation of lubricant oil bottle creep testing

In the simulation of creep testing, the total strain may contain a creep strain and an elastic strain, which can be defined by Equation 1 (Kraus, 1980):

$$\{\varepsilon\} = \{\varepsilon_E\} + \{\varepsilon_C\} \quad (1)$$

where $\{\varepsilon_E\}$ is the elastic strain matrix and $\{\varepsilon_C\}$ is the creep strain matrix.

The linear elasticity of stress/strain relationship is given by Equation 2:

$$\{\sigma\} = [D] \{\varepsilon\} \quad (2)$$

where $[D]$ is the constitutive matrix.

A typical creep model using the power law can be written as Equation 3:

$$\varepsilon_C = A\sigma^m t^n \quad (3)$$

where t is time and A , m and n are the constants.

Equation 3 can use to determine the increment of creep strain by differentiation with respect to time and can be expressed by Equations 4 or 5:

$$d\varepsilon_C = B\sigma^m t^{n-1} dt \quad (4)$$

Table 1 Load cases for creep testing of lubricant oil bottles.

Bottle capacity (L)	Bottle mass (g)	Bottle dimension (width×height×depth) (mm)	Creep load (N)	Number of samples
1	55	110×228×58	98.1, 132.435, 166.77	9
6	310	240×281×120	392.4, 490.5, 588.6	9

$$\varepsilon_C^{t+\Delta t} = \varepsilon_C^t + B\sigma^m t^{n-1} \Delta t \quad (5)$$

where B is a constant.

The following time integration scheme can be performed by setting $\varepsilon_C = 0$ at time $t = 0$. This gives the nodal displacement and stress at the start of problem by using Equation 2. The time increment is set to calculate the increment of creep strain by using Equation 5. Determination of the new creep strain uses Equation 6:

$$\varepsilon_C^{t+\Delta t} = \varepsilon_C^t + d\varepsilon_C \quad (6)$$

Then, the stress at the end of the time increment is determined. The stresses at the beginning are tested. If they are larger than the limitation that is the yield stress, the time increment is reduced. If the stresses are less than the yield stress another time increment is added and the previous calculations are repeated until a stationary state has been achieved.

The Computer Aided Design (CAD) models of 1 L and 6 L lubricant oil bottles were created as shown in Figure 3. The CAD models were then exported to the MSC Patran program (Version 2010; MSC. Software Corporation; Santa Ana, CA, USA) to create the finite element (FE) meshes. Figure 4 shows the FE meshes of the

lubricant oil bottles. The four-node rectangular elements and three-node triangular elements were used to construct the mesh. The FE mesh of the 1 L bottle consisted of 2,810 rectangular elements, 302 triangular elements and 2,964 nodes. The 6 L bottle FE mesh consisted of 13,196 rectangular elements, 440 triangular elements and 13,417 nodes. The element thickness of the 1 L and 6 L bottles were 0.966 mm and 1.542 mm, respectively. These values were derived from the relation between the mass, surface area of the bottle and the density of HDPE. The FE analysis was performed using the MSC Marc program (Version 2010; MSC. Software Corporation; Santa Ana, CA, USA). For the boundary conditions, the nodal displacements at the bottom of the bottles were fixed. In Figure 2, all top surfaces of the bottle move down simultaneously because of the vertical compression from the top plate. To mimic the experiment, the nodes on the top of the bottle were controlled to move down simultaneously using a so-called RBE2 element, which is a special element available in MSC Marc. The vertical creep loads to simulate the creep test were defined on a conjunction node of RBE2 elements as shown in

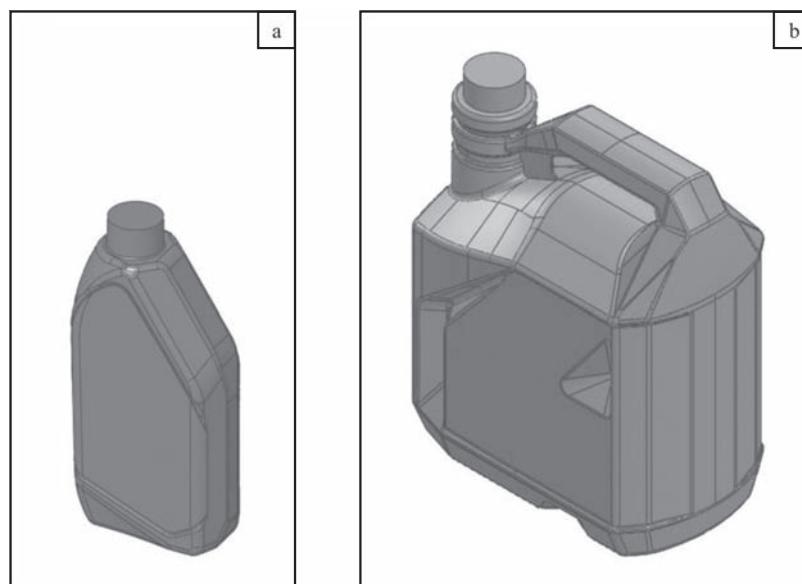


Figure 3 CAD models of: (a) 1 L bottle; (b) 6 L bottle.

Figure 5. The magnitudes of creep load were taken from Table 1. The HDPE material was assumed to be isotropic and elastic. The modulus of elasticity and Poisson's ratio of HDPE are 1,422 MPa and

0.38, respectively and the creep properties were defined by Equation 7 according to the study by Kachonboon and Suvanjumrat (2012):

$$\varepsilon_c = 2.13 \times 10^{-4} \sigma^{2.3} t^{0.169} \quad (7)$$

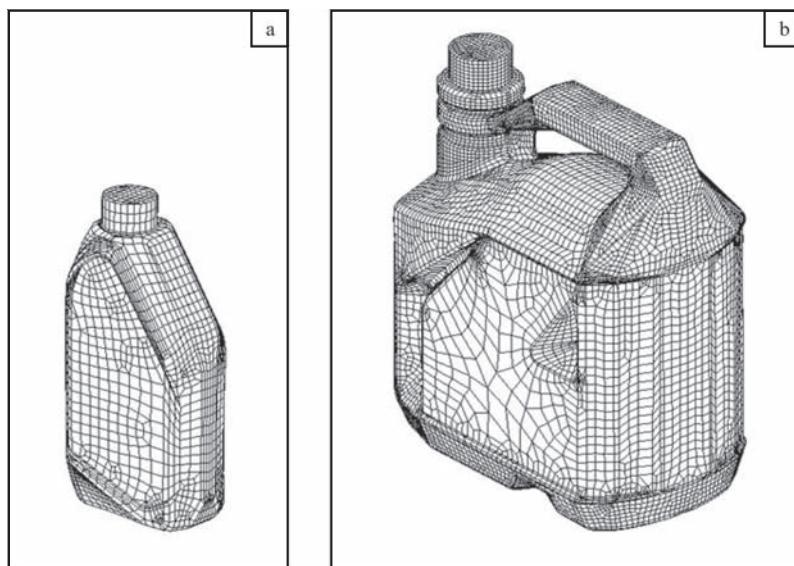


Figure 4 Finite element meshes of lubricant oil bottles: (a) 1 L bottle; (b) 6 L bottle.

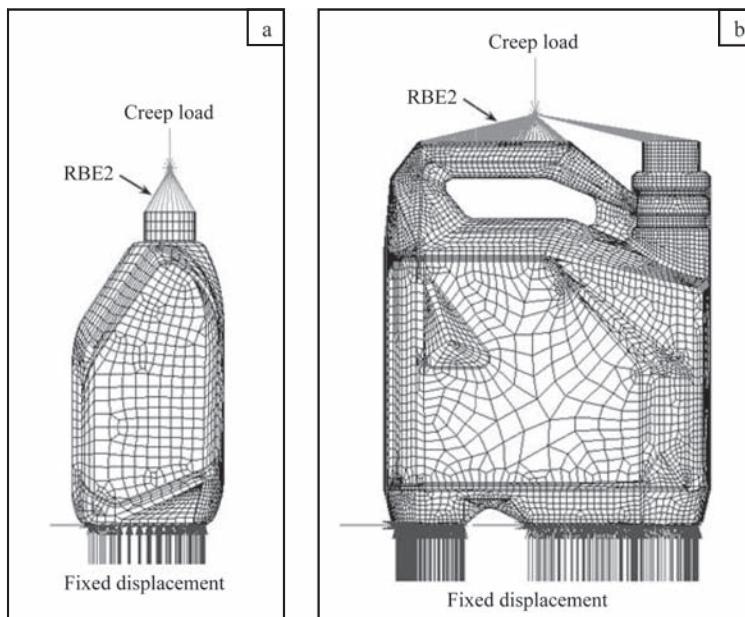


Figure 5 Finite element models of: (a) 1 L bottle; (b) 6 L bottle. (RBE2 = a special element available in the MSC Marc program (Version 2010; MSC. Software Corporation; Santa Ana, CA, USA.)

where ε_c is an actual creep strain, σ is a stress averaged from experiments and t is time. The simulation was performed from $t = 0$ s to $t = 2,592,000$ s (1 mth).

RESULTS AND DISCUSSION

Creep testing of lubricant oil bottle

All 1 L bottles deformed instantaneously when the masses were applied on the top plate of the creep testing apparatus. This instantaneous deformation represented an initial strain. The obvious deformations occurred at the bottle shoulder, which indicated that this was the weak point. The bottles deformed gradually during the 1 mth testing period. The deformations were measured directly using the vernier height gauge on the top plate during the test. The relationship of deformation over time for the 1 L bottle is shown in Figure 6. The 1 L bottle could support a load of 98.1 N for 1 mth with bottle deformation being less than 5.5 mm. The supporting load could be increased but this would have resulted in a reduced storage time for stacked bottles.

Instantaneous deformations were also observed with the 6 L bottles when top loads of 392.4, 490.5 and 588.6 N were applied on the creep testing apparatus. All 6 L bottle samples had the

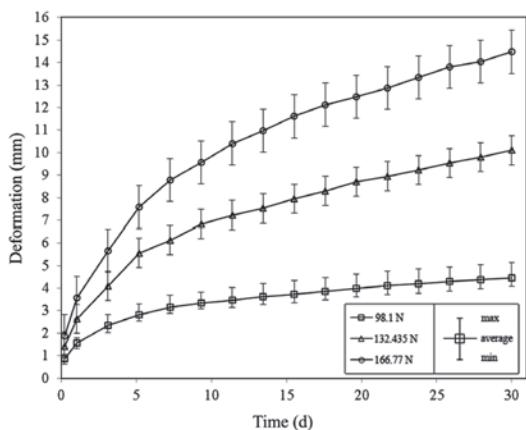


Figure 6 Deformation of 1 L bottle under creep testing with various top loads (max = Maximum; min = Minimum).

same critical area of deformation at the handle of the bottle. The bottles also deformed gradually during the 1 mth testing period. The relationship of deformation over time for the 6 L bottle is shown in Figure 7.

Numerical simulation of lubricant oil bottle creep testing

The comparisons between the simulation results and the experiment for deformation of the 1 L bottle under creep loads of 98.1, 132.435, and 166.77 N are shown in Figures 8–10 which indicate that the displacement calculated by finite element analysis (FEA) prediction had the same trend as the experiment. The deformation of bottle models increased with increasing loads and time. From Figures 8–10, the average percentage errors between the simulation and experiment for the 1 L bottle are shown in Table 2.

Examples of bottle deformation from the FEA simulation and the experiment are shown in Figure 11 which indicate that the deformation from the FEA simulation was similar to that in the experiment. The deformation occurred mainly at the shoulder of the bottle.

The simulated von Mises stress distributions on the bottle wall of the 1 L bottle caused by creep loads of 98.1, 132.435 and 166.77

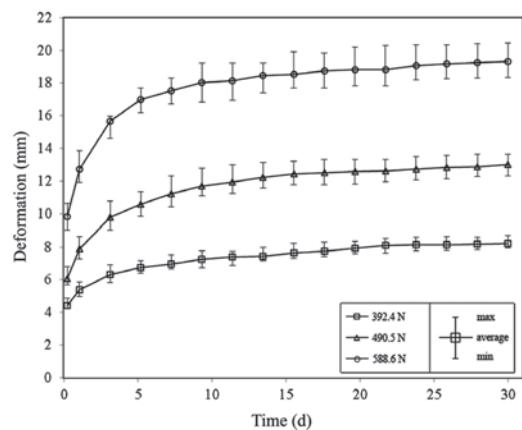


Figure 7 Deformation of 6 L bottle under creep testing with various top loads (max = Maximum; min = Minimum).

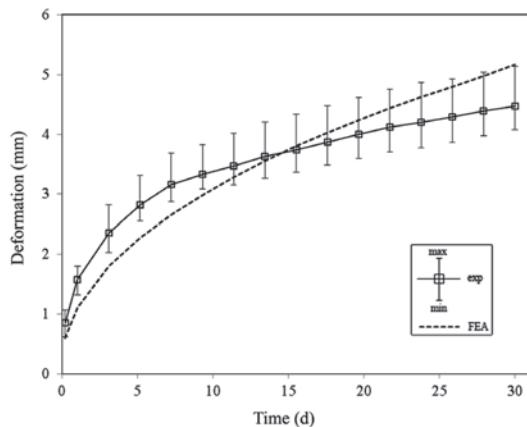


Figure 8 Comparison between finite element analysis (FEA) predictions and experimental (exp) results for creep testing of 1 L bottle under a top load of 98.1 N (max = Maximum; min = Minimum).

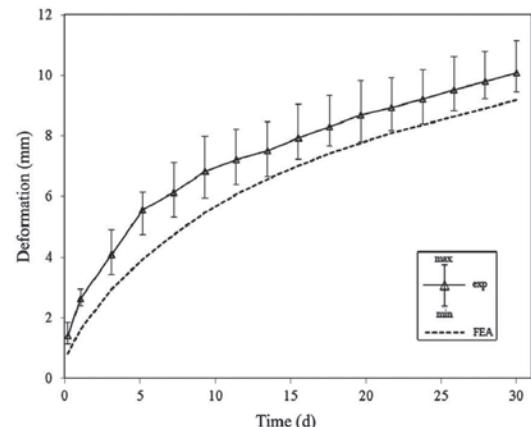


Figure 9 Comparison between finite element analysis (FEA) predictions and experimental (exp) results for creep testing of 1 L bottle under a top load of 132.435 N (max = Maximum; min = Minimum).

N for 1 mth are shown in Figure 12. An area of high stress was observed around the shoulder of the bottle. This area expanded when the creep load was increased. The high stress area corresponded to the deformation of the bottle shoulder observed in the experiment. Therefore, the shoulder of the 1 L bottle was the weak area based on the creep test using a top load. The maximum stress on the bottle wall after 1 mth under creep loads of 98.1, 132.435 and 166.77 N was 5.52, 6.22 and 7.32 MPa, respectively, and less than the yield stress ($\sigma_y = 16.45$ MPa) of HDPE material (Suvanjumrat and Puttapitakporn, 2011). These results confirmed that the creep behavior occurred within the elastic range of the material's properties.

The deformation of 6 L bottles determined by FEA simulation and from experiment was compared graphically under top loads of 392.4, 490.5 and 588.6 N after 1 mth (Figures 13–15, respectively). The deformation simulated by FEA was analogous to that from the experiment, with the average respective errors between the simulation and experiment presented in Table 3. The deformation of a 6 L bottle under a top

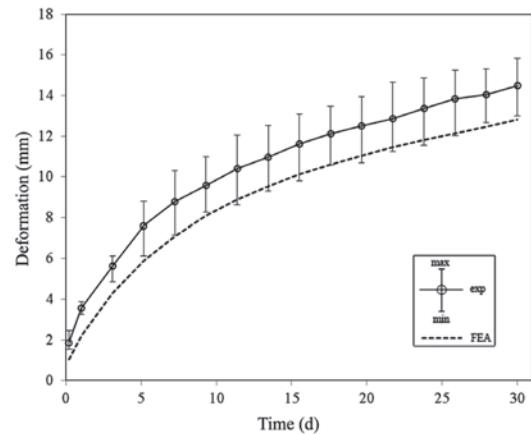


Figure 10 Comparison between finite element analysis (FEA) predictions and experimental (exp) results for creep testing of 1 L bottle under a top load of 166.77 N (max = Maximum; min = Minimum).

load of 490.5 N from the FEA simulation and the experiment is compared in Figure 16. The deformable area of the 6 L bottle models was mainly in the bottle handle as was presented in the experiments.

Table 2 Average error of 1 L bottles with finite element analysis creep simulation compared with experimental results.

Creep load (N)	Error (%)
98.1	12.91
132.435	17.86
166.77	17.82
Overall average	16.20

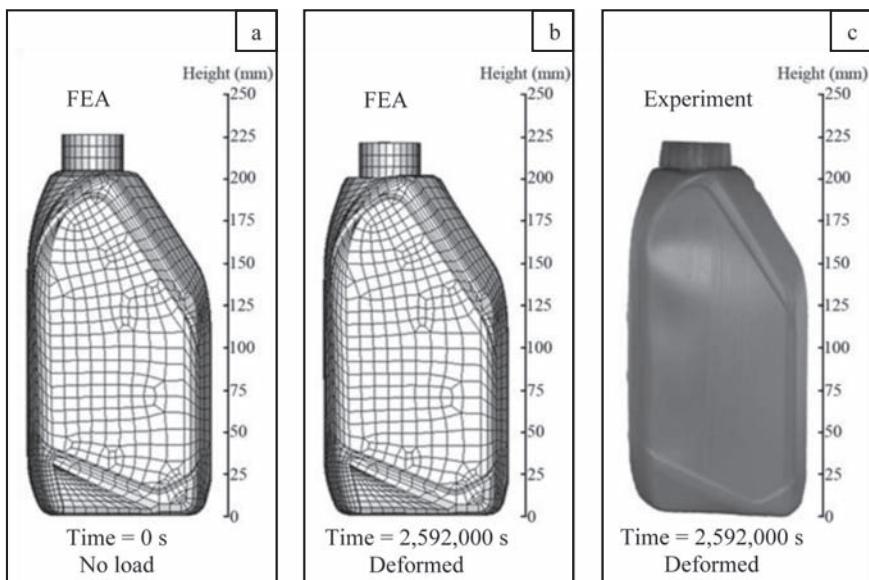


Figure 11 Comparison of deformation between the finite element analysis (FEA) simulation and the experiment for a 1 L bottle after 1 mth under an applied load of 98.1 N: (a) FEA at time = 0 s; (b) FEA at time = 2,592,000 s; (c) Experiment at time = 2,592,000 s.

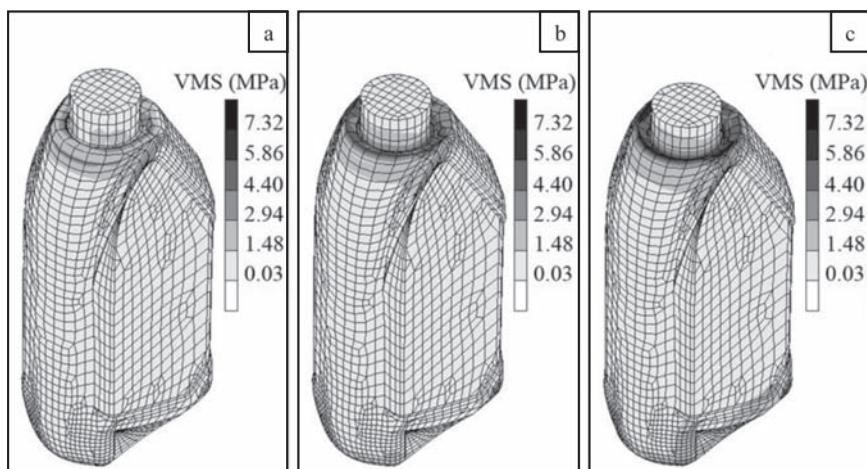


Figure 12 Contour plot of von Mises stress distribution of 1 L bottle wall under an applied load of: (a) 98.1 N; (b) 132.435 N; (c) 166.77 N (VMS = von Mises stress).

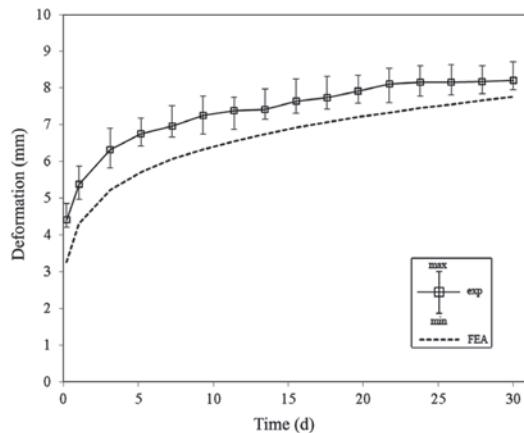


Figure 13 Comparison between finite element analysis (FEA) predictions and experimental (exp) results for creep testing of 6 L bottle under a top load of 392.4 N (max = Maximum; min = Minimum).

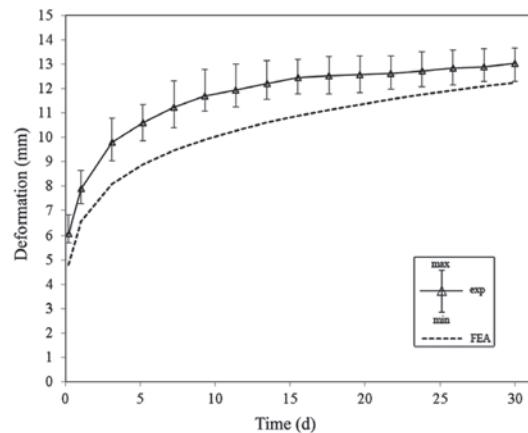


Figure 14 Comparison between finite element analysis (FEA) predictions and experimental (exp) results for creep testing of 6 L bottle under a top load of 490.5 N (max = Maximum; min = Minimum).

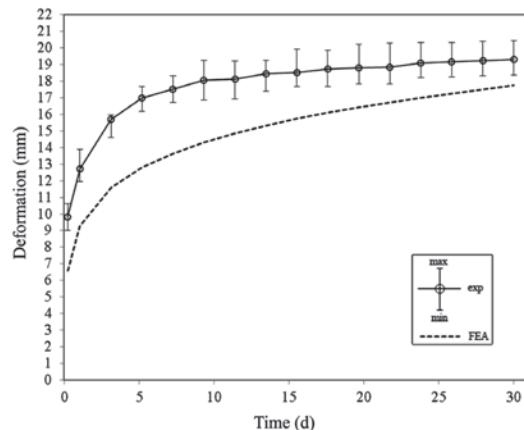


Figure 15 Comparison between finite element analysis (FEA) predictions and experimental (exp) results for creep testing of 6 L bottle under a top load of 588.6 N (max = Maximum; min = Minimum).

Figure 17 shows the von Mises stress distribution on the wall of the 6 L bottle under creep loads of 392.4, 490.5 and 588.6 N after 1 mth. High stress on the 6 L bottle wall was observed at the handle of the bottle since the

handle directly supported the vertical load. These signs of stress corresponded to the deformation of the bottle as shown in Figure 16. The maximum stress levels occurring under creep loads of 392.4, 490.5 and 588.6 N after 1 mth were 5.61, 6.71 and 7.65 MPa, respectively. These were also less than the yield stress of the HDPE material. Therefore, the creep behavior occurred within the elastic range of the material's properties.

CONCLUSION

FEA was established as a technique to test lubricant oil bottle creep. Creep tests on 1 L and 6 L lubricant oil bottles were performed to determine the resistance of the bottles after a constant load for 1 mth. The FEA mimicked the experiment with the creep function taken from experimental results in the literature. The results from FEA were compared with the experiment and the simulation results agreed with the experimental results. The overall difference in bottle deformation between FEA and the experiment was 15.06% which was due to the simulation assumption of uniform

thickness whereas in practice, the actual thickness of the bottle was not constant. However, the FEM was able to capture the trend of bottle deformation. The graphs comparing deformation over time from

the FEA can be applied in the management of the storage time of lubricant oil bottles by stacking. FEA was able to determine the weak point of the bottle by finding the point of maximum stress on

Table 3 Average error in finite element analysis creep simulation with 6 L bottles compared with experimental results.

Creep load (N)	Error (%)
392.4	11.84
490.5	12.41
588.6	17.49
Overall average	13.91

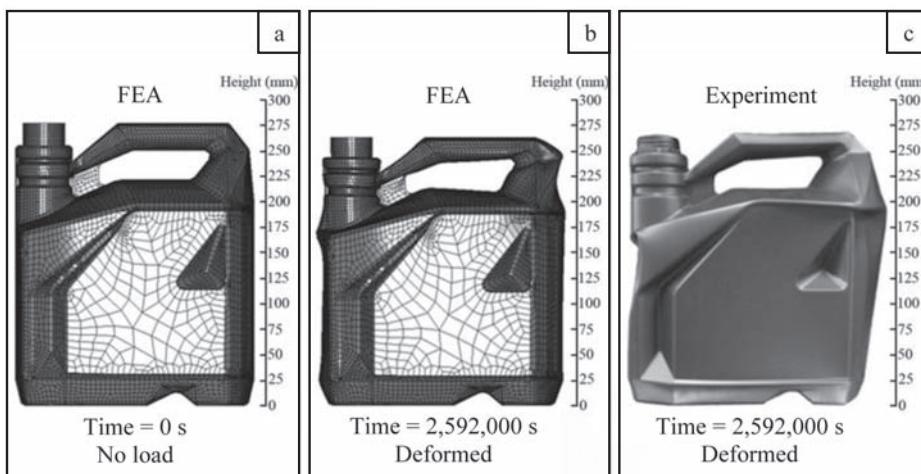


Figure 16 Comparison of deformation between the finite element analysis (FEA) simulation and the experiment for a 6 L bottle after 1 mth under an applied load of 490.5 N: (a) FEA at time = 0 s; (b) FEA at time = 2,592,000 s; (c) Experiment at time = 2,592,000 s.

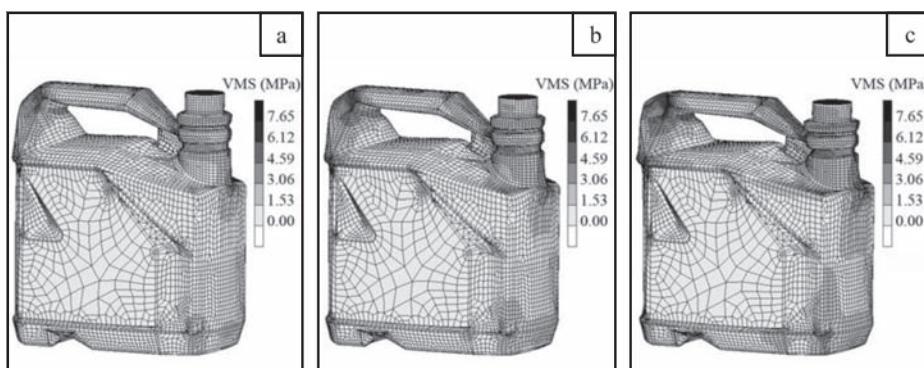


Figure 17 von Mises stress distribution of 6 L bottle wall under creep load of: (a) 392.4 N; (b) 490.5 N; (c) 588.6 N (VMS = von Mises stress).

the bottle wall which was the shoulder of the bottle in 1 L bottles while in the 6 L bottles the weak point was the handle of the bottle. Moreover, the FEM that was validated and verified in this study could be applied in the design of a new lubricant oil bottle subjected to creep load. This method can reduce the time and cost in the design and manufacturing of the lubricant oil bottle.

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