VIRTUAL TESTING OF DRY FILAMENT WOUND THICK WALLED PRESSURE VESSELS

J.J.M. Koppert*, H. de Boer*, A.P.D. Weustink*, A. Beukers, H.E.N. Bersee****
***Advanced Lightweight Engineering, **Delft University of Technology, Faculty of Aerospace Engineering, Design and Production of Composite Structures**

Keywords: *dry fibers, filament winding, thick walled pressure vessel, Finite Element Analysis*

Abstract

Advanced Lightweight Engineering (ALE) has developed and patented a breakthrough technology of the production and design of composite pressure vessels. The key issue is that dry fibers are used. Advantages of this technique are an increased impact resistance, recyclability and easy of production of the pressure vessel compared to conventional techniques. The dry wound technique has successfully been used for the development of LPG pressure vessels. In the near future, the market for lightweight storage tanks for hydrogen will increase. ALE has decided to use the dry wound technique for the development of high pressure vessels for hydrogen storage. The most important difference with the low pressure LPG tank is that the fiber package of a hydrogen storage tank can not be considered as 'thin' any more. This implies the need of a design tool for dry wound thick walled pressure vessels. The in-house developed design tool 'PresVes' is extended for design and analysis of thick walled vessels. Since there are no readily available analytical methods for structural analysis, the choice for a FE model is obvious. Issues such as modeling of dry fibers, compressibility of these fibers and liner shape are addressed. The final FE-model is able to predict the burst pressure within 5% accuracy.

1 Introduction

Advanced Lightweight Engineering (ALE) has developed and patented a breakthrough technology in the production and design of composite pressure vessels [1]. The key issue in the patent is that the fibers are not impregnated by any matrix and are directly dry wound on the mandrel. The preferred manufacturing technology is the filament winding technique. An example of a dry filament wound thick walled pressure vessel can be found in Fig. 1. The basic morphology of the vessel consists of a mandrel, a certain pattern of dry wound fibers and a coating on top of the dry fibers (not present in Fig. 1). The mandrel is typically made of an engineering thermoplastic using rotational or blow molding. The mandrel contains holes for the end-bosses on which valves can be mounted. The fiber bundles are placed on geodesic paths on the mandrel. Geodesic paths on a surface are defined as the shortest distance between two points on the surface. If the fibers on these trajectories are loaded, they do not relocate and the tension in the fiber bundle is constant within the entire fiber bundle. In this way, a so called isotensoidal pressure vessel is constructed. A thorough overview on the filament technique and modeling is provided in [2]. Notice that non-geodesic paths in dry filament winding are limited based on friction (for the first layer friction between mandrel and fiber and layers on top friction between the fibers). Moreover, non-geodesic paths do not result in a constant tension in the fiber bundle and they may relocate when loaded.

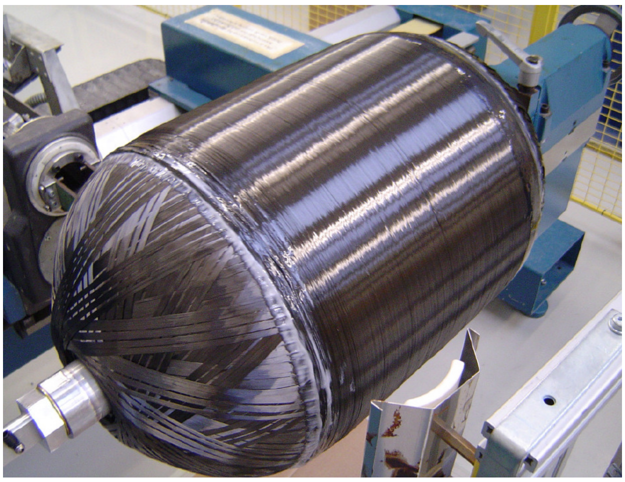

Fig. 1. Dry filament wound thick walled pressure vessel.

A rubber coating is placed on top of the fibers after winding to prevent the fibers as much as possible from relocating and damage, either by chemicals, mechanical loads or sharp objects.

In conventional wet-filament winding the fibers are generally impregnated *in-situ*. The final product quality is a trade off between the production speed and quality. The impregnation quality decreases with increasing process speed. Using dry fibers such a trade off is eliminated and higher economically viable process speeds become possible. Moreover, the impact resistance of a dry filament wound pressure vessel is largely increased and the fatigue properties are excellent. In Fig. 2 a picture of an impact test is shown. An additional advantage is that the vessel will not explode in case it is exposed to fire. The coating serves as a first protective layer. Finally the liner will melt far before the burst pressure of the vessel is reached and the contained gas can escape gradually. Hence, the thermoplastic liner serves as a melting device. Normally such a melting device is integrated in the valve.

Fig. 2. Impact test on a LPG pressure vessel.

Curing time for the finished product needed in wet-winding is no issue anymore. This implies that the production of the vessels can be done clean and efficient. At the end of the service life of a dry wound pressure vessel most fibers can be unwound and thus recycled for e.g. the production of fiber reinforced pellets for injection molding. The thermoplastic liner can be recycled 100%. The isotensoidal nature of the pressure vessels results in an efficient use of the fibers, i.e. theoretically the tension is equal in all fiber bundles.

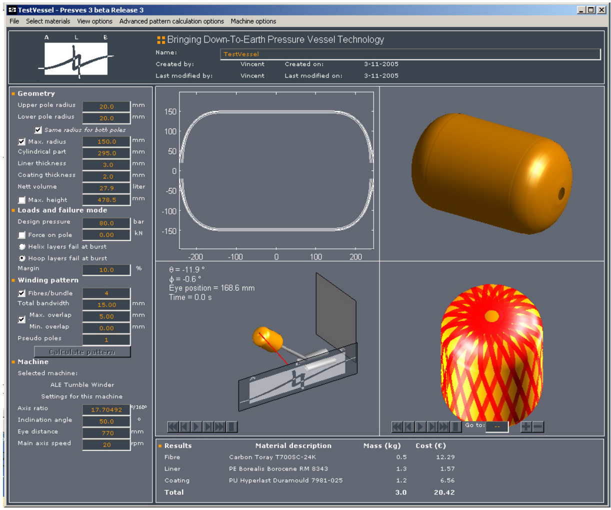

Fig. 3. Screen capture of the Graphical User Interface (GUI) of PresVes.

The technology of dry wound pressure vessels is mainly of interest where weight and damage tolerance are important issues. In the past ALE has used the technology for the development of a LPG-tank for automotive use. For the design of this particular tank an in-house design tool ‘PresVes’ is developed written in MATLAB. A screen capture of the Graphical User Interface (GUI) is shown in Fig. 3. This tool is able to design pressure vessels including the optimal winding pattern based on the desired burst pressure for the dry wound technique. Moreover, ‘PresVes’ can provide the appropriate machine data for our tumble winder (Fig. 4). Nowadays, storage of compressed hydrogen e.g. in automotive becomes of interest. The dry wound technique is in principal suited, however, working pressures are in the order of 350 bar or higher. Eventually, the wish from automotive industry is a working pressure of 700 bar. This pressure is significantly higher than for LPG storage with a working pressure around 10 bar. Since the demand for storage vessels for hydrogen is increasing, ALE has decided to apply the dry wound technique for this specific application. Most important aspect is that the fiber pattern can not be considered as ‘thin walled’ with respect to the radius of the vessel. Therefore, the design tool ‘PresVes’ has been extended for use for thick walled pressure vessels and now takes the thickness increase due to the fiber layers (including stacking at the poles) into account. During winding simulation in ‘PresVes’ for a certain layer, thickness is automatically updated. After winding simulation of a layer the outer contour of the new layers is determined. This contour may serve as the basis for the next layer.

Fig. 4. Tumble winder of ALE.

Since virtual testing is part of ALE's design strategy, the need for an accurate model for structural analysis arose. There are no readily available analytical methods for modeling thick walled matrix free wound composites. Hence, the choice of the development of an accurate Finite Element (FE) model is obvious. However, FE-modeling techniques of matrix free composites are substantially different than those for traditional composites.

The paper deals with the development of an accurate FE model, where burst pressure tests on thick walled cylinders are used for model validation and understanding. The final FE-model is able to predict the burst pressure within 5% accuracy.

2 Finite Element model development

There is commercial software available for structural analysis of composite pressure vessels, such as CADWIND [3], ABAQUS wound composites [4] and GENOA [5]. However, they all lack the option for modeling of *dry* filament wound pressure vessels.

Therefore, the in-house design tool 'PresVes' is extended with a module which can generate an ABAQUS FE input model for a dry wound thick walled pressure vessel. A typical example of a FE model generated by 'PresVes' is shown in Fig. 5. In the following sections the time-line in the development of the FE model is presented. The development is supported by experimental results and observations. The final FE-model is compared to experimental results for a pressure vessel with 4 helix layers and a hoop layer more extensively in Section 2.4. A summary of all features of the final FE model is provided in Section 2.5.

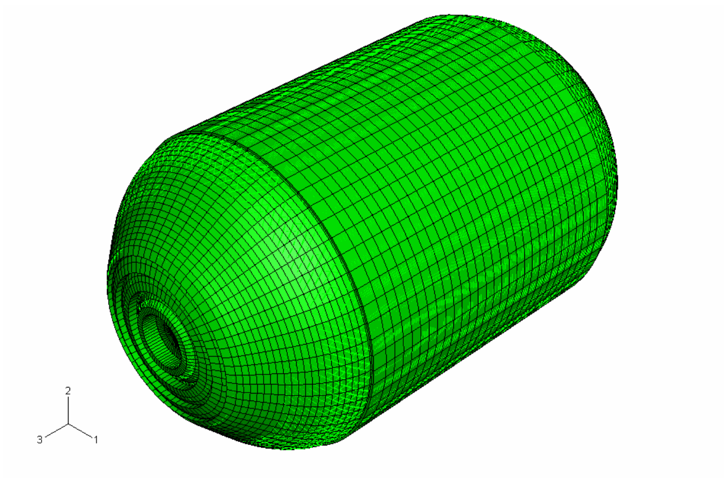

Fig. 5. FE model of a vessel with 4 helix layers and a hoop layer.

2.1 Initial FE model

The main problem in the development of a FE-model is modeling of the dry fibers and the compressibility of the dry fibers. This topic is addressed in Section 2.1.1. The initial FE model is a full 3 dimensional model which implies that no use of symmetry has been made. This choice has been made to circumvent the problem of condensing the winding pattern into a 2D axis-symmetric model. Penalty of this choice is obviously the increase of computation time. All layers are modeled individually. A contact model for the interaction between the individual winding layers is used. A friction coefficient of 0.05 is used and a penalty method which approximates hard pressure-overclosure behavior.

The end-bosses are schematically represented. This implies that the corresponding areas of the liner where the end-bosses are situated are assigned the material properties of the end-boss. The liner is made of Polyethylene (PE) and the end-boss of steel.

Carbon fiber Toray T700 24K is used with an empirical determined ultimate strain of 1.2%.

2.1.1 Modeling dry fibers

The fibers are modeled using truss-elements (T3D2). These elements do not have any bending stiffness which properly describes reality. However, using only these elements generally causes severe convergence problems in FE. Therefore, the truss elements are embedded in solid elements. The embedded element technique is used to specify an element or a group of elements that lie embedded in a group of host elements whose response will be used to constrain the translational degrees of freedom of the embedded nodes. In Fig. 6 the general idea is shown of embedded truss elements in an 8 node solid element.

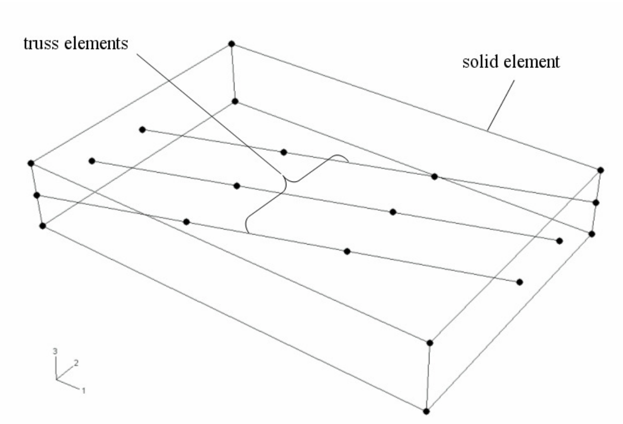

Fig. 6. Truss elements embedded in a solid element. The principle is used for modeling of dry wound fibers.

Solid elements do have bending stiffness by assigning the proper material properties and in this way the convergence problems are circumvent. Since the solid elements represent air, their stiffness should be as low as possible. For the fibers no compressive stress is allowed.

2.1.2 Results

The results from the initial FE model showed linear pressure-strain relations, see Fig. 7. Clearly, the results obtained in experiments demonstrate a nonlinear behavior, which is not captured by the FE model. Moreover, difference in strain between the inner and outer layer is small for the FE results. This is in contradiction with experiments. The improvement in the FE model, described in Section 2.2, is the inclusion of the actual fiber built-up and the compressibility of the fiber package.

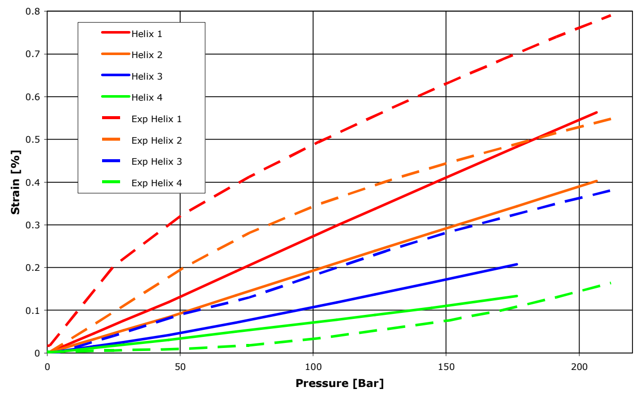

Fig. 7. Pressure-strain relations for a thick walled pressure vessel with 4 helix layers and a hoop layer.

2.2 Improvement: fiber built-up and compressibility

2.2.1 Fiber built-up

The fiber built-up is improved, which means that the effect of fiber stacking is included in the FE model. An example of fiber stacking at the pole for a four layered thick walled pressure vessel is shown in Fig. 8. The translation to the FE model is depicted in Fig. 9. The truss elements representing the fibers are still located at the middle of the layer, but the solid elements representing the layer thickness are thicker at the locations of fiber stacking. Although the complete pattern is located at the middle of a layer, the thickness of the layer is correct and determined by updating the thickness while performing the winding simulation.

2.2.2 Compressibility

The compressibility is added to include the effect observed in experiments that the strains in the first layer are significantly higher than the strains in the most outer layer. Due to the air present in the fiber package there is first compression before loading can start.

Due to stacking at the poles (Fig. 8) and fiber crossings there is much more air present between the fibers than on the cylindrical part of the vessel. The FE model of the vessel is divided in circular segments and 'PresVes' generates for each segment a value for the fiber volume. This value is based on the summation of the fiber thickness divided by the actual thickness of the layer. The value for the fiber volume ranges from 1 (no air) to (theoretically) 0 (no fibers). An example of the fiber volume provided as field values is depicted in Fig. 10. The material behavior for the solid elements, representing the air is implemented in user-subroutine UMAT. This user-subroutine is a standard routine in ABAQUS in which the user can define the mechanical behavior of a material. For regions with a lot of air, the stiffness normal to the surface of the vessel is initially reduced so that the fiber package compression is modeled.

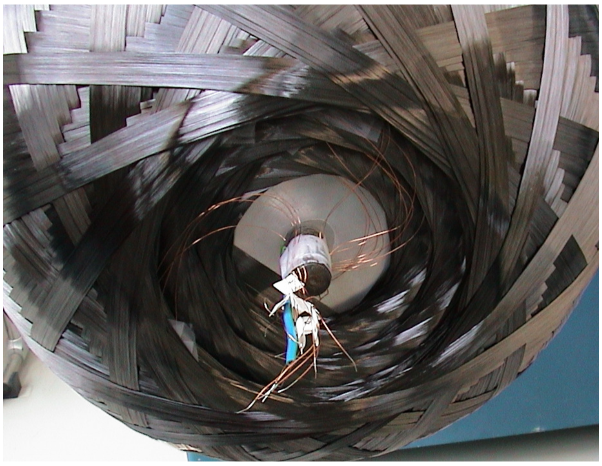

Fig. 8. Fiber stacking at the pole of a pressure vessel.

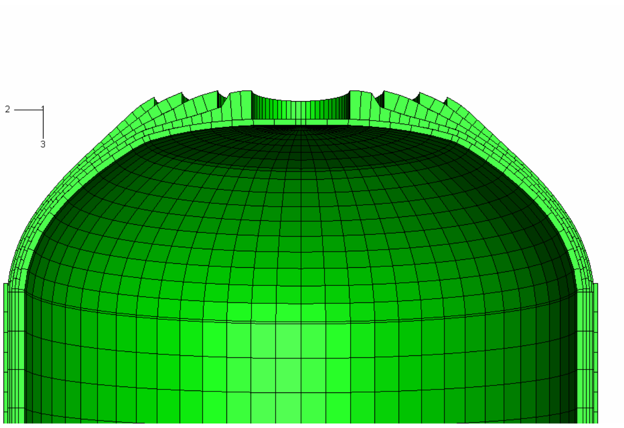

Fig. 9. FE element model for the layers (half of the model) shown at the poles.

2.2.3 Results

The FE model is able to accurately predict the burst pressure of a single-layered vessel with an experimental determined burst pressure of 130 bar. Also a two layered vessel with an experimentally determined burst pressure of 225 bar is accurately predicted by the FE model. However, the FE result appeared to be very sensitive to the amount of compressibility and the FE models are not able to predict the burst pressure for a pressure vessel with 3 or 4 layers. The following step in the improvement of the FE model is to include the actual distribution of the fibers though the thickness.

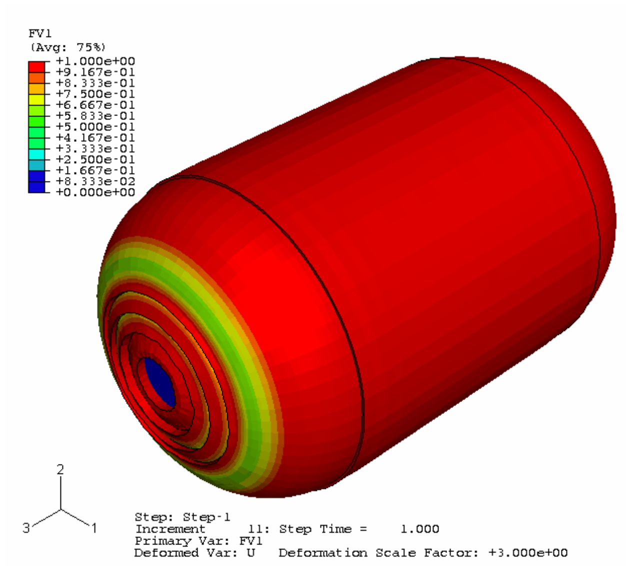

Fig. 10. Field values representing the fiber volume prescribed to the FE model.

2.3 Improvement: fiber distribution

The actual fiber distribution of the fibers within a layer is taken into account. This implies that the fibers are no longer located at exactly half of the thickness of the layer, but that the actual location is used.

The results for the FE model appeared to be less sensitive to compressibility, but still the burst pressure for a pressure vessel with 3 or 4 layers could not be predicted.

2.4 Improvement: actual liner shape

So far, the FE results have been compared to experimental results for a pressure vessel with 4 helix layers and a hoop layer, but the burst pressure predicted by the FE model is much higher compared to experiments. In the FE model, the isotensoidal contour of the liner as determined by 'PresVes' is used. The actual contour of the liner resulting from rotational molding appeared to be different from the mould shape due to shrinkage. The actual contour of the liner has been measured and inserted into 'PresVes' to generate the FE model. This FE model predicted the burst pressure accurately within 5% accuracy. The experimental results are provided in Section 2.4.1 and the FE results in Section 2.4.2, respectively.

2.4.1 Experimental results

A pressure vessel with 4 helix layers and a hoop layer has been tested to determine the burst pressure. Strain data for layer 1, 2 and 4 is recorded up to 290 bar. The results for the strain measurements can be found in Fig. 14. The burst pressure found is 495.3 bar. A picture of the pressure vessel after burst is shown in Fig. 11. Failure of the pressure vessel occurred in the helix layers by blown out of the steel end-boss shown in Fig. 12.

Fig. 11. Dry filament wound pressure vessel after burst test. Failure occurred at 495.3 bar.

Fig. 12. Insert blown out of the pressure vessel

2.4.2 FE-results

A FE model for the pressure vessel with 4 helix layers and a hoop layer has been created using 'PresVes'. The strains in the truss elements at a pressure of 276 bar are shown in Fig. 13. Fiber stacking at the pole can clearly be discerned in the picture even as the fiber distribution within a layer.

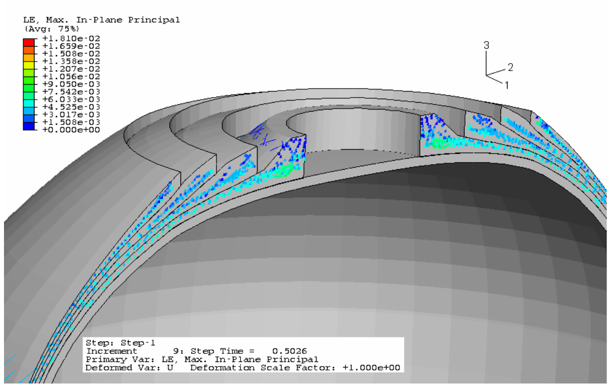

Fig. 13. Strain in the truss elements for a pressure of 276 bar.

The strains obtained at layer 1, 2 and 4 are shown in Fig. 14. In this figure, the strains obtained in experiments are provided as well. The maximum strain limit of 1.2% for Carbon Fiber Toray T700 is also included. The curves clearly demonstrate the nonlinear behavior of the strains in the fibers versus the pressure. This nonlinear behavior is included by incorporating the actual distribution of the fibers and the compressibility effect. The figure also shows that the first layer is the most heavily loaded layer and that for layers located more outward the load significantly decreases. With the decrease in load, the efficiency of the fibers for the layers located more outward is reduced.

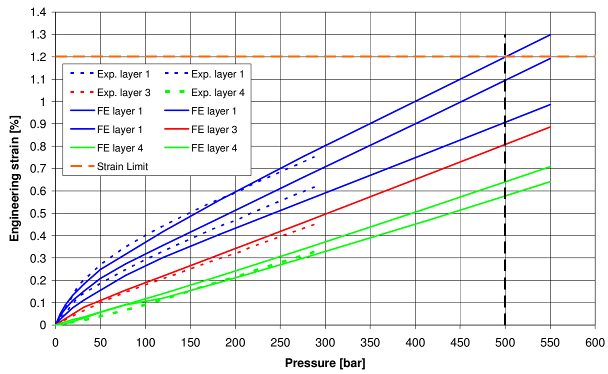

Fig. 14. Engineering strains as a function of the pressure for helix layer 1, 2 and 4 in experiment and for all helix layers in FE. The strain limit for Carbon Fiber Toray T700 24K is provided as well.

The experimental strains show a good agreement with strains obtained in experiments for all layers. The burst pressure is predicted to occur at 500 bar. The location on the pressure vessel where fiber failure is predicted is shown in Fig. 15. In this figure, the strain above the limit strain at a pressure of 550 bar is shown. A step in the ABAQUS analysis is not available at exactly 500 bar, therefore the step at 550 bar is used. For clearness of presentation, strains below the 1.1% are shown in black. Cleary two regions can be distinct where the strain limit is exceeded. The first region is a zone around the pole and the second region is a 'ring' exactly at the location where the transition between the end-boss and liner is situated. The fact that the region around the poles shows fiber failure is caused by a current shortcoming in 'PresVes' which does not always produce a smooth fiber trajectory near the pole. In combination with the approximation of the fiber path by truss elements numerical problem occur at the pole. Therefore, the current region has its origin in a modeling issue and is therefore excluded from evaluation for fiber failure. The other region demonstrates that fibers situated above the transition from steel end-boss to PE liner have failed. This prediction of fiber failure matched the failure of the burst pressure test where the end-boss is blown out (Fig. 12). The sharp transition of the stiffness (steel versus PE) is the cause.

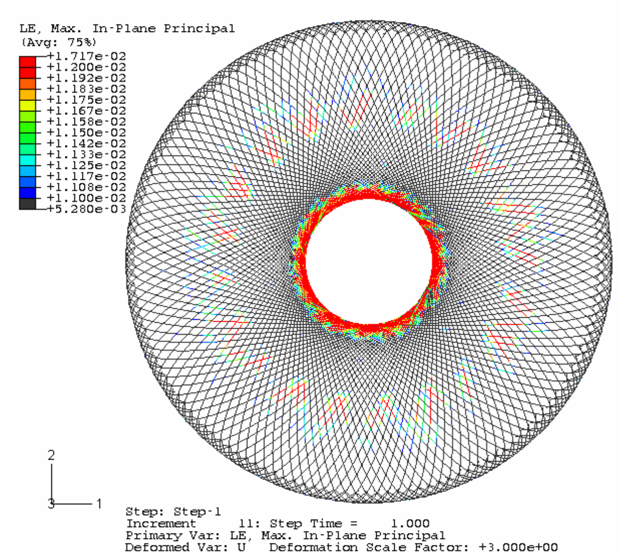

Fig. 15. Strain in the first helix layer at a pressure of 550 bar.

2.5 Summary FE model characteristics

Summarizing, the ABAQUS FE model generated by the module in 'PresVes' has the following characteristics:

- A full 3D model of the pressure vessel is generated. This choice has been made to circumvent the problem of condensing the winding pattern into a 2D axis-symmetric model. Penalty of this choice is obviously the computation time.
- Dry fibers are modeled by truss elements embedded in solid elements.
- The actual distribution of the fibers in the layers is taken into account including fiber stacking at the poles.
- Compressibility of the layers is taken into account.
- Different winding layers are modeled individually.
- A contact model for the interaction between the individual winding layers is used. A friction coefficient of 0.05 is used and a penalty method which approximates hard pressure-overclosure behavior.

'PresVes' is able to generate a complete FE-model ready for FE analysis. If desired, modifications can still be done by importing the FE model in ABAQUS/CAE.

3 Conclusions and discussion

A design tool has been developed for structural analysis of dry wound thick walled pressure vessels. The in-house developed design tool 'PresVes' determines the optimal winding pattern and automatically produces an ABAQUS FE model. As validated by experiment, the burst pressure for dry wound thick pressure vessels can be predicted within 5% accuracy. For the case considered, the failure mode is properly predicted as well. It can be concluded that a proper design tool has been established for dry wound thick walled pressure vessels.

Aspects which significantly influence the efficiency of a pressure vessel are:

- *The actual shape of the liner*. The FE model using the isotensoidal liner predicted a much higher burst pressure than using the actual liner shape resulting from rotation molding.

- *The end-boss design*. The FE results in Section 2.4.2 have shown that failure occurs at the location to the stiffness transition from steel insert to PE liner. This implies that sharp stiffness transition in the design of the liner and end-boss should be avoided.
- *The amount of compressibility*. The efficiency of the vessel decreases if the compressibility in the fiber package is large. The first layer will be the most heavily loaded layer and if there is a significant amount of compressibility, the load transfer to the layer above is diminished.

Initially, the choice has been made to model the entire pressure vessel without using symmetry of the vessel. Penalty of this choice is obviously the computation time. The numerical efficiency of the FE-model has to be increased, because the FE model will be applied in optimization and design sensitivity analysis in future. Generally, such analyses require many design evaluations, and therefore, the time for a design evaluation should be reduced as much as possible. Currently, the CPU time for the FE model in Section 2.4.2 is 2.6 hours (2xDual Core AMD Opteron Processors 280, 12Gb memory, Suse Enterprise 9.0).

A possible way for increasing the efficiency is to develop a 2D axis-symmetric model. However, in that case the problem of condensing the fiber pattern into a 2D model has to be solved.

References

[1] Debecker A., van der Jagt O. and Koppert J.J.M., "*Fibre-reinforced pressure vessel and method of manufacturing fibre-reinforced pressure vessels*", Patent WO 01/57429 A1, 2001.

[2] Koussios S., "*Filament winding: a unified approach*", Dissertation, Delft University of Technology, 2004.

[3] http://www.material.be

[4] http://www.abaqus.com

[5] http://www.alphastar.com