

New methodologies for characterization and modelling of filament-wounded composite pressure vessels

M. Bruyneel^{1,2}, M. Haeseleer¹, F. Strepenne¹, T. Watanabe³, Y. Urushiyama³, Y. Tsuchiyama³

1: GDTech, 7 Avenue de l'Expansion, B-4432 Alleur, Belgium

2: University of Liège, Liège, Belgium

3: Honda R&D Co., Ltd. Innovative Research Excellence,
4630 Shimotakanezawa, Haga-machi, Haga-gun, Tochigi, 321-3393 Japan

Abstract: This paper describes research activities carried out in the field of Composite Overwrapped Pressure Vessels (COPV), with the goal to develop an accurate modelling methodology for the dome area. Different aspects are considered: material characterization at coupon level for a structure with curvatures, and definition of an adapted so called "soccer-ball mandrel" that presents flat faces; identification of the parameters of a specific material model that can account for progressive damage and permanent deformation; development of a methodology for modeling with FEM coupons extracted from the dome area, in shell and 3D-solid elements formulations; prediction of multi-sequence lay-up thickness coming from the filament winding process, in an axisymmetric representation, accounting for interaction with the boss; FEM simulation of the filament winding process, in order to better understand the behavior of the tapes deposited during filament winding. Good agreements are obtained between modeling/simulations and tests/measurements.

Keywords: composite, pressure vessel, modelling

1. Problem statement

This paper describes research activities carried out in the field of Composite Overwrapped Pressure Vessels (COPV), with the goal to develop an accurate modelling methodology for the dome area.

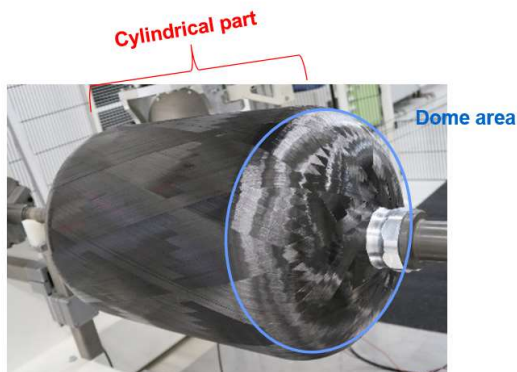


Figure 1: COPV with its cylindrical part and dome area

2. Manufacturing and testing

In order to reproduce the unique complex fiber arrangements at the dome of a COPV while providing flat coupons, a hexagonal-shaped so-called "soccer ball" mandrel is used, which has cleverly-designed flat faces in the dome and cylindrical regions.



Figure 2: Filament winding on the soccer-ball mandrel

Coupons extracted from the cylindrical part are used to identify the parameters of a composite material model that takes into account progressive damage and permanent deformation. Standard testing is used, like ASTM D3039.

At the dome area, extracted coupons are submitted to a four-point bending test. Coupons in longitudinal and transversal directions are considered.



Figure 3: 4-points bending on coupons in longitudinal (left) and circumferential (right) directions, extracted from the dome

3. Material modelling

The formulation of the material model is described in Figure 3, in plane stress conditions. It includes 3 damage variables, and proved to be efficient in solving very complex problems for composites [1]. The material model is proprietary and implemented in LS-Dyna via user-material routines.

$$e_d = \frac{\sigma_{11}^2}{2E_1^0} - \frac{\nu_{12}}{E_{11}^0} \sigma_{11}\sigma_{22} + \frac{\sigma_{22}^2}{2E_2^0} + \frac{\sigma_{12}^2}{2G_{12}^0}$$

↓ Damage variables d_{11} , d_{12} , d_{22}

$$e_d = \frac{\sigma_{11}^2}{2(1-d_{11})E_1^0} - \frac{\nu_{12}}{E_{11}^0} \sigma_{11}\sigma_{22} + \frac{\sigma_{22}^2}{2(1-d_{22})E_2^0} + \frac{\sigma_{12}^2}{2(1-d_{12})G_{12}^0}$$

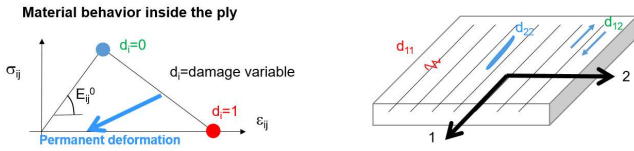


Figure 4: Formulation of the composite material model

Next Figures compare test results and simulations, for different laminate stacking sequences, once the parameters of the material model have been identified.

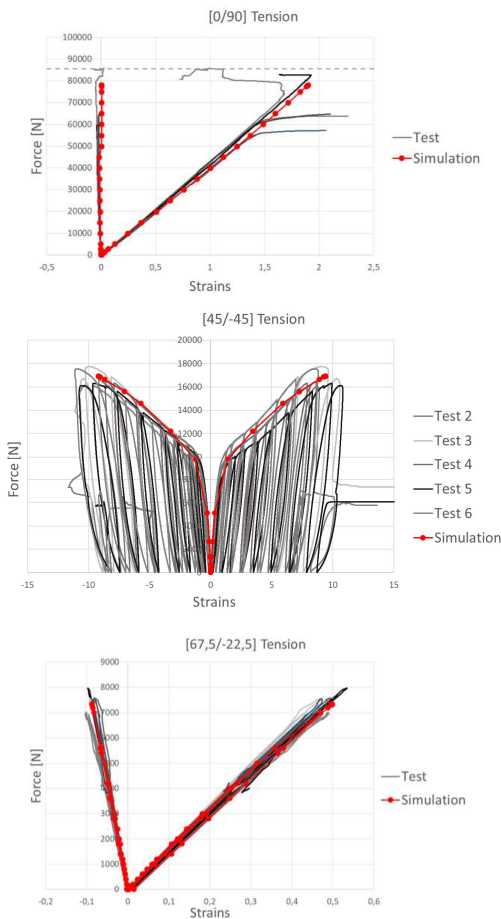


Figure 5: Comparison between tests and simulations for coupons at cylindrical area

4. Modelling coupons at dome area [2]

Coupons in the longitudinal and circumferential directions are considered at the dome area. First, the tape pattern from the filament winding process is reproduced (as in Figure 2), and groups of finite elements are defined. The local fibre orientations are

then assigned to each group of elements. 2D-multi-layer shell elements are used.

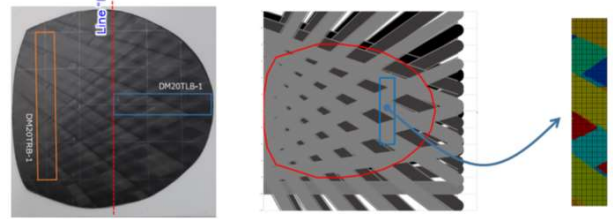


Figure 6: Coupons (orange and blue), model of the composite pattern, and FEM model of a coupon

3D-solid elements models are then build starting from the shell models, using an inflation technique.

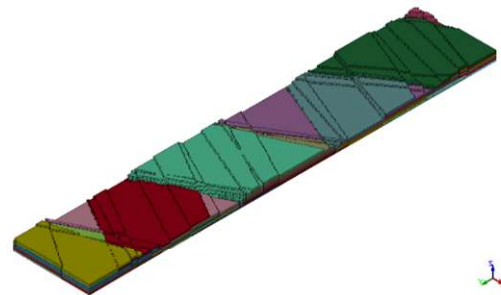


Figure 7: 3D-solid elements model of a coupon

Comparison between tests and simulation of a four-points bending scenario is provided in the following Figures, for $\pm 20^\circ$ orientations at the cylindrical part. It is clear that very good simulation results are obtained when a model including 3D-solid elements is used.

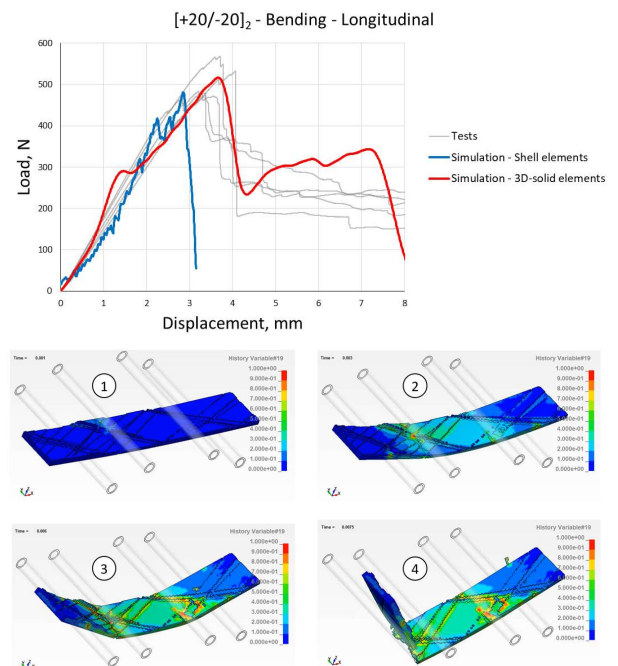


Figure 8: Comparison between tests and simulations for coupon at dome area (longitudinal)

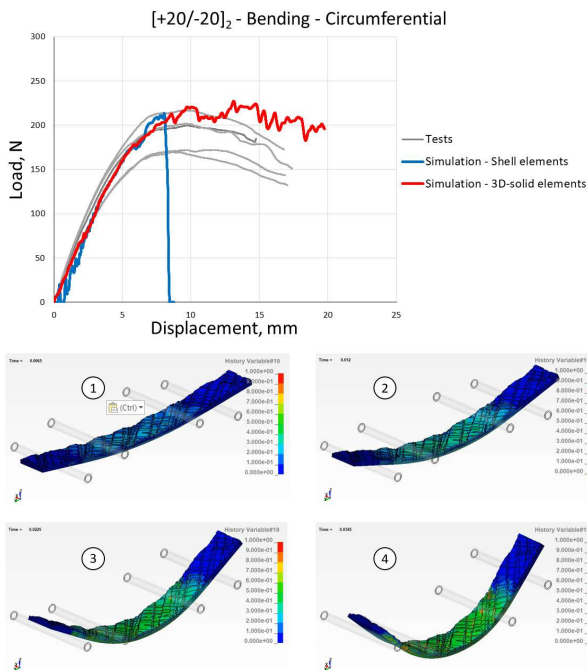


Figure 9: Comparison between tests and simulations for coupon at dome area (circumferential)

5. Prediction of layer thickness

The prediction of layers thickness at the dome area in a multi-sequence lay-up scenario including any mix of increasing/decreasing fiber orientation (as defined in the cylindrical region) is a very difficult task [3]. It is even more difficult when interaction with the boss is to be considered [4], what is most of the time the case in practice. Motivated by the lack of accuracy of existing commercial and published solutions, and extending the work of [3-4], a computer program was developed, and validated with measurements done on vessels of different capacities, for the case of geodesic trajectories. The input data are, for each layer, the corresponding angle at the cylindrical part, as well as tape width and thickness, and the dome and boss geometries. Results obtained for a 15L and 120L COPV are given in Figure 10, and show a very good agreement with the measures from real COPV, not only for the general layer thickness definition but also for the layer thickness interacting with the boss.

6. FEM simulation of the manufacturing process

Based on its expertise in modelling braiding of composite fibers [5], GDTech started working on the development of a methodology for simulating the filament winding process, with a finite element approach. Contrary to working with classical CAD pieces of software like COMPOSICAD, that are based on purely geometrical approaches, using a finite element modelling allows the introduction of interactions between tapes and mandrel, governed by

e.g. friction coefficient, and a natural management of the interaction/contact with the boss.

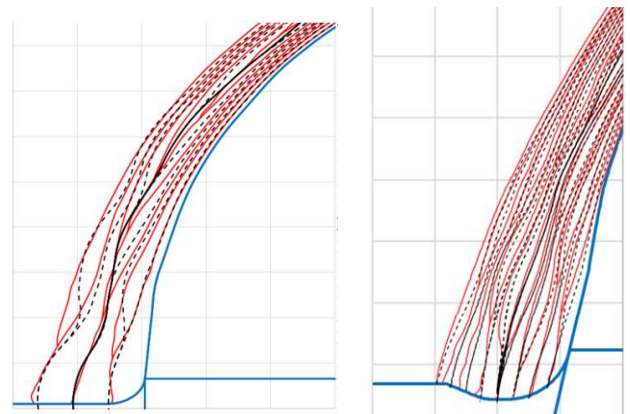


Figure 10: Comparison between measures (red) and predictions (black) for 15L (left) and 120L (right)

LS-Dyna is used. Input data (“raw machine inputs”) come from the “.pat” file of COMPOSICAD software, which provides the position and rotation of the deposition head over time during the process, and the rotation of the mandrel. For the moment, only one cycle is considered. First attempts considered the deposition of a single tape of constant width. Results are provided below, together with a comparison between the predicted tape trajectory and the one determined by COMPOSICAD (“.pth” file).

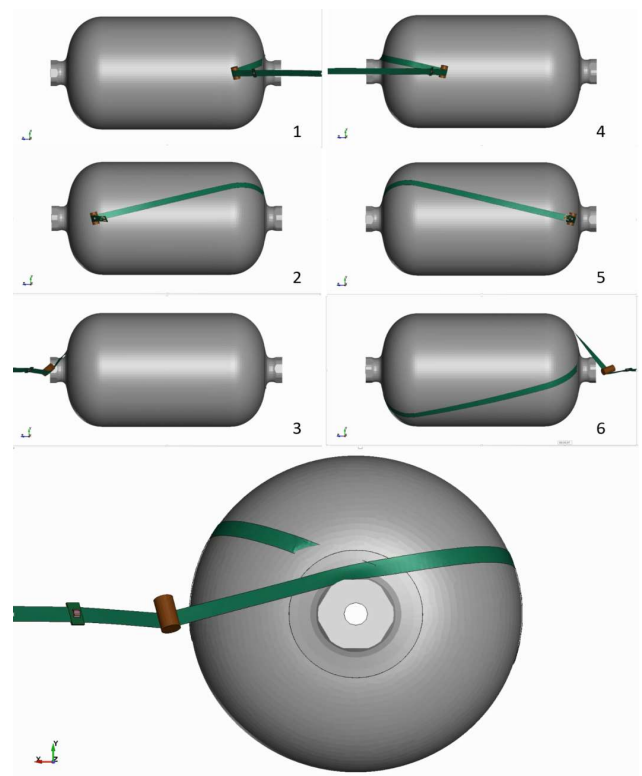


Figure 11: Filament winding process simulation with a single tape

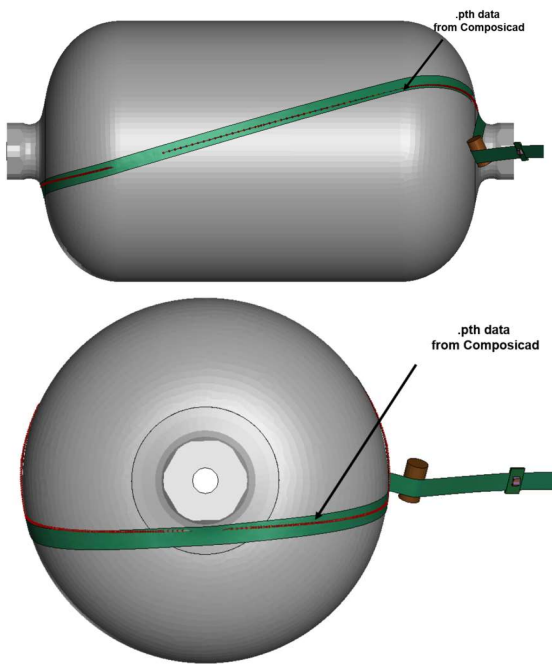


Figure 12: Filament winding process simulation with a single tape: comparison between FEM predicted trajectory and geometric trajectories

First results were also obtained for the case of 5 “adjacent” thinner tows simultaneously deposited on the mandrel. That way of working allows to identify changes in “global tape” width during the deposition, depending on the location on the mandrel (e.g. smaller width due to interaction between tapes and boss). A comparison between the predicted tape trajectory and the one determined by COMPOSICAD is provided in Figure 13.

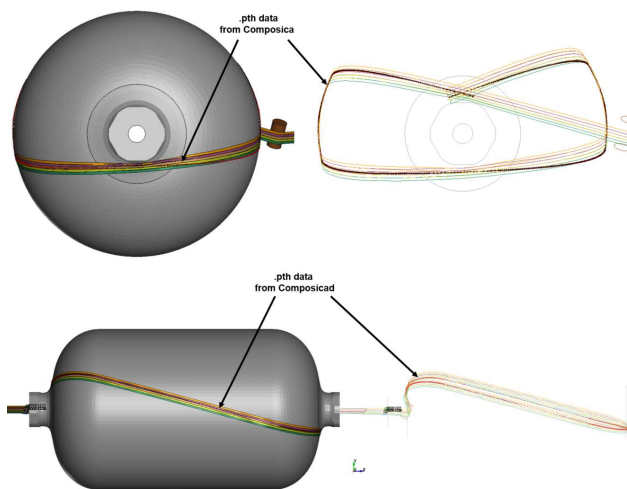


Figure 13: Filament winding process simulation with 5 tapes: comparison between FEM predicted trajectory and geometric trajectories

Results of such FEM simulations will feed the program used for the prediction of layers thickness, as described in Section 5, what is expected to provide even more accurate solutions.

7. Conclusion

This paper has presented several advances recently obtained for the reliable characterization and accurate modelling of composite pressure vessels: production and testing of flat coupons for identification of the parameters of an advanced material model, and demonstration of the performance of a detailed FEM modelling methodology based on 3D-solid elements; new approach for the accurate prediction of layer thickness for multi-sequence lay-up in filament winding, considering complex interaction with the boss; and finally, FEM modelling and simulation of the filament winding process itself. Numerical results showed very good agreements when compared to test results or measurements done on produced COPV.

8. Acknowledgement

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9. References

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