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Validation of thermoplastic composites forming simulations

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1. Introduction

Press forming of thermoplastic continuous fiber composite materials is a high-efficiency manufacturing process enabled by the properties of thermoplastic matrices, which can be remelted multiple times. Flat laminates of desired layups are usually consolidated on large continual forming presses. The laminates are cut into blanks from which is then final part formed. These blanks undergo heating in an infrared oven, causing the thermoplastic matrix to melt. Subsequently, they are rapidly transported to the press area and formed. Tooling is heated to temperature that is lower than melting temperature of matrix, ensuring immediate cooling upon contact. This allows manufacturing cycle that can be done in a few minutes (depends on matrix material, part thickness, oven power, etc.), which is significantly lower time than for conventional manufacturing process utilizing thermoset prepregs and autoclave curing.

Numerical simulation tools, like AniForm [1], can be employed to design manufacturing process as they help in avoiding defects such as wrinkles or folds and optimizing mold geometry. The development of an appropriate mold design is a crucial element in the press forming process and typically follows an iterative process: The mold is manufactured, a part is press-formed, the part's geometry is examined, mold geometry is compensated, and so on. This is precisely where numerical simulations play a pivotal role.

Modelling of material behaviour during press forming is challenging due to interaction of several deformation mechanisms and dificulties with characterization of material in molten (matrix) state. The deformation of laminate in press forming process is driven by several mechanisms which can be divided to (i) Intra-ply mechanisms: in-plane shear, out-of-plane bending, fibre extension and compression and transverse extension and compression, (ii) Interface mechanisms: ply-ply, tool-ply friction and ply-ply, tool-ply separation.

These mechanisms can be described by various mathematical models. For example, intra-ply mechanisms can be modelled as (i) Elastic: linear/orthotropic, Mooney-Rivlin, etc. (ii) Viscous: Newtonian fluid, Cross-viscosity fluid, etc. Usually superposition of several models is employed, such that the total stress results from the addition of the selected models individual stress components. Furthermore, characterization methods for thermoplastic composites in processing temperatures are not standardized.

With wide array of choices, many simulation settings are possible. To evaluate the capabilities and accuracy of these simulations, a robust validation tool becomes essential. In this work, experimental campaign for validation of press forming simulations was carried out using double-curvature geometry.

2. Dome forming experiments

Two commercially available unidirectional thermoplastic composite materials, namely Toray TC1225 (T700 carbon fiber with low melt PAEK matrix) and Solvay APC (AS4D carbon fiber with PEKK matrix) were examined. The layup and width of specimens were varied to examine formability and wrinkling severity. The test matrix is summarized in Table 1, 0 fiber direction is aligned with specimen longer dimension and right hand rule is applied for other directions. For every specimen set were made 3 repetitions.

Table 1. Overview of specimen sets

Layup	Width [mm]
$[0, 45, 90, -45]_s$	40
$[0, 45, 90, -45]_s$	80
$[90, -45, 0, 45]_s$	80
$[0, 90]_{2s}$	80

The plies were cut from the role of material and stacked into mold according to desired layup and flat laminates were consolidated. Laminates were cut into rough dimensions and dot pattern for deformation tracking was applied. The dimensions of the pattern were: dot size 1 mm with 3 mm spacing. The dot pattern was applied by combination of exposure mask, photoresist film, sandblasting and heat resistant spray paint. The specimens were then machined to final dimensions $295 \times (40, 80)$ mm.

Dot pattern of flat laminate was digitized by photogrammetry technique. The setup consists of remote-controlled turntable, polarized lighting and digital camera. Photographs were captured at 16 equidistant angles. These photos were further analysed in PhotoModeler software [3] where dots are automatically marked, referenced and 3D position of dots with its precision can be exported. Photogrammetry is then repeated after press forming in the same manner. Example photos before and after press forming are depicted in Fig. 1.

Press forming experiments were carried out on 200-ton press from Pinette Emidecau Industries at the TPRC. Steel hemisphere tool was used. Laminates were placed in the shuttle frame, heated in infra-red oven, rapidly transported and press formed (see Fig. 2). The tooling was not fully closed but additional 2 mm gap was left to be able clearly observe wrinkles.

The digitized dot patterns are meshed in Matlab with a regular triangular mesh. Green-Lagrange strains, shear angles and fiber directions are calculated as in the previous publication by Brands et al. [2]. The results of 3 specimens are averaged.

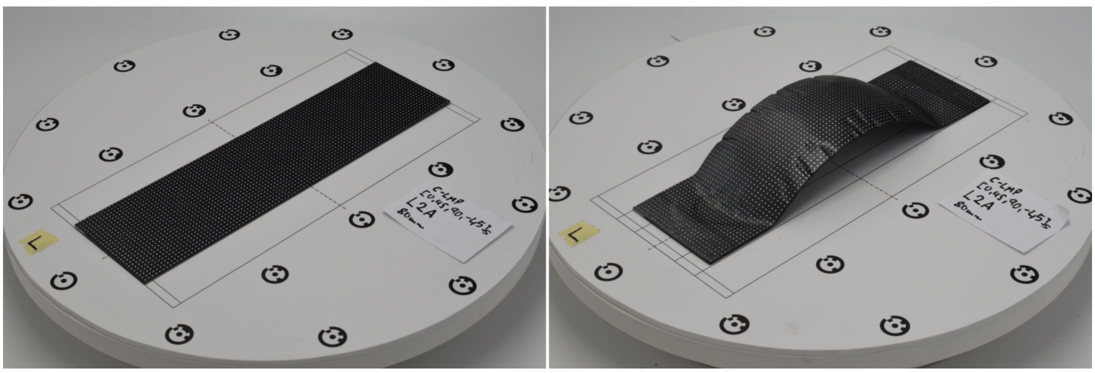

Fig. 1. Example of photos for photogrammetry, before and after forming

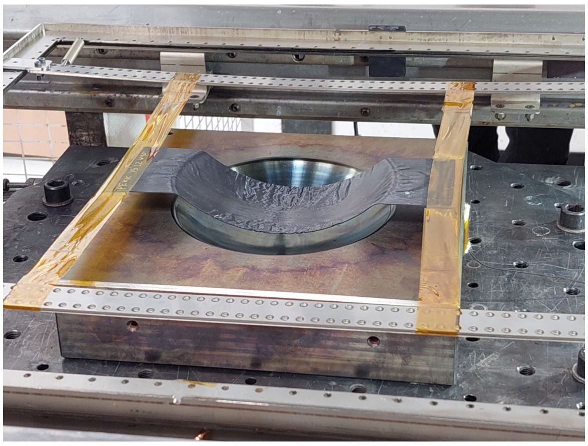

Fig. 2. Lower tool, press formed specimen and laminate handling setup

3. Results and discussion

Fig. 3 shows one selected part per specimen set of 4 different layups for both materials. The Solvay APC material exhibits slightly better formability compared to the similar Toray TC1225 material.

For both 40 mm quasi-isotropic (QI) $[0/45/90/\text{-}45]_s$ specimens, we observe only minimal wrinkling, which is likely to disappear when the molds fully close. However, when the same layup is scaled to a width of 80 mm, we observe more pronounced wrinkles. Interestingly, when this layup is rotated 90 degrees clockwise, resulting in the $[90/\text{-}45/0/45]_s$ layup we still observe wrinkles, but they are less severe. This phenomenon may be attributed to the presence of the 90-degree layer on the laminate's surface, which has less resistance to bending compared to the outer 0-degree ply and may also experience some extension in the transverse direction (longitudinal direction of the specimen). The ply-ply friction is the main deformation mechanism for QI laminates and in-plane shear deformation is limited. In contrast, for cross-ply $[0, 90]_{2s}$ specimens, we observe a significantly higher degree of shear deformation compared to QI laminates. This results in lower levels of out-of-plane deformation and, consequently, fewer wrinkles in the material.

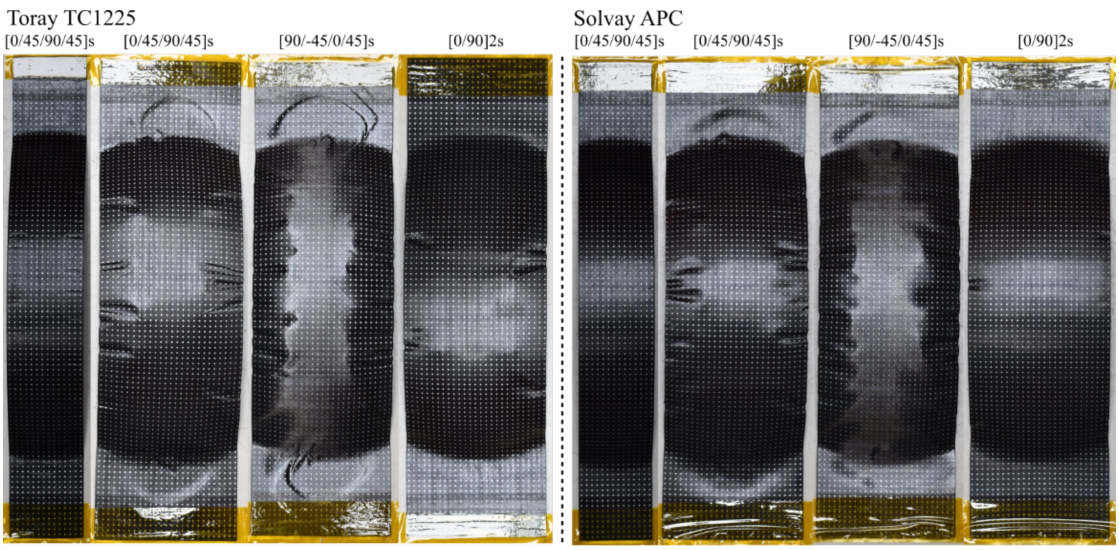

Fig. 3. Press formed specimens

Comparison of Green-Lagrange shear strain average over 3 specimens between QI and cross-ply specimens from TC1225 is visible in Fig. 4. This picture also shows Green-Lagrange shear strains of two AniForm simulations with different material models employed and demonstrates possible use of presented dataset for validation of press forming simulations.

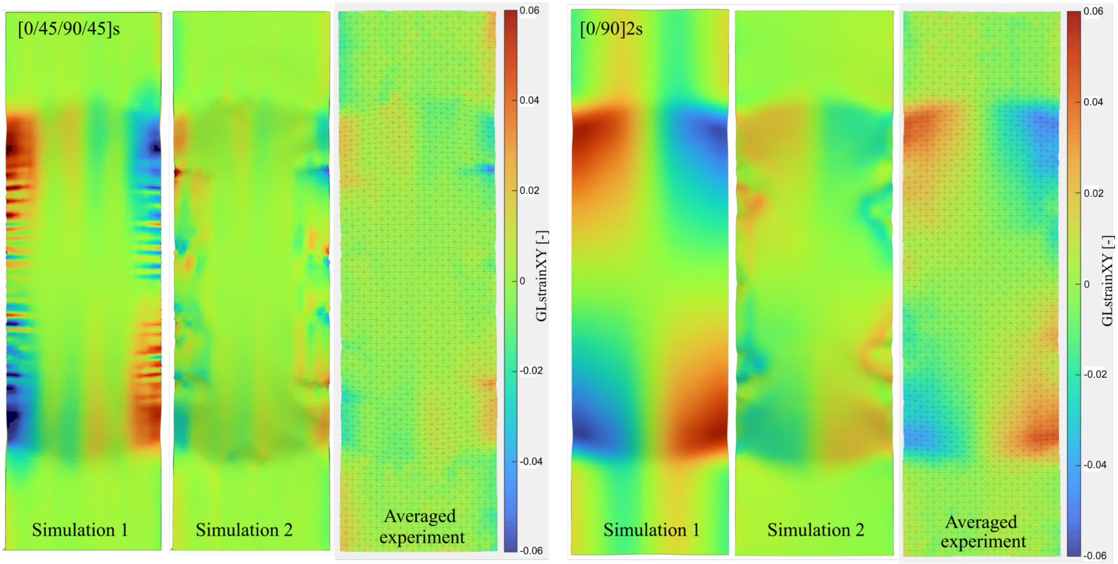

Fig. 4. Comparison of Green-Lagrange shear strains of two simulations with different material models employed and experimentally obtained Green-Lagrange shear strain for QI and cross-ply layups of TC1225 material

4. Conclusion

Press forming experiments of two unidirectional thermoplastic composite materials were performed. To track deformation during the forming process, a dot pattern was applied and subsequently digitized by photogrammetry technique and Green-Lagrange strains were calculated. This obtained dataset can serve as basis for validation of press forming simulations.

Acknowledgements

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[3] PhotoModeler Technologies, PhotoModeler Premium.