THE DESIGN OF A PRE-WARPED BUS DOOR FOR LOW COST COMPOSITE MANUFACTURING

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1 Introduction
Mass transportation Original Equipment Manufacturers (OEMs) are increasingly adopting composite technologies to develop light, strong and durable components. Continuously rising gas prices and the approach of new, stricter Corporate Average Fuel Economy (CAFE) standards further force these OEMs to actively seek increases in fuel economy and lower cost solutions. For those who have already had composite production lines for years, it is an urgent requirement to update their manufacturing technology, in order to take advantage of new materials and techniques. They must also optimize their designs to further trim weight and manufacturing costs while maintaining or improving structural performance.

In this paper, a bus entrance door was redesigned under the request of a bus OEM to adopt a low cost manufacturing technology and improve the structural performance. The manufacturing process was changed from Resin Transfer Molding (RTM) to Light Resin Transfer Molding (RTM lite). The weight of the part was reduced by simplifying the structure. The new door’s upper structure was inwardly pre-warped at its closed position to decrease the thermal deformation of the original design. Finite element analyses (FEA) were implemented to validate the structural change and material selections.

2 Original Entrance Door
The entrance door is a front side door for passengers to enter/exit the bus as shown in Figure 1. The current production door is a thick sandwich structure manufactured by RTM. The fibre reinforcements are primarily randomly oriented glass mats. Polyurethane foam is used as the core material. Figure 2 shows the composite door’s interior geometry. Figure 3 illustrates the core structure.

When subjected to an extreme temperature difference of +72.5F interior/-40F exterior, the upper end of the door displaces up to 1 in. outward from the original position. Figure 4 is a FEA illustration of the thermal deformation.

Several modifications to the door have been attempted to minimize the thermal displacement. These include stiffening the upper frame with a pair of slender steel plates to resist the thermal bending (Figure 5), and patching the frame with unidirectional fibre reinforcements that have lower thermal expansion coefficients. However, none of these solutions resulted in a significant improvement.

3 Redesign Requirements
The new door is to be made by RTM lite processing to ease manufacturing and lessen production associated capital investments. For this purpose, the original structure had to be simplified. The new design is expected to minimize thermal deformation with respect to the door frame. In addition, the new door should weigh less than the current production door.

4 Preliminary Designs
4.1 Preliminary Structural Design
The current production door’s external surface, shown in Figure 6, was retained to be the moulding surface for RTM lite processing. By keeping the surface profile and features of the production door the smoothness of the bus exterior can be maintained. A new RTM lite tool was also designed to provide a class A surface finish.

The interior structure of the new door was a simplification from the original. To reduce weight and thermal displacement, the middle section became a framed laminated structure. Only the perimeter, cross frames, and rub rail were constructed with sandwich construction. The core
height was reduced by 0.8 in. A sheet metal brace was designed to bridge the perimeter frame for handle and hinge installation. The new design suitable for RTM lite processing is shown in Figure 7.

4.2 Finite Element Model
A finite element model (FEM) of the preliminary design was created using Siemens NX 8.0. The door hinges were included to provide constraint supports to the door structure. The laminate skin, metallic brackets and glass were modeled with 2D Tria3 and Quad4 elements. Core and door hinges were simulated with 3D tetrahedron 4 brick elements. The model is shown in Figure 8.

4.3 Preliminary Material Selection
Instead of the randomly oriented fibre mats used for the current production door, the following fibre reinforcements were selected for the redesigned door and RTM lite processing:

- Fibre_1 – a 0.17lb/sq.ft fibre mat serving as both fibre reinforcement and the flow media for liquid resin infusion;
- Fibre_2 – a 0.13lb/sq.ft unidirectional fibre mat serving as a structural reinforcement;
- Fibre_3 – a 0.18lb/sq.ft +45/-45 double bias fibre mat serving as a structural reinforcement.

Fibre_2 and Fibre_3 primarily serve as structural layers providing stiffness and load carrying capacity. These particular fibre reinforcements are the frequent supplies of the OEM’s shop floor. Therefore, the material costs could be controlled.

A thin cork core was incorporated into the door’s exterior skin to act as a print blocker and improve the surface finish. The following core materials were assessed for the new design:

- Core_1 – the same polyurethane foam used for the current production door;
- Core_2 – 0.0056lb/cu.ft balsa. The balsa has similar density as the polyurethane foam but is stiffer and has a lower coefficient of thermal expansion;
- Core_3 – a 3D flexible foam core with closed cells. This core has the lowest density and is stiffer than its polyurethane counterparts.

The preliminary lay-up sequence for the laminated structure was selected as following:

Fibre_1/Fibre_2/Fibre 3/Corecork/Fibre_3/Fibre_2/Fibre_1

The door’s vertical direction was taken as the longitudinal direction for the fibre reinforcements.

Sandwich construction was preliminarily defined as:

Fibre_1/Fibre_2/Fibre 3/Corecork/Core/Fibre_3/Fibre_2/Fibre_1

4.4 Mechanical Performance
The entrance door was conservatively assessed using a set of extreme g loads that were obtained from a track test. Table 1 displays the load ratios in the x, y and z axis of the globe coordinate system.

x-axis represented the bus lateral direction, y-axis represented the bus longitudinal direction, and z-axis represented the bus vertical direction.

The door’s reaction to the g loads was assessed at the condition that the door was fully closed, e.g. the hinges and latches were fully constrained in the finite element model.

The extreme load case was the outward lateral (+x axis) acceleration combined with negative longitudinal (-y axis) and vertical (-z axis) acceleration. Figure 9 shows the reaction displacement to this load case. The results were generated using Siemens NX NASTRAN solver.

The predicted minor deformations were negligible for this application. The maximum ply and core stresses (Figure 10, Figure 11) were also small and resulted in a high margin of safety. The redesigned composite structure was sufficiently strong.

4.5 Thermal Performance
4.5.1 Temperature Difference
The door is required to sustain an extreme temperature scenario where its exterior surface is at a temperature of -40F while its interior surface is heated by blowing hot air at 72.5F. The door should be fully latched and closed for this scenario except at the upper end. The exterior door face was set to -40F. To simulate the flow of air over the door from the window defroster a convection coefficient of 1.28 Btu/hr·ft²·F at an internal air temperature of 72.5F was applied to the interior core surfaces. Due to limitations with the analysis solver, Siemens NX
NASTRAN, it was assumed that the temperature across the thickness of the laminate was constant. This is a reasonable approximation since the laminate is relatively thin. The calculated temperature distribution was used for thermal displacement analysis. Figure 12 illustrates the temperature distribution of the door with polyurethane core.

4.5.2 Thermal Bending

Siemens NX NA STRAN was used for the thermal analysis. The door hinges and middle latch were the only parts constrained to allow the top end of the door to displace freely as shown in Figure 13.

The door with polyurethane core was analyzed first. The results indicated that the new door structure did not reduce the thermal deflections. The top end still displaced 1 in. when subjected to the extreme temperature case.

4.5.3 Material Iterations

Several material and layup iterations were attempted with the intention to reduce the thermal displacement. The material and lay-up changes achieved only limited success. The maximum reduction in thermal displacement was only 15%

Figure 14 illustrates the thermal displacement of the door with laminate skin consisting of only unidirectional fibre. This laminate configuration is an extreme case to demonstrate the fibre’s capacity of minimizing the thermal displacement. The unidirectional laminate skin with low coefficient of thermal expansion could reduce the door’s thermal displacement to 0.86 in. However, It is not suitable for RTM lite processing due to a resulted low permeability for liquid resin flow.

It was expected that a core with higher stiffness might provide resistance to the thermal bending. Two stiffer core materials, Core_2 and Core_3 were assessed by first recalculating the temperature distribution. Figure 15 and Figure 16 display the analysis results. Both cores reduced the door’s thermal displacement, but the magnitude was too small to be useful.

The analysis indicates that the thermal displacement could not be significantly reduced by only replacing the material and changing the lay-up, a structural modification was necessary.

5. Pre-Warped Design

5.1 Modified Structural Design

The geometry of the preliminary design was altered in order to compensate for the thermal deflection. The upper half of the door was bent inwards 0.7 in. along a line running parallel to the bottom of the window. Figure 17 compares the original RTM lite door geometry with the new pre-warped design.

The layup used for the modified structures is given below.

Fibre_1/Fibre_2/Fibre2/Corecork/Core/Fibre_2/Fibre_2/Fibre_1

5.2 Temperature Profile

The deflection of the door under extreme cold was examined. The pre-warped door was evaluated using the same thermal conditions discussed in Section 4.5.1. The temperature profile of the door is shown in Figure 18.

5.3 Thermal Deflection

To close the door a load cylinder applies a force to the bottom hinge. The upper and mid-door latches do not engage until the door and frame dovetails are engaged as shown in Figure 19. Therefore, the deflection of the upper part of the door away from the upper latch was measured once the dovetails were fully engaged.

In order to analyze this problem a force of 100 lbf was applied to the lower hinge in the direction of the load cylinder arm. The pin locations at both the upper and lower hinges were fixed in all degrees of freedom except for the pin rotation. Surface-to-surface contact simulation objects were used to model the contact between the door panel and the frame and the seal. By pre-warping the door the deflection of the door away from the upper latch was decreased to only 0.1 in. as shown in Figure 20.

5.4 Pre-Warped Door Strength

The stresses in the laminate and core were examined when the door was in its fully closed position. The strength ratio of each ply was calculated using the Hoffman failure criterion. The lowest strength ratio was 1.32 and occurred in one of the unidirectional plies at the corner of the lowest tapping plate. The strength ratio values for the critical ply are shown in
Figure 21 where the darkest color represents the lowest strength ratio.

The highest core stresses occurred at the upper tapping plate and the corners of the rub rail as shown in Figure 22. The minimum safety factor for the core was 1.42.

5.5 Manual Closing Force

It was thought that the pre-warp in the door would make it more difficult to manually close if required. An additional analysis was performed to ensure that one person could manually shut the entrance door. This analysis was performed at room temperature and with all other loads removed. A force of 50 lbf was applied to the door between the door handle opening and the frame. Figure 23 shows that the 50 lbf force was sufficient to close the door and compress the seal.

6 Design Improvements

The redesigned door provided additional benefits besides the improved thermal performance. The weight was reduced by 31 lb, a 22% reduction from the current production door. Additionally, the cost to manufacture the new RTM lite door was reduced by 45%.

7 Conclusions

A bus entrance door was successfully redesigned to reduce manufacturing costs and weight, and to decrease the thermal displacement. The new RTM lite door was pre-warped inward and resulted in greatly reduced deflection of the door under a severe thermal gradient. The redesigned door was also estimated to be 24% lighter, and 45% less expensive, than its original RTM counterpart.
Fig. 4. Thermal deformation of the production door

Fig. 5. Attempted modification - stiffened door frame

Fig. 6. External surface

Fig. 7. Preliminary interior structure design

Fig. 8. FEM for the preliminary design

Figure 9. Lateral displacements due to outward acceleration
Fig. 10. Maximum ply stress of the laminate skin

Fig. 11. Maximum stress in core structure

Fig. 12. Temperature distribution

Fig. 13. Thermal displacement of new door structure

Fig. 14. Door constructed with unidirectional laminate

Fig. 15. Door with balsa core
Fig. 16. Door with 3D flexible foam core

Fig. 17. Original prototype geometry compared to pre-warped prototype geometry

Fig. 18. Temperature profile of the pre-warped door

Fig. 19. Dovetails fully engaged

Fig. 20. The deflection away from the upper latch
Fig. 21. Strength ratio for the critical ply

Fig. 22. Stress in the core

Fig. 23. Door profile under 50lbf of closing force