# Characterization of Defects in Low-Cost Resin-Infused Aeronautical Structures

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**SUMMARY**: Mechanical tests have shown that vacuum assisted resin transfer molding (VARTM) produces consistent, high quality solid laminates made with E-glass/epoxy vinyl ester. However, these laminates have never been employed in certified aeronautical structures and the process for certification of sandwich structures is even more complex. The objective of this work was to develop an understanding of process-induced defects in E-glass/epoxy vinyl ester sandwich panels with a PVC closed cell foam core, fabricated using VARTM. A variety of non-destructive evaluation (NDE) techniques were used to establish their potential for identifying these defects and to correlate the results with visual observations. It was found that thermography and bondline analysis were effective at detecting and characterizing defects such as dry spots and incomplete resin infiltration. Preliminary evaluations of the flow rate under the influence of processing excursions showed that even a small air leak could increase infiltration time by as much as 25%.

**KEYWORDS**: VARTM, defects, sandwich structure, closed-cell foam core, fiberglass, non-destructive evaluation

## INTRODUCTION AND BACKGROUND

E-glass/epoxy vinyl ester composites fabricated by the vacuum assisted resin transfer molding (VARTM) process have shown excellent potential in a range of applications, including kit aircraft, but have never been employed in certified aeronautical structures. Certification-related mechanical tests have shown that VARTM produces consistent, high quality solid laminates [1]; however, the more complex certification of sandwich structures has yet to be addressed. To support this certification process, an understanding of process-induced defects is critical. Previous work in the area of the effect of defects on composite structural performance has shown that tensile, flexural and shear strengths were reduced in the presence of defects such as dry fibers, interfacial cracks, or inclusions in the skin [2].

For example, studies have shown that interfacial cracks artificially induced by Teflon inserts can have an adverse effect on shear strength after they reach a critical length between 25 and 30 mm [3]. However, only limited work has been performed specifically on the evaluation of process-induced defects [4]. The aim of this work was to gain a better understanding of the flow patterns and process-induced defect development in a particular VARTM process variant. An analysis of the flow through the fiber preform was carried out and an assessment of the commonly occurring defects, along with the NDE techniques to detect them, was performed.

## EXPERIMENTAL APPROACH

### *Specimen Fabrication*

Trials were performed on 7781 E-glass and PVC closed cell foam core sandwich structures with Derakane Momentum 411-350 epoxy vinyl ester resin (Fig. 1). The core material had a density of 86.5 kg/m$^3$ and a thickness of 6.4 mm. Three plies of 0.5 mm thick glass fabric were used for the sandwich panel skins. One layer of distribution medium was placed on the top skin. Infiltration of the bottom skin was accomplished by an array of small holes drilled in the foam core. The hole spacing was set to 25.4 mm and 30 mm in the panel width and flow directions, respectively. Specimens were fabricated in an instrumented VARTM test cell where the flow front evolution was recorded by two digital cameras mounted above and below a glass tool plate. Prior to the infusion, the resin viscosity was adjusted to 275 cP by adding monomeric styrene. The vacuum pressure was adjusted to 96.5 kPa and the infusion was performed at room temperature (20 °C).

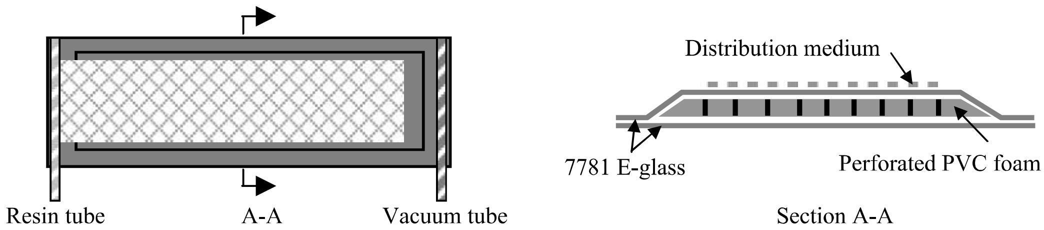


Fig. 1 Schematic of sandwich panel specimen

### Non-Destructive Evalutaion

A series of non-destructive evaluation techniques were used to examine two representative specimens containing a dry spot and exhibiting incomplete resin infiltration. These specimens were examined using image analysis, edge of light (EOL), thermography, ultrasonic (UT) C-scan, X-radiography, and bondline testing [5,6].

## RESULTS AND DISCUSSION

### *Identification of Defects*

A trial and error approach was used to fabricate specimens containing process-induced defects and resulted in the identification of three types of defects: bubbles, dry spots, and incomplete resin infiltration. Bubbles were categorized as air that infiltrated the resin during infusion because of vacuum bag leakage. Two common sources of leaks appeared to be poor vacuum bag integrity caused by damage or aging, and degradation of the seal between the bag and the tool. These problems were easy to rectify prior to infusion by monitoring the pressure of the bag after the vacuum pump was turned off. The flow disturbances resulting from an undetected leak were analyzed using a flow rate image analysis program and are reported in Fig. 2. It was clear that even a small leak could significantly affect the specimen infiltration time, since the presence of such a leak increased the specimen total infiltration time by 25%, from 16 minutes to 20 minutes.

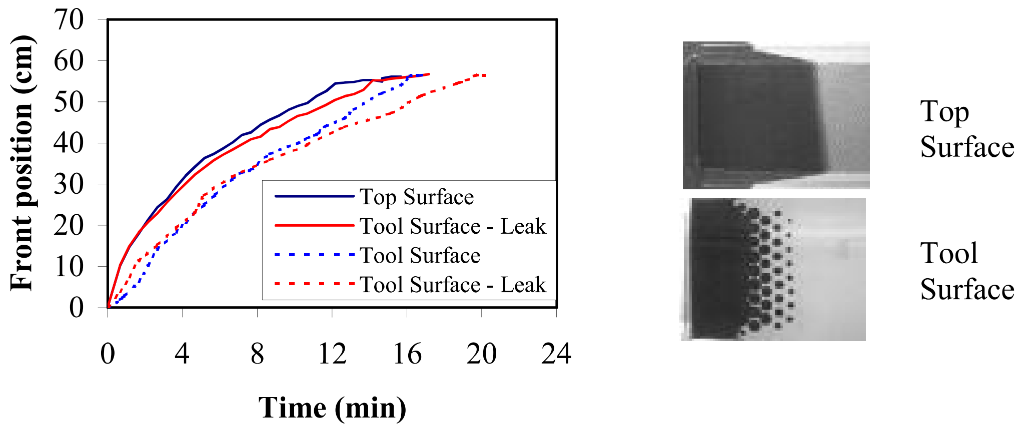


Fig. 2 Effect of vacuum bag leak on top and tool side flow front position and typical specimen infiltration pattern.

Two other defects, dry spots and incomplete resin infiltration, were examined by a number of non-destructive inspection (NDE) techniques. Dry spots occurred where resin did not saturate the preform due to race-tracking on an alternate flow path. It was observed that depending on the location of the dry spot, if the gel time was sufficiently long and the resin viscosity remained sufficiently low, then any dry spots would eventually become saturated with resin unless the resin reached the vacuum port first. Incomplete resin infiltration was related to the flow of the resin through the infiltration holes in the foam core. In some cases, the resin did not fully coalesce on the tool side of the part so the resin flow pattern could be detected.

### *Summary of NDE results*

One specimen with a visually evident dry spot and one specimen with incomplete resin infiltration were analyzed with the NDE techniques identified previously. With the exception of bondline analysis and X-radiography, images from each NDE method are included in this paper. Although newer bond-testing equipment has a recorded output, the bondline analysis equipment available at NRC does not have this capability.

However, manual results indicated that this method was very effective for detection of most of the visible defects. The X-radiography results provided visual analysis of the defects, but only very large defects were apparent, even with the aid of high intensity light and magnification. Therefore, this technique is not recommended for these types of specimens with similar defects. The NDE images acquired for a specimen with a dry spot are summarized in Fig. 3.

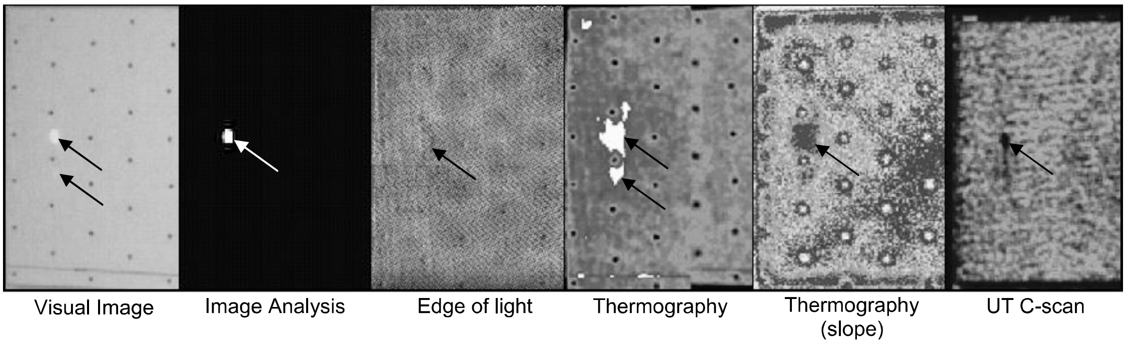


Fig. 3  Results of NDE of specimen containing a dry spot

The first image on the left shows the extent of the defect apparent to the naked eye, including a very obvious dry spot with a smaller spot beneath. The larger dry spot was detectable by all of the NDE techniques shown; however, the smaller spot could only be identified in the thermography images. It should be noted that the results from the UT C-scan image were not conclusive since similar signals that did not correspond to dry spots appeared elsewhere on the specimens. It is obvious that thermography provided a clear image of the defects and the most conservative estimate of the extent of the defect. It will be necessary to perform destructive inspection to determine if the extent of the defect is more closely represented by the infrared image or the slope of the infrared image. Similar NDE analysis was performed on a specimen that experienced incomplete resin saturation, as shown in Fig. 4

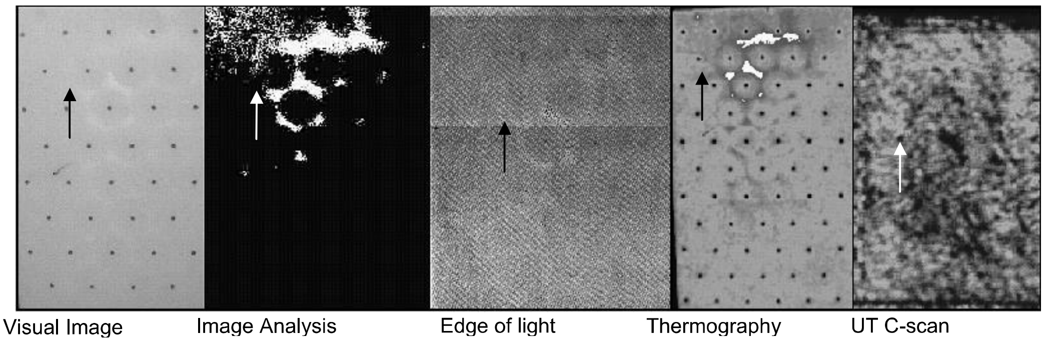


Fig. 4  Results of NDE of specimen containing incomplete resin infiltration

The image on the left again shows the extent of the defect that was visually evident. With the exception of the UT C-scan image, each technique was able to identify the defect. In fact, with thermography and image analysis, the extent of the defect is apparently larger than in the visual image.

The UT C-scan did not provide a clear representation of the defect and therefore, was not used for further investigations. While EOL was capable of detecting the defects, it was more time consuming and would only detect the defect if there were associated surface anomalies.

**CONCLUSIONS**

Several NDE techniques were evaluated for their ability to characterize process-induced defects. This work showed that thermography was a very effective method. There is also potential in bondline analysis provided that it includes a recorded output. Further work must evaluate the defects to develop a system of defect metrics that could be used for modeling applications. Preliminary studies on the effects of process parameters on part quality showed that there was a significant effect of vacuum pressure loss on both the development of defects and the resin flow rate.

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