Direct Fabrication of Polymer Composite Structures with Curved LOM

Donald Klosterman, Richard Chartoff, Mukesh Agarwala
Ira Fiscus, John Murphy, Sean Cullen, Mark Yeazell

Rapid Prototype Development Laboratory
University of Dayton
300 College Park
Dayton, OH 45469-0131

ABSTRACT

This report describes the application of Curved LOM to the direct fabrication of polymer matrix composites (PMCs). The overall methodology of directly fabricating PMC parts involved the use of the Curved LOM machine to lay-up and shape "green" composite laminates from prepreg feedstocks, followed by vacuum bag / oven cure and consolidation. The conventional Curved LOM laminator was replaced with a vacuum thermoforming apparatus to better accommodate the bonding of commercially available prepregs. The study also demonstrated that it is possible to interface a general composite design software package with the Curved LOM machine via the curved slice file (.CSF) format. Taken together, these two improvements allow for improved flexibility in manufacturing PMC components, from both a material handling and a design point-of-view. A simple C-shaped panel was fabricated and tested to demonstrate the overall feasibility of the process for PMCs. A glass fiber / epoxy prepreg obtained from a commercial supplier was used as a model material system. It was found that the cumulative accuracy of the overall process was good, and the mechanical properties of the laminates were acceptable for non-structural applications for which the material is normally used.

INTRODUCTION

The Curved-Layer Laminated Object Manufacturing process (Curved LOM) was developed for direct, automated fabrication of curved layer structures made from high temperature materials such as ceramic matrix composites (CMCs) or monolithic ceramics. Full description of the process can be found in previous publications [1, 2, 3]. Described in this report is the application of Curved LOM to the direct fabrication of polymer matrix composites (PMCs). The availability of a direct method for rapidly and inexpensively producing PMC prototype components would be of great benefit to the composites design and manufacturing community. Currently, the effort and cost involved in the design and fabrication of PMC prototype components can be great. The design community needs a rapid, low-cost prototype manufacturing capability that can fabricate prototype parts of comparable quality to those produced via traditional techniques. In fact, aerospace designers have been recently turning to rapid prototyping technologies for potential new solutions [4]. Using LOM for the lay-up of PMC prototype laminates will allow for the simultaneous evaluation of new materials and design concepts, enabling rapid design and fabrication of competing prototypes.

The purpose of this report is to describe recent improvements made to the hardware and software capabilities of the Curved LOM apparatus (see [3] for a previous status report). These updates were made to allow for improved flexibility in manufacturing PMC components, from both a material handling and a design point-of-view. A simple C-shaped fiber glass / epoxy panel was fabricated to demonstrate the overall feasibility of the process for PMCs. Using this demonstration component and other fabricated flat panels, the dimensional accuracy of the overall process was determined, and the quality of the panels was assessed through measurements of the fiber volume fraction and interlaminar shear strength.

HARDWARE IMPROVEMENTS

Improvements were made to the Curved LOM apparatus to better accommodate commonly available PMC materials. Preimpregnated fiber preforms, or "prepregs", are widely used by manufacturers of composite products. Prepregs are flat sheets containing fibers (usually continuous unidirectional or woven fabrics) and a polymer resin. It is common industrial practice to build parts by cutting the prepregs to shape and laying them up manually. Layers are compacted manually using a roller and/or vacuum diaphragm in order to dispel air from in between layers. This compaction capability was not available on the initial version of the Curved LOM machine [3]. Thus, a vacuum thermoforming apparatus was developed in order to improve on total pressure available and pressure uniformity.

The new laminator design is illustrated in Figure 1. A flexible, resistively heated pad is sandwiched between two silicone rubber diaphragms. The composite diaphragm is stretched over and secured to the open side of a 13 inch x 13 inch x 3 inch aluminum box. This mechanism is shuttled directly over the LOM-paper mandrel, which is supported by a vacuum plate. A prepreg is placed over the mandrel, and the build platform is elevated until it seals with the laminator. A vacuum is drawn through a perimeter channel that has been bored in the vacuum plate. A porous "breather ply" (not shown), such as a woven fiberglass layer, can be placed over the lay-up to ensure even vacuum distribution over the entire part area. With a breather ply in place, the vacuum pressures at the top center and far edge of the part were measured to be 11.8 psi and 12.0 psi, respectively. It is possible to provide additional pressure via compressed gas using the vent tube. Currently, the maximum size part that can be made is 8 inch x 8 inch x 3 inch. Given the envelope of the LOM machine housing, it is possible to scale-up to 30 inch x 20 inch x 5 inch parts.

SOFTWARE IMPROVEMENTS

The interaction of software programs necessary for Curved LOM is illustrated in Figure 2 (see [1] for an expanded description). The algorithms are incorporated in two separate packages. First, LOMSlice 2.0 is used to slice an .STL file into a series of curved layers. The information of each layer, namely the X Y Z coordinates of the layer cross section, is stored in a separate .CSF (Curved Slice File) file. Thus, each part is represented by a series of .CSF files, equal to the total number of layers required to build the part. Next, the .CSF files are exported to 3D LOMSlice which drives the Curved LOM machine via an eight-axis motion control card.

This scheme is problematic for building PMC parts, based on the inherent shortcomings of the .STL file format. Because the .STL format is a surface representation, it cannot contain layer-by-layer information such as ply architecture (i.e. fiber direction) needed to fully describe a composite structure. Furthermore, engineers who design composite structures are typically not familiar with the .STL format. On the other hand, the .CSF format *is* of the appropriate geometrical format, although it is also relatively unknown to composite designers. One purpose of this study was to demonstrate the potential use of .CSF files as a "neutral exchange" format, providing the link between the Curved LOM machine and software/file formats typically used by composite designers.

The design of composite structures is normally accomplished with suites of software packages that have been developed to accommodate all aspects of composite design, such as ply shape definition, prepreg orientation and stacking sequence, and structural analysis and optimization [e.g. 5]. Through simulation, designers determine the best ply architecture (i.e., shape, sequence, and orientation of prepreg layers) for a given part subjected to the expected loading conditions. Some software packages [6] have the additional capability of providing a direct link from 3D CAD geometry to automated equipment, such as prepreg cutters and laser projection systems used on the manufacturing floor.

Based on this existing capability for direct machine control, it is not difficult to envision the possibility of controlling the Curved LOM machine by these packages. The motions of the various Curved LOM hardware elements are controlled by an off-the-shelf machine control board (Galil DMC-1000). However, instead of having commercial design software packages interface directly with this DMC card, it may be easier to output .CSF files. Illustrated in Figure 3 is an example of a software package that accomplishes this task. This package, referred to as Curved Composite Panel Designer (CCPD), creates the ply information for simple "C" shell composite panels. The user inputs the desired width, height, length, shell thickness, layer thickness, and layer-by-layer ply orientation of a simple "C" panel containing parabolic surfaces. The program outputs a series of .CSF files, each containing the XYZ coordinates and ply orientation of a single layer. The program is also capable of creating a simple "tool outline" file, which greatly simplifies the accurate placement and registration of the LOM-paper mandrel in the Curved LOM machine. In a similar manner, it is thought that commercially available software design packages could be readily augmented with a "Curved LOM" output module or "translator" to perform the same function, as illustrated in Figure 2. Since such software programs are CAD-based, it would also be possible to output the necessary .STL files for creating the curved mandrels, which can then be built with flat LOM or other SFF techniques. Overall, the benefit of such an effort would be to drastically improve the availability of rapid prototyping methods such as LOM to the composite design community.

PMC PROTOTYPE FABRICATION

The methodology for direct fabrication PMC components with Curved LOM is illustrated in Figure 4. Prepregs are used as feedstocks due to their wide commercial availability and ease of processing. The LOM machine is used as a means of automated lay-up and cutting, ideally eliminating touch labor and improving accuracy and consistency. Throughout the process, some heat can be used to assist lamination if necessary. However, it is desirable to keep the prepregs and the part in a state of minimal cure. It is advantageous to perform most of the cure and consolidation in one step *after* the part is completely layed-up. This approach will ensure that layer compaction, resin flow (which assists compaction), and the majority of the resin polymerization will occur simultaneously *and* uniformly throughout the part, as a result of the steady pressure and temperature conditions. This consolidation cycle can be performed using a variety of techniques, such as an autoclave cure or matched die press molding, but vacuum bag / oven cure was chosen to remain consistent with the idea of low cost processing.

A simple "C" shell panel was fabricated for the purpose of demonstrating the overall Curved LOM fabrication of a PMC, including the new hardware and software capabilities. A glass fiber / epoxy prepreg, obtained from a commercial supplier [7], was used as a model PMC material system. The prepreg was comprised of a woven E-glass fiber mat (plain weave, style 7628) impregnated with a B-staged (partially cured), catalyzed Novolac epoxy resin system. The resin content and thickness of the prepreg were 35 wt% and 0.0085 inches, respectively. The prepreg was slightly tacky to the touch at room temperature, and thus it was supplied with a removable backing ply (thin plastic sheet, like cellophane).

First, a LOM-paper mandrel was created to support the "C" shell. An .STL file for the LOM-paper mandrel was created using the .STL file of a "C"shell part and LOMSlice 2.0 software, as illustrated in Figure 2. The mandrel was built on a LOM 1015 machine using Helisys LPH008 paper. Next, the dimensions of the "C" shell, the average cured thickness of the prepreg (0.007 inches), and the lay-up sequence (16 ply, quasi-isotropic), were input to CCPD software program. The resulting sixteen .CSF files were loaded into 3D LOMSlice. The LOM-paper mandrel was placed on the Curved LOM build platform. The prepregs were layed-up on the mandrel by hand (the automatic sheet feeder was disassembled due to redesign and implementation of the new laminator). A mylar film and woven glass fiber mat (Crowfoot weave, Style 120) were placed over each layer to serve as release and breather plies, respectively. Each layer was laminated for 30 seconds at room temperature. After lamination, the mylar and breather plies were removed prior to laser cutting. All sixteen plies were processed without problem.

The finished green part with attached LOM-paper mandrel were removed in one piece from the Curved LOM machine, placed on an aluminum sheet, vacuum bagged [8], and placed in a temperature-controlled oven. The cure cycle was 25 to 150°C in one hour, three-hour hold at 150°C, and free cool to 25°C. The vacuum pressure was maintained at >14 psi for the duration. The resulting part and a similarly fabricated body armor panel are shown in Figure 5. During the cure cycle the LOM paper mandrel shrunk by 11% in the z direction, and zero in the width and length. The "C" shell experienced spring-back (which is normally encountered in curved PMC panels), and thus, its dimensional change was much less than the mandrel. In fact, the cured "C" shell fit almost perfectly on a freshly-built mandrel, as illustrated in Figure 5.

DIMENSIONAL ACCURACY AND MECHANICAL PROPERTIES

The cumulative dimensional accuracy of the process is summarized in Table 1. No attempt was made to incorporate shrinkage compensation factors into the original dimensions. All measured final dimensions except height were within 1% of the design specification. Two possible sources of error for the height dimension are: LOM process-related error (likely due to platform motion and level control) and cure shrinkage in the direction of curvature. Due to the reinforcing fibers, it is unlikely that the second consideration is significant. Thus, additional study of the platform motion and control is needed. On the other hand, the laser gantry X Y motions seem to be highly accurate, as manifested by the small deviations in the length and width dimensions.

Table 1: Cumulative dimensional accuracy of glass fiber / epoxy "C" shell part made with Curved LOM / vacuum bag oven cure process.

Dimension	Target / Design Specification	Measured on Final Cured Part	Deviation
Length (inch)	5.00	4.98 ± 0.01	-0.4%
Width (inch)	4.818	4.775 ± .0003	-0.9%
Height (inch)	0.956	0.88 ± 0.01	-7.9%
Part Thickness (inch)	0.112	0.113 ± 0.003	+1.0%

Edge burning can clearly be seen on the PMC parts, due to charring from the cutting action of the CO_2 laser. Figure 6 shows a close-up of a laser cut line on the glass fiber / epoxy prepreg. The total laser kerf, including char zone, is about 0.5 mm. Previous studies have shown that this degradation can be minimized or eliminated only by using other types of lasers capable of photoablation [9]. The effect of the charred edges on the mechanical properties of the resulting panels is unknown.

In general, the fiber volume fraction in composite panels serves as a primary point of comparison. Based on the cured thickness, number of plies, prepreg fiber areal weight, and fiber theoretical density, the fiber volume fraction was calculated to be 44%. Given the method of consolidation, i.e. vacuum bag / oven cure, this result was promising. Furthermore, this number was moderately repeatable (41-45 volume%) for several flat and curved panels made from the same prepreg in a variety of sizes (2.5"x4" to 6"x6", 5 to 18 layers thick). In high performance aerospace applications, composites with fiber volume fraction of 60-70% are required. However, this usually necessitates the use of expensive autoclaves for consolidation and cure. Thus, the LOM / vacuum bag processing route seems to be a feasible method for quick, low-cost manufacture of reasonable quality PMC parts. If higher fiber volume fraction is desired, the uncured LOM laminates could be consolidated in an autoclave.

The interlaminar shear strength test [10] is widely used as a screening tool for PMCs. Flat panels of two different thicknesses were fabricated on the Curved LOM machine using the glass fiber / epoxy prepreg, followed by the vacuum bag / oven cure cycle as described above. Test coupons were cut from the cured panels using a diamond cutter. The test results are given in Table 2. It is often difficult to size the specimens such that a delamination/shear failure is observed in the test. In the present case, two different sized specimens failed in the proper mode, with almost identical match in the calculated interlaminar shear strength. Another specimen failed at a higher strength, but the observed failure mode was not shear. Thus, it would be prudent to report a value of approximately 3600 psi as the measured shear strength.

Table 2: shear strength results[1] for flat panel, glass fiber / epoxy composites fabricated with Curved LOM and vacuum bag / oven cure cycle.

Sample Set # (nominal width x thickness)	Bend Configuration	# layers in sample	Failure Mode	Short Beam Shear Strength (psi)	σ (4 samples each)
#1 (0.25"x0.07")	3 point (0.5" span)	10	Delamination	3637	328
#2 (0.375"x0.125")	3 point (1.0" span)	18	Delamination	3565	191
#3 (0.375"x0.125")	4 point (1.0" span)	18	Compression from pins	5838	732

[1] Span:depth ratio in all cases was ~ 8:1. Test conditions were 0.05 inches/minute crosshead speed, 0.25 inch diameter loading pins, and room temperature.

No manufacturer data was available on the shear strength properties of this prepreg. In general the highest performance composites, fabricated from structural resins and consolidated with autoclaves, have shear strength values as high as 12,000-18,000 psi. Possible reasons for the shear strength of the current material being lower than this are the following: the resin is inherently not suited for structural applications; vacuum bag consolidation does not lead to the highest possible fiber volume fraction; and the span:depth ratio (8:1) was larger than normally used in the short beam shear test (5:1), which will reduce the apparent shear strength. However, the normal use of the current material is in abrasion resistant, electrical applications, such as bearing insulation. It is thought that the shear strength is adequate for such applications.

RELATED RESEARCH

Significant related research has recently been completed that provides science-based tools to quantify the ability to laminate PMC prepregs on the Curved LOM machine, predict layer compaction, and predict the extent of cure during LOM processing. These results are the subject of future publications [11, 12, 13]. This new approach will eliminate trial-and-error methods of determining the suitability of new materials in the Curved LOM process, as well as guide the user in determining machine operating conditions.

CONCLUSIONS

Hardware and software for the Curved LOM Process was upgraded to improve the ability for direct fabrication of polymer composite prototypes. A simple "C" shell was fabricated from a commercially available prepreg to demonstrate the new capabilities. The Curved LOM process was used to fabricate the "green" (uncured) part, and a vacuum bag / oven cure cycle was used to provide final consolidation and cure. The accuracy of the overall process was found to be good, as most dimensions were within 1% of the design specification without incorporating shrinkage compensation factors. The interlaminar shear properties of the cured laminates was judged as acceptable for the normal applications of the material.

ACKNOWLEDGMENTS

The authors wish to thank Dr. William Coblenz (DARPA) and Dr. Steven Fishman (ONR) who have supported the development of Curved LOM over the past several years. Application of Curved LOM to polymer matrix composites was supported by a Research Challenge Grant from the Ohio Board of Regents. The authors would like to thank Mr. Jerry Fleeson of Lectromat, Inc. for donating the polymer pregpreg used throughout the study. The authors would also like to acknowledge Mr. Don Byrge for mechanical testing advice and Mr. Gary Andrews for specimen preparation.

REFERENCES

1. Klosterman, D., R. Chartoff, N. Osborne, G. Graves, A. Lightman, G. Han, A. Bezeredi, S. Rodrigues, "Development of a Curved Layer LOM Process for Monolithic Ceramics and Ceramic Matrix Composites," *Rapid Prototyping Journal*, Vol. 5, Issue 2, 1999.
2. Klosterman, D., R. Chartoff, N. Osborne, G. Graves, A. Lightman, G. Han, A. Bezeredi, S. Rodrigues, "Development of a Curved Layer Process for Fiber-Reinforced Composite Materials," *Eighth European Conference on Rapid Prototyping and Manufacturing,* Nottingham, UK, July, 1999.
3. Klosterman, D., R. Chartoff, N. Osborne, G. Graves, A. Lightman, G. Han, A. Bezeredi, S. Rodrigues, "Curved Layer LOM of Ceramics and Composites," *Solid Freeform Fabrication Symposium Proceedings,* University of Texas at Austin, Austin, TX, August, 1998, pp. 671-680.
4. Hayse, S. R., "RTM Aerospace Components Developed Using Rapid Prototype Tooling," *43rd International SAMPE Symposium Proceedings*, Anaheim, CA, May 31-June 4, 1998, pp. 1715-1723.
5. *CompositePro*, Peak Composite Innovations, 11372 W. Parkhill Dr., Littleton Colorado, 80127 USA.
6. *FiberSim™*, Composite Design Technologies, Inc., 235 Wyman St., Suite 110, Waltham, MA 02451-1219 USA.
7. Product 95-147, Lectromat, Inc., P.O. Box 608, Mars, PA, 16046, USA.
8. According to *Standard Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation*, ASTM Standard D5687 / D5687M–95.
9. Lightman, A., G. Han, "Laser Cutting of Ceramic Composite Layers," ," *Solid Freeform Fabrication Symposium Proceedings,* University of Texas at Austin, Austin, TX, August, 1996, pp. 291-298.
10. *Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method,* ASTM Standard D2344 – 84.
11. Popp, A., D. Klosterman, R. Chartoff, "Development of Science-Based Tools for Material and Process Considerations in Curved LOM, Part I: Application and Use of a Tack Test," *Rapid Prototyping Journal*, manuscript in development.
12. Bryant, E., D. Klosterman, L. Flach, R. Chartoff, "Development of Science-Based Tools for Material and Process Considerations in Curved LOM, Part II: Development and Verification of a Thermal / Cure Model" *Rapid Prototyping Journal,* manuscript in development.
13. Bryant, E., *Development and Verification of a Thermal and Kinetic Model for Curved-Layer Laminated Object Manufacturing of Polymer Matrix Composites*, M.S. Thesis, Chemical Engineering, University of Dayton, December, 1999.

ILLUSTRATIONS

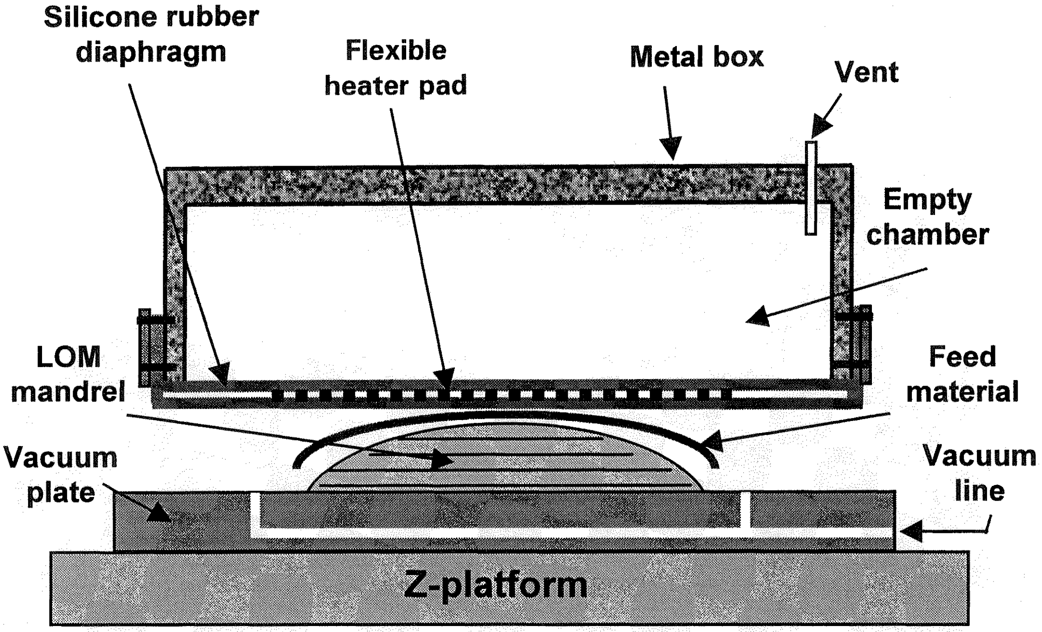


Figure 1: cross sectional schematic of Curved LOM laminator and platform.

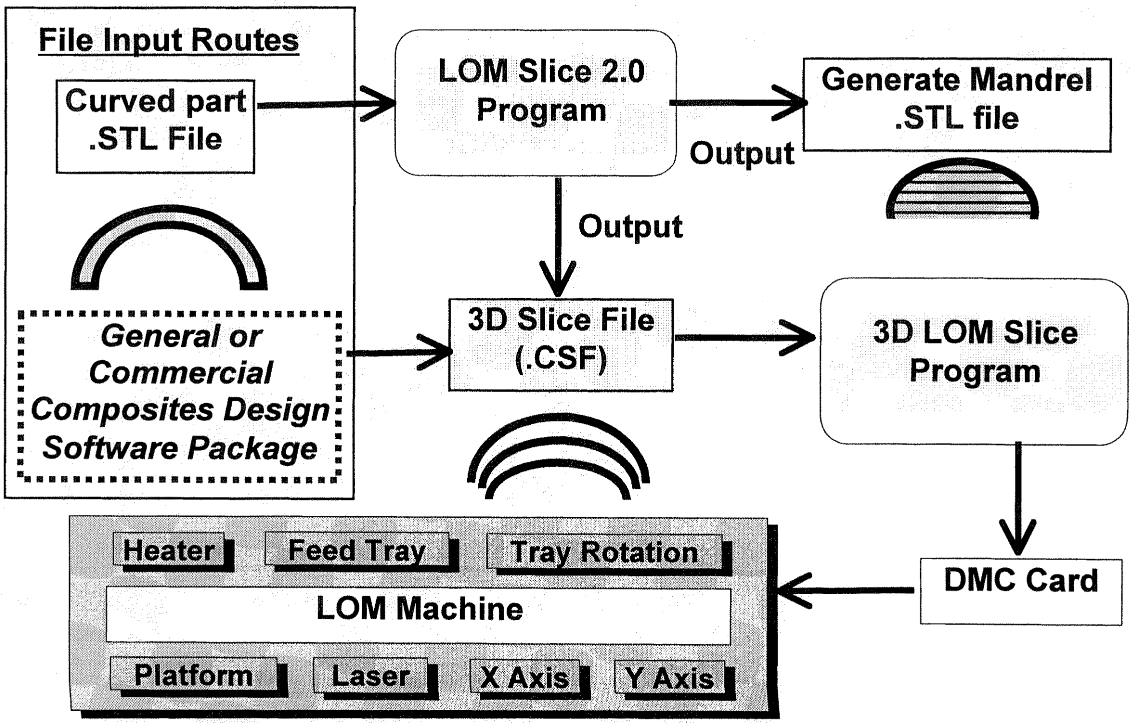
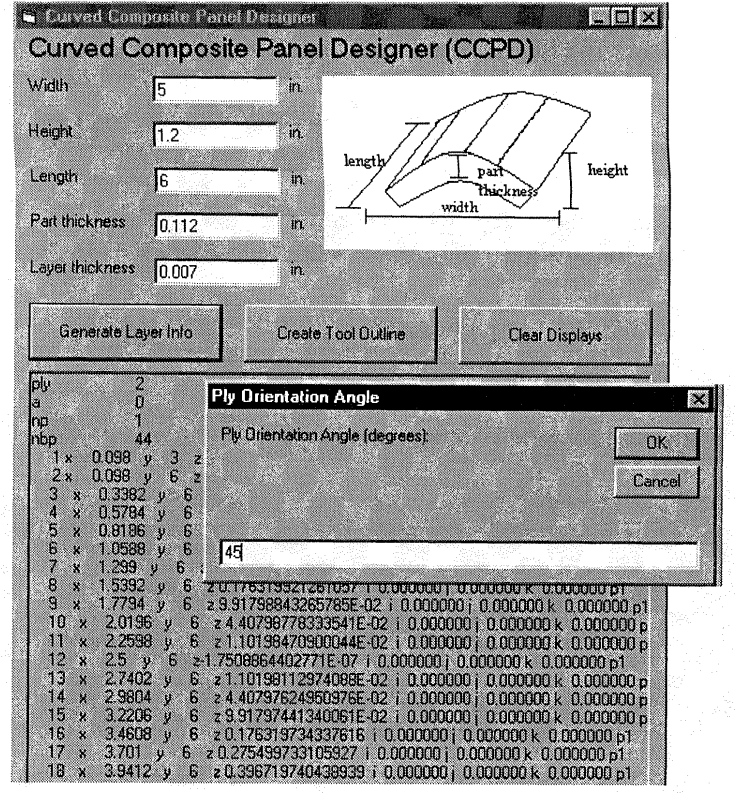


Figure 2: Interaction of software packages and file formats required for Curved LOM. The use of CSF files allows for direct use of general/commercial composite design software packages, by-passing the STL file.



Curved Composite Panel Designer (CCPD)

Width: 5 in.

Height: 1.2 in.

Length: 6 in.

Part thickness: 0.112 in.

Layer thickness: 0.007 in.

Ply Orientation Angle (degrees): 45

```
ply        2
a          0
np         1
nbp       44
  1 x   0.098  y  3  z
  2 x   0.098  y  6  z
  3  x  0.3382  y  6
  4  x  0.5784  y  6
  5  x  0.8186  y  6
  6  x  1.0588  y  6
  7  x  1.299   y  6
  8  x  1.5392  y  6  z 0.176319921261037 i 0.000000 j 0.000000 k 0.000000 p1
  9  x  1.7794  y  6  z 9.91798843265785E-02 i 0.000000 j 0.000000 k 0.000000 p1
 10  x  2.0196  y  6  z 4.40798778333541E-02 i 0.000000 j 0.000000 k 0.000000 p
 11  x  2.2598  y  6  z 1.10198470900044E-02 i 0.000000 j 0.000000 k 0.000000 p
 12  x  2.5  y  6  z-1.75088644027771E-07 i 0.000000 j 0.000000 k 0.000000 p1
 13  x  2.7402  y  6  z 1.10198112974088E-02 i 0.000000 j 0.000000 k 0.000000 p
 14  x  2.9804  y  6  z 4.40797624950976E-02 i 0.000000 j 0.000000 k 0.000000 p
 15  x  3.2206  y  6  z 9.91797441340061E-02 i 0.000000 j 0.000000 k 0.000000 p
 16  x  3.4608  y  6  z 0.176319734337616 i 0.000000 j 0.000000 k 0.000000 p1
 17  x  3.701  y  6  z 0.275499733105927 i 0.000000 j 0.000000 k 0.000000 p1
 18  x  3.9412  y  6  z 0.396719740438939 i 0.000000 j 0.000000 k 0.000000 p1
```

Figure 3: example of general composite design package, Curved Composite Panel Designer (CCPD), in which composite ply information is output as XYZ coordinates.

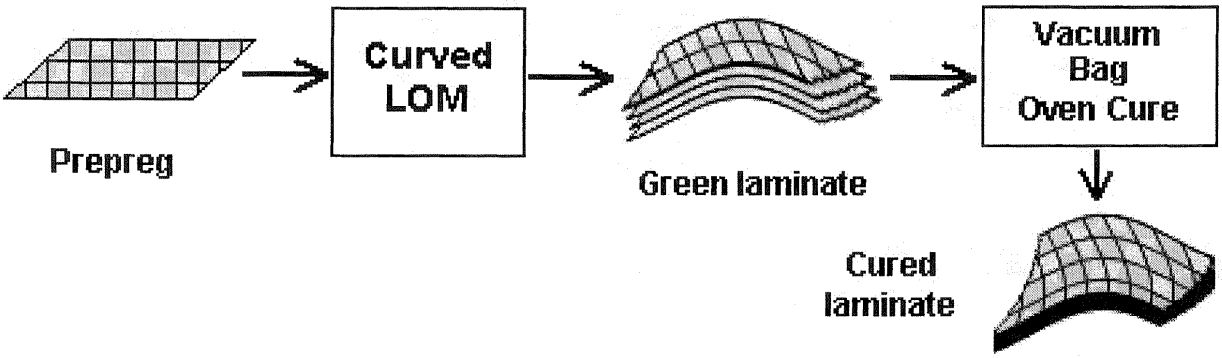


Figure 4: Curved LOM processing methodology for polymer composites, involving use of Curved LOM to form "green" (uncured) panels which are subsequently cured in a low-cost vacuum bag / oven cure cycle.

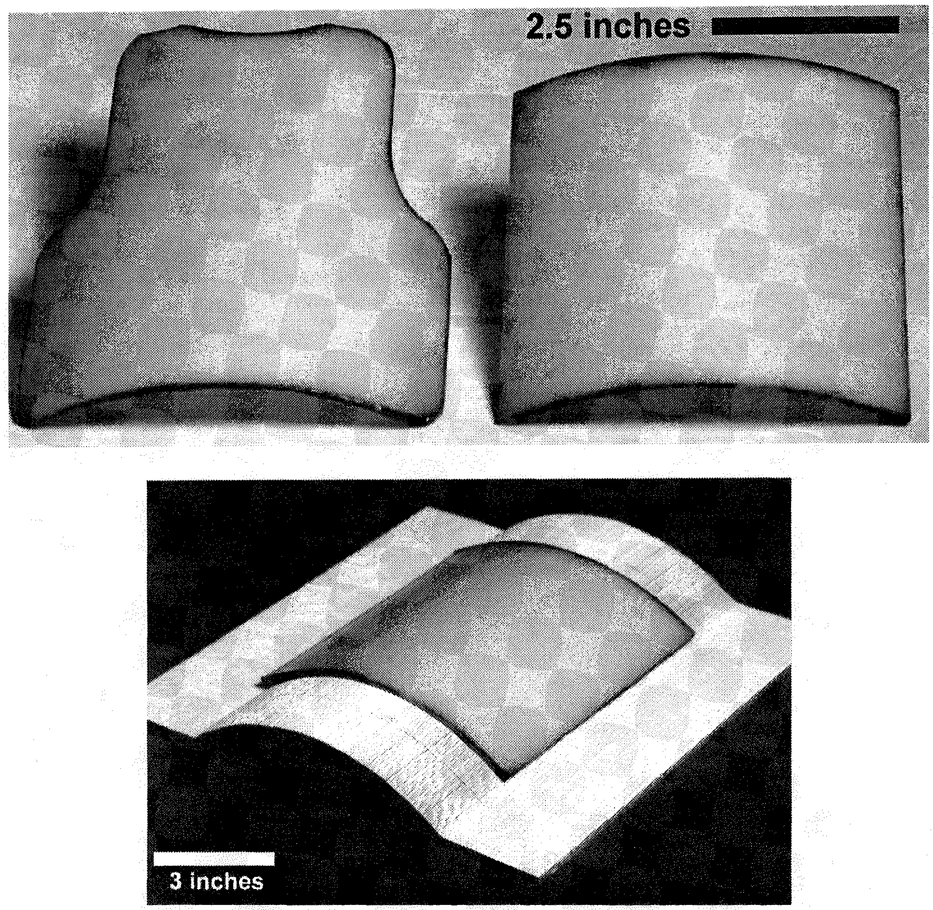


Figure 5: (above) cured, glass fiber/epoxy composite parts made with Curved LOM, and (below) cured, curved layer part resting on fresh LOM-paper mandrel.

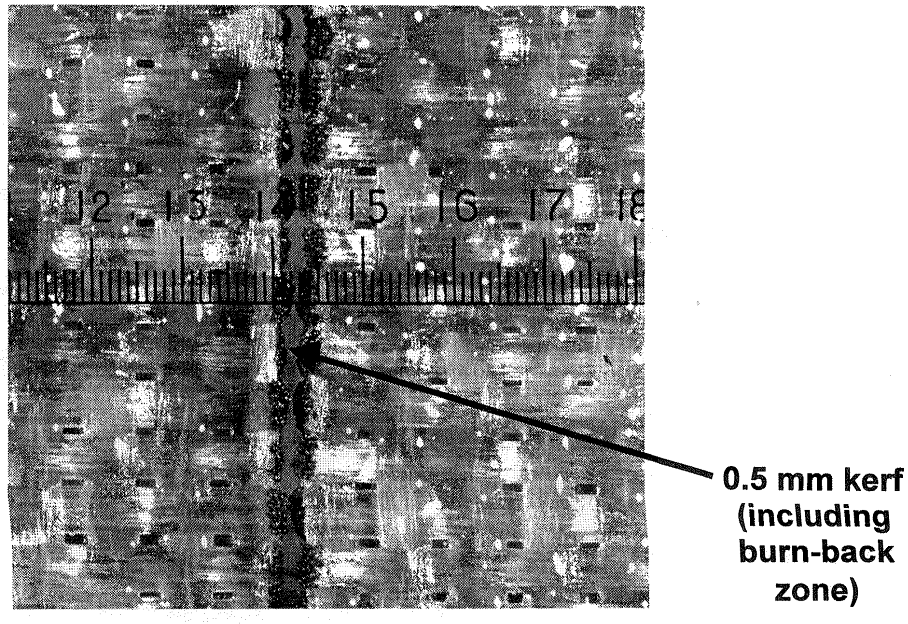


Figure 6: photomicrograph of glass fiber / epoxy prepreg cut with CO_2 laser on Curved LOM machine.