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A Design Method to Exploit Synergies Between Fiber-Reinforce Composites and Additive Manufactured Processes

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Abstract

This paper proposes a design method for devices composed of long fiber-reinforced composites (FRC) and additive manufactured (AM) parts. Both FRC and AM processes have similar application characteristics: suitable for small production volumes, additive in nature, and capable of being highly automated. On the other hand, the classes have distinct characteristics. FRC components tend to be large and of simple shapes, while AM components tend to be small with highly complex geometry. Their combination has the potential for significant synergies, while mitigating their individual limitations. A decision guide is proposed, in the form of a series of questions, to guide the designer to determine if their application is a good candidate for FRC+AM. The decision guide is reformulated into a proposed design process that guides the designer to advantageously benefit from AM and FRC characteristics. The tools are illustrated with an example of a composite pressure vessel with integrated pressure reducer.

1 Background

This paper proposes a design method for devices composed of long fiber-reinforced composites (FRC) and additive manufactured (AM) parts. Both FRP and AM processes have similar application characteristics such as being suitable for small production volumes, being additive in nature, and capable of being highly automated. On the other hand, the two classes of processes have distinct characteristics. FRP components are superior for large structures with simple shapes and load cases [1], where directed fiber optimizations can be exploited fully. However, composites are difficult to use for complex components, because of the inherent design and manufacturing complexity. AM excels for highly complex components and customization, but usually are limited in size [2]. Regarding their manufacturing processes, composite processing is becoming more automated, making the approach somewhat similar to AM [3,4]. Manufacturing lot sizes for composites and AM have traditionally been low, but with technological advances are now reaching up to tens of thousands. Therefore, the combination of both technologies promises enormous potential, if experience in their integrated design can be codified and disseminated and design guidelines established.

The authors have many years of design and fabrication experience with either FRC or AM. They recently completed a significant research project to investigate opportunities to leverage the unique capabilities of FRC and AM, and overcome their limitations. As a result, both a decision guide and a design process were proposed for FRC+AM devices; that is, devices composed of components manufactured by either AM or FRC. The proposed decision guide is a structured series of questions that is intended to guide the designer to determine if their application is a good candidate for FRC+AM. The decision guide questions are reformulated into a proposed design process that can guide the designer to advantageously benefit from AM and FRC characteristics. The decision guide and design process are illustrated with an example of a composite pressure vessel with integrated pressure reducer.

The specific pressure vessel under study, and its construction, is shown in Figure 1. The composite pressure vessel (CPV) is manufactured by filament winding of carbon fiber tapes impregnated with polyamide-6 (PA6) thermoplastic. The CPV construction consists of the pressure vessel body, end-caps at both ends, and an internal liner. The combination of the pressure vessel body, liner, and end-caps serves as the mandrel on which filament winding is performed. These CPVs have pressure ratings up to 350 bar (5000 psi). The design objective investigated in the research project was to determine if part or all of the pressure reducer could be redesigned and integrated into an end-cap, which would be manufactured via AM.

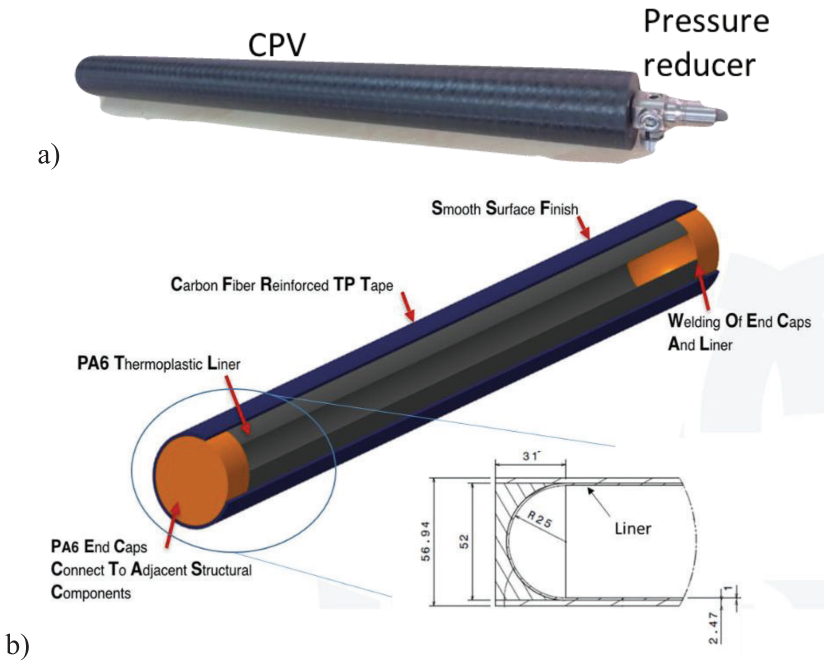


Figure 1: Cylindrical polymer composite pressure vessel a) with standard pressure reducer, and b) showing internal configuration.

2 Composites and AM Processes

An introduction to polymer composites manufacturing and AM processes will be provided to serve as a baseline of understanding for the DFM presentation.

2.1 Composites manufacturing processes

Composite structures are superior for large / extended structures and simple load case scenarios, where directed fiber optimizations can be exploited fully. However, composites are difficult to use for complex components, because of the inherent design & manufacturing complexity. Composite manufacturing is becoming more and more automated, making the approach somewhat similar to AM (composite manufacturing is always additive). Manufacturing lot sizes for composites and AM have traditionally been low (handful to few hundreds), but with technological advances are now reaching up to tens of thousands.

A wide variety of long fiber reinforced polymer composite manufacturing processes have been developed [5]. They are all additive in nature in that fibers, tows, or mats are impregnated with polymer and deposited onto the workpiece. Typically, a mold or mandrel is used to provide the desired part shape and the fiber-polymer material is deposited onto the tool or onto already-deposited material. Common composites manufacturing processes include [6]:

- sheet forming: a flat sheet of composite material is formed by pressing in dies. This is an analogous process to sheet metal forming or stamping.
- filament winding: fibers and polymer matrix are wound onto a rotating mandrel to form the part.
- resin transfer molding: fiber reinforcement is formed in the mold cavity, then thermosetting resin is forced into the mold at high pressure. A variation is to utilize a vacuum to assist resin infusion.
- pultrusion: fibers or braids are pulled through a resin bath and a die to fabricate constant cross-section components (combination of pull and extrusion)

What these processes have in common is the capability of forming a wide variety of part geometries by adding and processing material using hard tooling. Overall part geometries can be fabricated but, typically, small details for assembly and joining, or for local functional purposes, cannot be fabricated without secondary operations.

For thermosetting polymers, an additional step is often needed for the polymerization reaction to occur. Different types of polymer matrix infusion or infiltration are used. However, these aspects of the processes are not important for this paper.

2.2 Filament winding

Since filament winding will be used in the case study for this paper, additional information about the process will be presented. As mentioned, in this process, a filament consisting of fibers and polymer matrix is deposited onto a mandrel as the mandrel rotates on a spindle. A carriage containing the deposition head translates back-and-forth along the mandrel, resulting in the filament being wound onto the mandrel. Most filament winding machines incorporate only these two degrees-of-freedom: spindle rotation and carriage translation along the spindle. Some high-end filament winding machines incorporate additional degrees-of-freedom in the deposition head to enable more motion options and deposition patterns.

Most often, several layers of filament will be deposited to fabricate the part. Filament deposition angle can be varied by varying the ratio of spindle rotation to carriage translation speeds. High angles (close to 90 degrees relative to the spindle axis) yield parts with high circumferential strength, while lower angles result in parts with greater axial strength. Many times, deposition angles will be varied in different layers in order to impart good overall strength characteristics [7].

Since parts are fabricated on a rotating spindle with two degree-of-freedom machines, parts are typically simple shapes, such as cylinders. Pressure vessels with hemispherical ends can be fabricated. Since the mandrel is incorporated into the spindle, part ends cannot be completely closed by the filament winding process. As a result, end-caps or some other means of closing ends are needed.

Figure 2 shows a schematic of the spindle-mandrel assembly and filament winding machine that was used for pressure vessel fabrication for this paper. In the schematic, the part labeled "Liner" and the Endcaps comprise the mandrel.

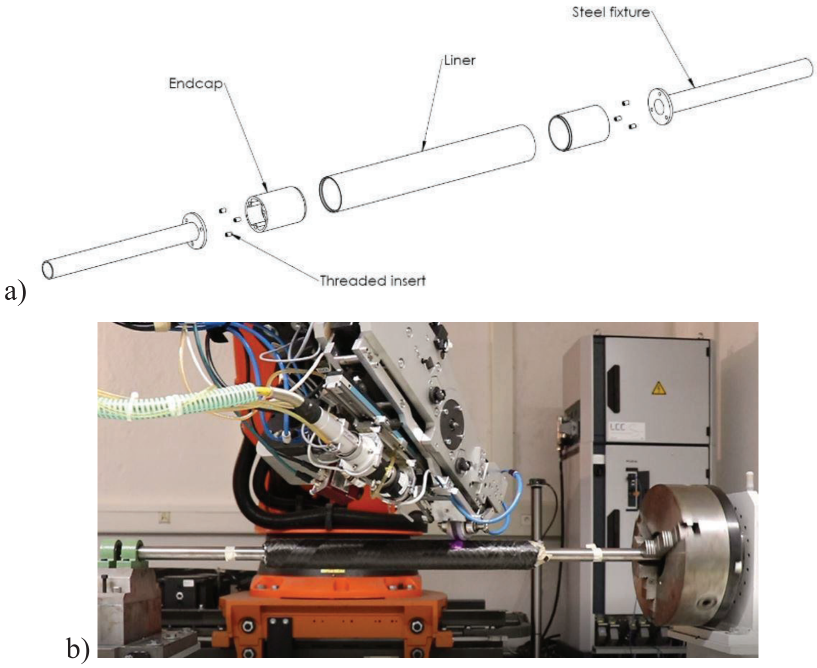


Figure 2. Filament winding process for the composite pressure vessels, showing a) a schematic of the spindle-mandrel assembly and b) pressure vessel fabrication on a filament winding machine.

2.3 Additive manufacturing processes

The AM processes of interest in this paper fabricate parts in polymer and polymer composite materials. Of most interest are material extrusion, material jetting, and powder bed fusion processes, although vat photopolymerization and binder jetting processes could be utilized as well. As is well known, AM processes fabricate parts in a layer-by-layer manner by one of two routes: depositing and processing material, or depositing energy into a material vat in order to process the material. Material extrusion and jetting are examples of the former, while powder bed fusion utilizes the latter.

In contrast to polymer composites, AM machines tend to have smaller build volumes resulting in smaller parts. AM processes are capable of fabricating parts with complex geometries. This manifests in the capabilities of:

- combining several conventionally manufactured parts into one AM part,
- fabricating cellular structures, such as lattices and foams
- fabricating parts with integral assembly and joining features
- fabricating custom parts

To date, the material extrusion process has been adapted to fabricate long fiber reinforced composites. Two machine vendors, Markforged and Arevo, have developed systems that deposit both thermoplastic filament and a fiber from two deposition heads. In the Markforged system, fibers are deposited in the same 2D layers that the polymer filaments are deposited in, while Arevo claims to enable 3D deposition. Research systems are being developed that utilize automated fiber placement heads on robotic arms that enable 3D deposition that promise large, complex geometry, 3D fiber reinforced composite parts.

An increasing interest in design for AM (DFAM) is indicated by a variety of proposed DFAM methods in recent years. Principles for DFAM have been proposed [8] and DFAM methods have been developed to take advantage of AM opportunities [9], as well as design rules for designing around manufacturing process constraints [10].

3 FRP+AM Decision Guide

Based on a structured design thinking process and supported by experiences with composites and AM, a decision guide has been developed to support the design of integrated additive manufacturing and composite components and modules. The objectives of the decision guide are to help the designer identify whether FRP+AM is suitable for their application and, if so, to identify which parts of the application are suitable for composites and which are suitable for AM.

The guide is presented here as a series of questions and actions to perform.

1. Are polymer or polymer composite materials suitable for the intended application?
2. Is the artifact large enough to be a candidate for composites?
3. Look for opportunities to integrate additional modules into the artifact.
4. Does the artifact, or could the artifact, have geometric detail too small for typical composite manufacturing processes?
5. Can the geometric detail be isolated into specific regions, where other regions have simple shapes?
6. For each geometric region,
    - if simple shape
        - is it suitable for composite manufacturing?
            - identify potential fiber and matrix materials
            - identify potential composite manufacturing processes
    - if complex shape
        - is it suitable for AM?
            - identify potential AM materials
            - identify potential AM processes
    - Develop functional requirements from overall device requirements (behaviors, mechanical properties, etc.)
    - Determine economic and sourcing requirements (cost, time, availability of equipment, etc.)
7. Can similar/same materials be used for both composite and AM parts to simplify joining?
8. Investigate joining methods for the various parts
9. Integrate assembly and joining features into part designs where possible
10. Can part designs be modified to facilitate composites manufacturing processes; e.g., add sacrificial material for fixturing, add fixturing features, etc.
11. Compare part designs with functional, economic, and sourcing requirements

4 FRC+AM Design Method

Based on the decision guide questions and thought process, a flowchart version of a design process is presented in Figure 3. The proposed design method starts with a device configuration which has been developed already, based on the decision guide just presented. Conceptual and embodiment design stages should be conducted to identify the primary modules with some preliminary attempts performed to relate functionality to specific geometric regions. Following the decision procedure, some geometric regions should be of simple shape with a small number of functions allocated to them, with the idea that these will be candidates for composites manufacturing processes. Other geometric regions should be smaller in size with a higher concentration of functional elements. These should be candidates for AM.

The proposed method proceeds to guide the designer to focus on each geometric region individually and to develop detailed designs for each. Materials and manufacturing processes should be identified and design for manufacturing performed. If multiple parts are needed in a region, each should be designed to a similar level of detail. As necessary, the designer should ensure the soundness of their functional module designs if they consist of more than one geometric region.

After the design of all modules, the designer should assemble the modules into a complete system design. The right-most sequence of activities, starting at marker B, should be performed. The designer should investigate the assembly of components and identify suitable joining methods. Concurrently, the designer should consider compatibility among materials and determine if material substitutions should be made for either the composites or AM parts. When joining and assembly methods have been identified, part designs should be refined to incorporate any additional assembly or joining features that are needed to facilitate assembly, such as chamfers (for insertion), snap fits, steps or notches to ensure parts are aligned correctly, etc.

As appropriate, the designer should consider costs, delivery times, and other aspects of sourcing for each component and for the entire system. These considerations should be compared with requirements or targets and the design process iterated if needed.

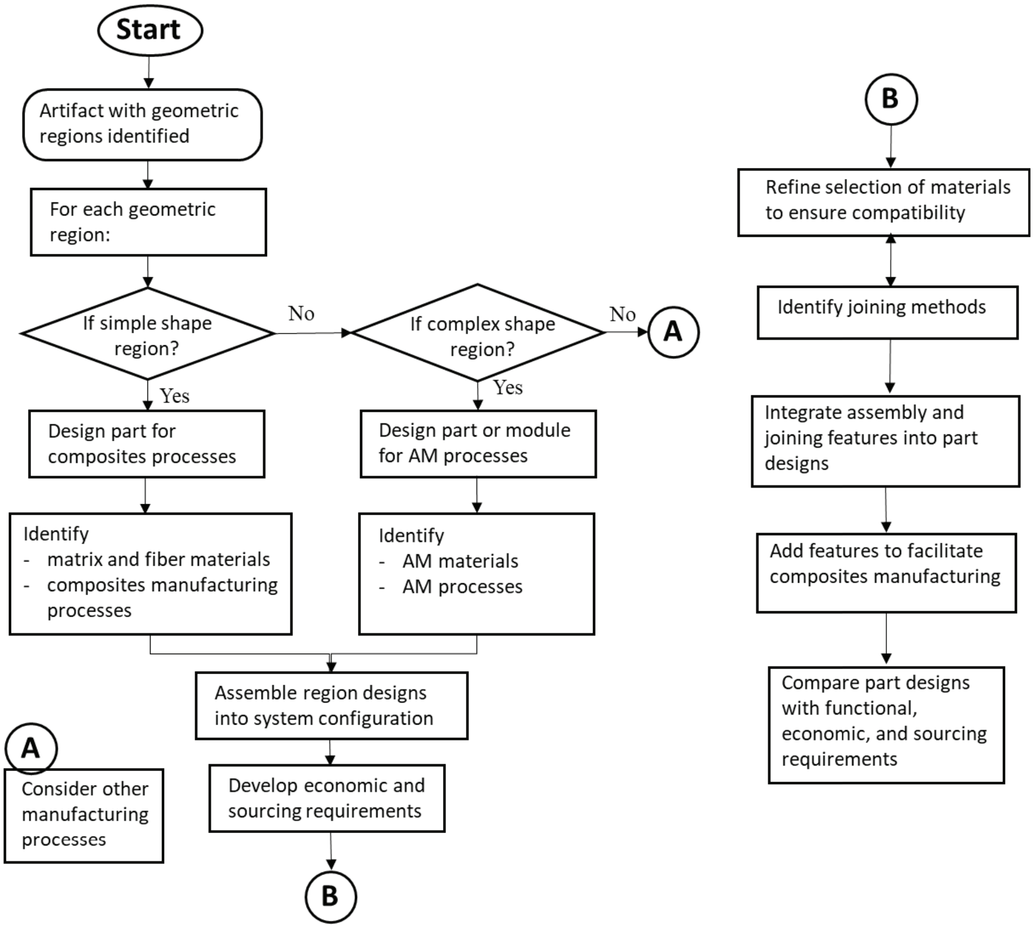


Figure 3. Flowchart of proposed composites+AM design process.

5 Composite Pressure Vessel

In this section, the example will be present of the composites+AM design process, beginning with a description of the application. The decision procedure presented in Section 3 will be applied to this design problem, which identifies the opportunity to integrate the pressure reducer into an end-cap of the composite pressure vessel (CPV). The design of the integrated end-cap is used to illustrate the application of the proposed design process.

5.1 Description of Application

The integration of an AM pressure reducer into a composite pressure vessel (CPV) was identified as an ideal platform to explore and evaluate the synergies between composites and AM for the following main reasons:

- Limitations of Conventional CPVs: major points of concern for users of pressure vessels are protruding pressure reducers (packaging, safety) and the disadvantages from missing integration of CPVs and reducers (weight, cost, etc.).
- Technical opportunity through combination of AM + composite technologies: AM offers advantages for complicated inner structures, such as pressure reducers, because complexity comes without extra cost and the process allows for designs that are otherwise not possible to manufacture. CPVs are a structure ideally suited for composite materials due to their simple load case scenario and the resulting possibility of exploiting anisotropic features of fiber reinforcement.
- Market opportunity: CPVs are seeing a large market growth, based on two growth drivers:
  - with the advancement of design and manufacturing technologies an increasing number of pressure cylinders will be made from composite materials.
  - the global demand for pressure vessels (composite and metal) is growing due to a sharp increase in usage, such as for automotive (hydrogen and CNG), leisure (paintball) and some niche markets (fuel-cells).

5.2 Decision Procedure

The decision procedure from Section 3 is applied to the composite pressure vessel application. To address the first two questions, these pressure vessels were already manufactured using filament winding. The issue is whether or not some level of integration can be achieved with external components. When thinking about question 3, the idea of integrating the pressure reducer into an end-cap emerged as a possibility.

To address question 4, it is important to realize that the end-caps were manufacturing using injection molding in polyamide 6. The liner was machined to size from a hollow tube of polyamide 6 polymer. Together they form the mandrel on which the body of the pressure vessel is fabricated, as shown in Fig. 2. Further, these components become parts of the final product, instead of utilizing hard tooling that is re-used to fabricate the next part. Taken together, questions 4 and 5 raise the possibility of consolidating pressure reducer functionality into an end-cap. The resulting design will contain geometric detail too small and complex for composites fabrication processes. This complexity can be isolated in the end-caps, which will be fabricating using AM processes.

When considering question 6, the cylindrical pressure vessel will continue to be filament wound. In fact, its design and manufacturing process remain largely unchanged from pressure vessel designs with simple, conventional end-caps. The end-caps with pressure reducer functionality will be fabricated by one of the polymer AM processes. Both powder bed fusion and material extrusion utilize polyamide materials, including polyamide 11 and 12, with glass-filled variants of these materials. These processes and materials will be leading candidates for the end-caps.

Regarding question 7, polyamide 6 is used as the thermoplastic matrix for the pressure vessel, which is the same material as the end-caps and liner. If polyamide 11 or 12 is used for the end-caps, the materials are very compatible. In fact, no additional joining considerations are needed for this example. This means that questions 8 and 9 can be addressed trivially.

To address question 10, the existing filament winding process must be examined in more detail. As shown in Figure 2, spindle fixtures are bolted to the end-caps so that the spindle-mandrel assembly can be installed on the filament winding machine. This requires extensions on the end-caps that can accommodate bolts, which is readily achievable by adding material to lengthen the end-caps. This extra material can be cut off after the pressure vessel is fabricated.

As indicated by questions 6 and 11, it is important to consider functionality and economics of AM production of end-caps.

After completing the decision process, the possibility of integrating pressure reducer functionality into end-caps and fabricating the end-cap designs via AM seems worthwhile to consider further.

5.3 CPV Design

Given the positive indications for proceeding from the decision process, attention can turn to redesigning the CPV with a focus on the end-caps. The design objective for the pressure reducer was to incorporate all of its components into the end-cap. It was deemed acceptable to increase the size of the end-cap, provided that its length was less than the total length of the original end-cap plus conventional pressure reducer. Also, pressure reduction capability was to be demonstrated, but only for “shop floor” pressure levels of up to 100 psi, rather than pressures to which the CPV is rated (~3000 psi). This enabled the exploration of design concepts and composites vs. AM trade-off exploration without having to perform time-consuming engineering studies.

With regards to the design process proposed in Section 4, three geometric regions of the CPV were identified: the main cylindrical pressure vessel, one end-cap with the conventional design, and one end-cap with integrated pressure reducer. The design of the main CPV body remains unchanged, with typical filament winding patterns of PA6 thermoplastic matrix reinforced with continuous carbon fibers. Filament winding will be performed over a PA6 liner. The plain end-cap will again be injection molded in PA6. That leaves the design of the end-cap with integrated pressure reducer, which will be described in the remainder of this subsection.

After an initial conceptual design exploration in which over 10 design concepts were generated, several concepts were selected for more detailed design studies. One of these designs was developed to the prototyping stage, as shown in Fig. 4, and consists of one pressure reducing valve stage. A description of its operation will help with understanding the design. Gas from the pressure vessel enters the poppet chamber (region with the poppet spring), which tends to push the poppet forward into the seat, blocking the delivery of gas to the output. If the user sets the valve handle to a positive pressure, the diaphragm spring compresses and exerts a force on the diaphragm which causes the poppet to displace and allows gas to pass into the diaphragm chamber. As pressure builds in the diaphragm chamber, the rising pressure exerts a force on the diaphragm that displaces the poppet back towards its original position, closing the valve. The balance of input and output pressures through the poppet displacement ensures that the output pressure stays at or below its setting.

The design in Fig. 4 shows the pressure reducer stage adjacent to the outer boundary of the end-cap where the end-cap’s thickness is greatest. Channels connect the pressure vessel to the poppet chamber through the feature labeled Restrictor and the diaphragm chamber to the output (labeled Output Air). In this design, the poppet and diaphragm were combined into a single part. This combined part and the part labeled Slider were to be fabricated separately, using AM, from the end-cap and assembled with poppet and diaphragm springs (purchased parts). Additionally, a cover part was designed to cover and seal the pressure reducer cavities.

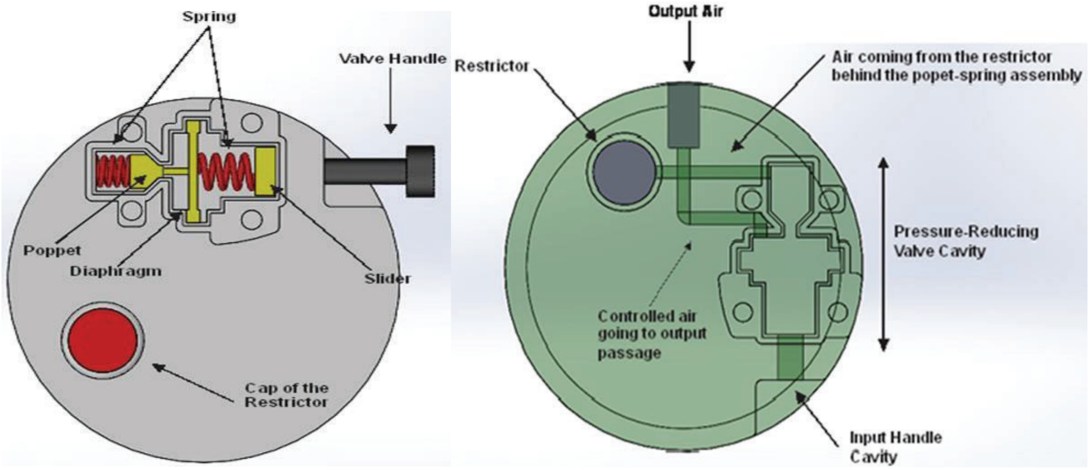
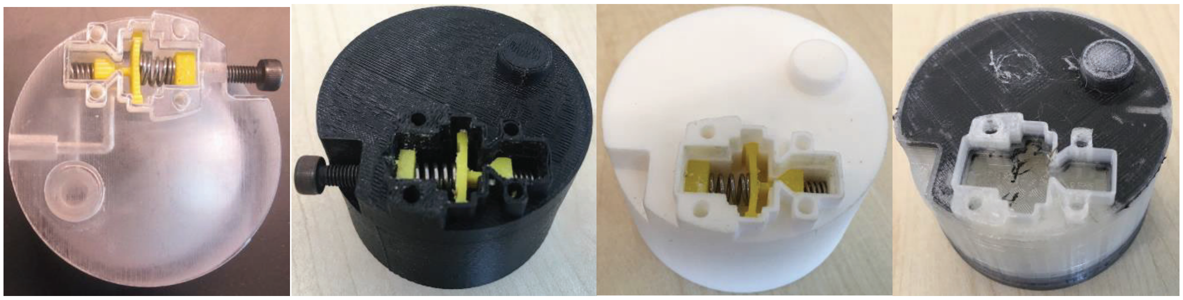


Fig. 4: Initial end-cap design.

To explore the capabilities of various fabrication processes, several versions were fabricated in the Stratasys J750 (a), Stratasys Fortus 450mc (b), EOS P396 laser sintering (c), and Markforged Mark 2 (d) printers, as shown in Fig. 5. End-caps from the J750 and P396 were of high enough quality to provide pressure reducing functionality. The material extrusion fabricated end-caps did not have a high enough feature resolution and precision to prevent leaks and had other assembly and operational problems. Since the materials used in the Stratasys J750 were acrylate-based photopolymers, it was decided to not attempt to use J750 fabricated end-caps for functional testing or fabrication of complete CPVs. However, the J750 was easy to use and resulted in transparent end-caps that enabled visualization of internal features, so was used to fabricate many end-cap prototypes. The material used in the P396 was polyamide 12 (PA12), which is the same family of thermoplastics used as the matrix material in the CPVs to be fabricated. Hence, PA12 end-caps fabricated in the P396 were selected for usage in the project demonstration CPV.



a) b) c) d)

Fig. 5: End-caps fabricated in a) Stratasys J750, b) Stratasys Fortus 450mc, c) EOS P396 laser sintering, and d) Markforged Mark 2 printers.

Several months of engineering design, analysis, prototyping, and refinement were undertaken. Finite element analysis demonstrated that the end-cap thicknesses must be increased by approximately 20mm in order to prevent failure at 3000 psi pressure. With this additional space in the end-cap, the layout of the pressure reducer was changed with the objective of eliminating leaks. Two major design changes were made. First, the pressure reducer was placed inside the end-cap, without the need for a cover plate. This avoided significant sealing challenges. Second, an in-line configuration of chambers and components was used in order to facilitate assembly and sealing.

The final end-cap design is shown in Fig. 6. The end-cap shown in Fig. 6b was fabricated in Vero Clear material on the J750 since its transparency allows visualization of internal features. For testing and filament winding, the end-cap was fabricated in polyamide 12 on the EOS P396. Internal components were fabricated using Vero White material on the J750 since they could be produced with good precision. The diaphragm and poppet spring holders were screwed into place. O-rings and springs were sized appropriately for the pressure reducer functionality and were purchased as stock parts.

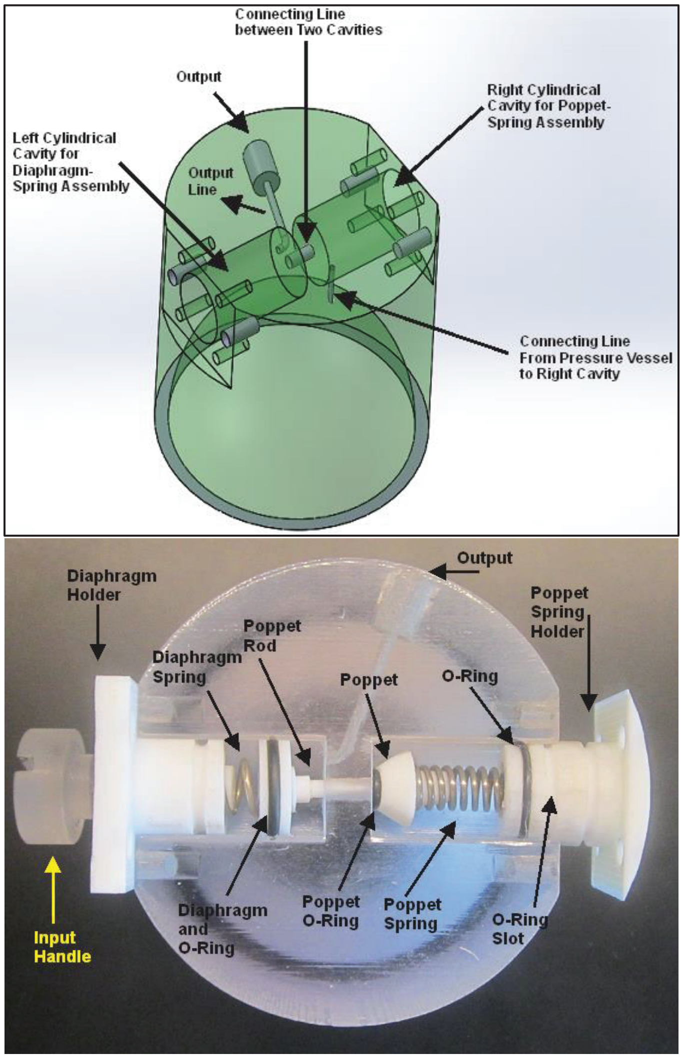


Figure 6. Final end-cap design (a) and assembled prototype (b).

After assembly, the final end-cap design was tested using a specially constructed pressure vessel and performed successfully with air pressures up to 90 psi.

5.4 CPV Manufacturing

To fabricate the complete CPV, all of the components shown in Fig. 2a need to be fabricated and assembled. As mentioned, the liner is machined from stock pipe, and the standard end-cap is molded. Before either end-cap was fabricated, however, extensions were added to allow for mounting the end-cap and liner structure to a fixture for the process (Figure 7). The extension was designed as a sacrificial element to the end-cap, to be removed later in the manufacturing process. The fixtures on the ends of the assembly are standard components. These components were assembled in preparation for CPV filament winding.

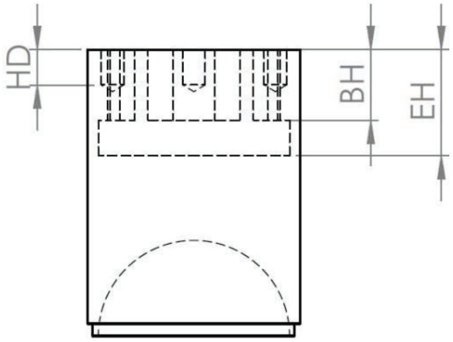


Figure 7. The extension, indicated by EH (Extended Height), incorporated as mounting points for attachment fixtures, removable after completion of the winding process.

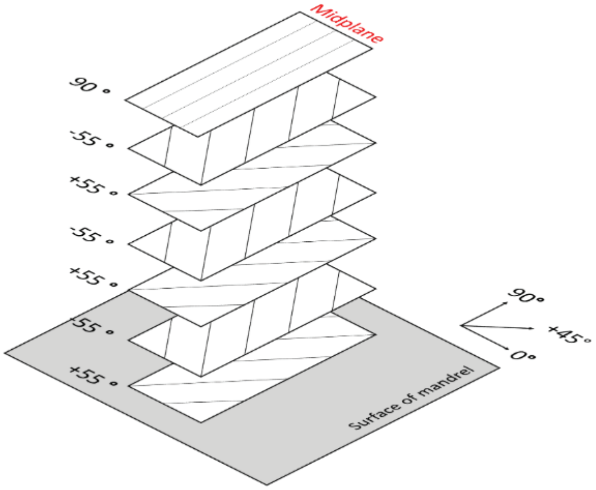


Figure 8. Laminate layup sequence and angles.

The layup sequence for the composite vessel must be symmetric about its middle surface to reduce strain variations through the laminate wall and to avoid warping upon subjected to high internal pressures. The winding angle of the fibers is the major variable determining the mechanical performance of the pressure vessel. Based on references from literature [7], the optimum angle for a thin pipe vessel to withstand the maximum burst pressure is considered to be at ±55°. The laminate layup sequence and angles used are illustrated in Figure 8.

Filament winding was performed with carbon fiber tapes impregnated with PA6 thermoplastic. Completed CPVs are shown in Figure 9. One pressure vessel with 3D printed end-caps was tested for leaks with air pressure up to 50 psi. No leakage was evident in the joint regions between the pressure vessel and the end-caps.

Figure 9. Fabricated CPV with AM-fabricated end-cap with integrated pressure reducer.

6 Closure

The issue of how to take advantage of the advantages of fiber-reinforced polymer composites and AM processes was explored in this paper. A decision guide and design process were proposed to guide the designer in designing a device that consists of both composite and AM parts. Overall, the guidance encourages the development of relatively large regions with simple shapes, and other, smaller regions with potentially complex shapes. The large, simple regions are candidates for composites, while the smaller, complex regions are candidates for AM. The decision guide and design process were illustrated by the design of a composite pressure vessel, where it was desired to integrate a pressure reducer into an end-cap of the vessel. The end-cap was redesigned to incorporate pressure reducer components and fabricated using powder bed fusion technology. Other pressure reducer components were designed and fabricated, including the poppet and diaphragm, and assembled with purchased springs and o-rings. After assembly, the AM fabricated end-cap performed successfully under air pressures up to 90 psi. The pressure vessel body was fabricated by filament winding with carbon fiber tapes impregnated with polyamide 6 thermoplastic. Several pressure vessels were fabricated with the redesigned AM end-caps and tested successfully for leaks.

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