CONFORMABLE COMPACTION SYSTEM USED IN AUTOMATED FIBER PLACEMENT OF LARGE COMPOSITE AEROSPACE STRUCTURES

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ABSTRACT

A NASA Phase I SBIR program entitled "Low Cost Processing of Large Composite Structures (1)" reviewed processes for fabricating very large composite parts like the RLV liquid hydrogen tanks. Autoclave and candidate out-of-autoclave processes were compared in order to downselect the most promising out-of-autoclave process for development and demonstration. Thermoplastic in situ fiber placement and the more embryonic layer-by-layer E-Beam fiber placement process were down-selected. Both utilize a high normal force to compact the microstructure as an integral step in consolidating or curing the laminate, and show promise in fabricating parts. However, airframe and spaceframe complex geometry includes both singly and doubly curved skins that require conformance on a large scale, and just as importantly, padups, pandowns, ply details, and joggles that appear on curved and even flat laminates. Thus, even after the down-selection, it was further concluded that both processes would be ineffective without incorporating a proven conformable compaction system in the deposition head to provide for an adequate normal consolidation force while placing the complex geometric shapes. The goal of the NASA Phase II SBIR program now underway is to develop and prove out a number of innovative conformable compactors for assembly into deposition heads. This paper describes the need for conformable compactors for ATP deposition heads, reviews the specification for the compactors, shows the overall process concept and equipment, then describes the compaction module hardware.

KEY WORDS: Conformable Compaction Systems, Thermoplastics, Automated Fiber Placement, Fiber Placement Head, In Situ Consolidation, Electron Beam Curing, E-Beam Curing

1. INTRODUCTION

Major aerospace initiatives oftentimes drive the development of advanced composite processing technologies. One current example is the need for cost-effective fabrication of large composite parts for a reusable launch vehicle (RLV). The current cost on a payload basis to launch the U.S. Space Shuttle into orbit ranges from $2,300/kg to $6,800/kg ($5,000/lb. to $15,000/lb.). In the late 1990's, NASA initiated an RLV development effort aimed at reducing this cost to $450/kg ($1,000/lb). Significant savings result from eliminating the expendable booster rockets, so RLV designs carry the rockets and fuel tanks to orbit and return them to Earth intact. The fuel tanks themselves form part of the vehicle structure, and their structural weight competes with payload capacity and fuel under a fixed gross liftoff weight limit. Thus, the best-quality minimum-weight composite laminates are required for the tanks. Lockheed-Martin's RLV concept enclosed two large main liquid hydrogen (LH_2) tanks behind one large liquid oxygen (LOX) tank in the nose section. The LH_2 tanks are made from four 19.3m (760.86-in) long quarter-lobes, each fitting inside a 4.8m by 3.7m (189.5-in by 145.2-in) cross-section. The tanks must withstand primary vehicle loads including landing gear loads. They are subject to -253°C when filled with liquid hydrogen, then alternate between very high and extremely low temperatures while in orbit. Finally, the LH_2 tank walls must be impermeable to the liquid hydrogen.

Fabricating the tanks using autoclave consolidation after fiber placement would be complex and expensive. Sections 2 and 3 review autoclave and candidate out-of-autoclave processes to determine if any out-of-autoclave processes show sufficient promise to warrant consideration. It is assumed for the comparison that any selected out-of-autoclave process must ultimately prove mechanical property equivalency with the traditional thermoset autoclave process.

2. AUTOCLAVE FABRICATION PROCESS FOR RLV TANKS AND OTHER LARGE COMPOSITE PARTS

The baseline fabrication process for large composite skins is automated tape/tow placement (ATP) followed by autoclave curing. ATP/autoclave provides a baseline standard for both quality and cost targets. In this manufacturing scheme, RLV tanks would be fabricated by joining smaller autoclave-consolidated panels.

2.1 ATP/Autoclave Fabrication

ATP/autoclave fabrication makes many impressive claims:

- Fabricating laminates via ATP/autoclaving is a mature demonstrated technology.
- Highly productive, efficient fiber placement machines and tape layers are commercially available from Cincinnati Machine and Ingersol. These machines effectively deposit thermoset composite tows and tapes onto tools with high throughput and repeatability.
- Composite tape and tow material feedstocks are commercially available.
- Good part dimensional control can be achieved with appropriate tooling to control thermal expansion or accommodate thermal mismatch.
- Substantial NDI techniques and experience exist to verify laminate high quality.
- Conventional debulking and autoclave curing technology is available at many airframers and suppliers. For moderately sized autoclaves, substantial U.S. capacity exists.
- For moderately sized parts, ATP/autoclave fabrication can be the cost-effective solution.

The most significant advantage provided by autoclaving is the 0.69-1.38 MPa (100-200 psi) compaction pressure applied to the laminate during cure. This compaction force follows the principle of force control; that is, as the curing laminate reduces in thickness, the high-pressure gas reliably follows the bag-covered layers, maintaining normal pressure throughout the cure cycle. With the excellent compaction, the laminate mechanical properties achieved following autoclave processing generally have 100% property translation from laboratory coupons into the complex geometry part, prompting the genesis of the term *"Autoclave Properties."*

2.2 Autoclave Fabrication Limitations

There are detractors to the autoclave fabrication process, especially when the structural assembly is built by joining many smaller laminates:

- The large equipment cost [2]. A large autoclave requires a capital investment exceeding perhaps $40 million and brings along large operating expenditures. Additional costs accrue for the many autoclave tools. In the RLV tank example, autoclave tools are required to fabricate approximately 200 panels per tank.
- The autoclave interior dimensions limit part size, so panels must be joined. Joints in composite parts are complex, heavy, expensive, and risky. They require shims at the interface to accommodate part mismatch. Even with shims, the dimensional accuracy of the assembled structure is inferior to that of a monolithic component. Additionally, mechanical properties such as the structural buckling sensitivity would be adversely affected in a joined component.
- Each panel joining operation would require templates, assembly jigs, and tooling that adds extra expense over any out-of-autoclave fabrication process that manufactures full-length parts and avoids post consolidation joining tools.
- There are risks in fabricating very large PMC honeycomb laminates, including thermoset prepreg out-time stability, autoclave temperature non-uniformity, vacuum bag integrity, process-induced residual stresses, and wrinkling of thin sections.

3. COMPACTION PRESSURE AVAILABLE BY PROCESS

Six processes being developed for out-of-autoclave fabrication of polymer composite parts can be considered for fabrication of large composite laminates such as the RLV LH_2 tanks:

- Cure-On-the-Fly™ (COTF™) processing pioneered by Hercules (now Alliant Techsystems) in 1988-1991 - a slightly heated ATP head stages thermoset tows during placement. The laminate is completed with a freestanding or vacuum bag/oven cure.
- Automated fiber placement (ATP)/oven cure – novel thermoset resins allow a vacuum bag/oven cure to complete the laminate processing following conventional fiber placement.
- Automated fiber placement (ATP) with thermoplastic in situ consolidation – an ATP machine is outfitted with a heated head that incorporates a polymer process to melt, deposit, and refreeze thermoplastic tows or tapes, layer-by-layer, onto a tool surface.
- Vacuum Assisted Resin Transfer Molding (VARTM) - a fiber preform is laid onto a one-sided hard tool and bagged. Pulling a vacuum on the preform augments the subsequent resin transfer. Cure is also under vacuum.
- Automated fiber placement (ATP)/Electron-beam cure - a fiber placement machine is used to deposit an E-Beam curable tow, and the part is irradiated with a high-power E-Beam inside a protective concrete vault to complete the cure.
- Layer-by-layer Electron-beam placement - a low-power E-Beam is added to an ATP head, and E-Beam curable tows are deposited and irradiated layer-by-layer, onto a tool surface.

Some of the above processes have been used to fabricate commercialized parts, although no parts as large as RLV tanks.

3.1 Compaction and Laminate Quality

To downselect from this list, the six out-of-autoclave processes were ranked opposite ATP/autoclaving based upon their ability to produce high-strength laminates. For each process, either the deposition equipment and/or a post cure combined with perhaps a vacuum bag is directly responsible for the time/temperature/pressure history required to create quality microstructure. All six processes can provide adequate energy to fully advance or consolidate the resin, but the actual compaction pressure varies widely, as shown in Figure 1. Thermoset ATP/oven, VARTM, COTF™, and all-at-once E-Beam curing apply at most vacuum bag pressure during the final cure, and no pressure at all if they employ a freestanding cure. The remaining three processes all employ a significant laminate consolidation force. Autoclaves provide pressure capabilities of 0.69-1.38 MPa (100-200 psi). Layer-by-layer E-Beam and thermoplastic in situ consolidation processes apply their compaction pressure by translating a reaction force from the fiber placement machine or stout gantry tape layer through the deposition head. This compaction force is concentrated within a small area using a roller or shaped compactor. Because the preceding layers had been cured/consolidated in layer-by-layer processing, high pressures, 3.4 MPa (500 psi) or above, can be applied during ATP. Note that this is characteristically different from the compaction force used for thermoset fiber placement, which applies a modest pressure to assist deposition, not ultimate compaction. A high force is detrimental to the unconsolidated thermoset laminate that cannot support itself prior to cure, and is useless since the cure occurs within the autoclave.

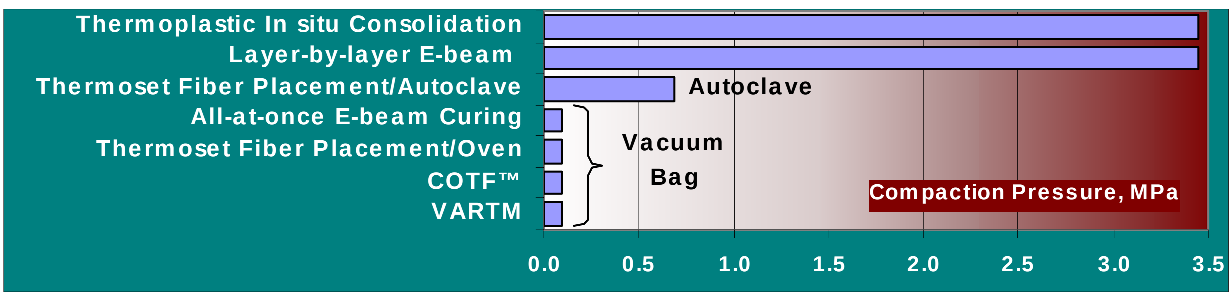


Figure 1 Four processes provide only vacuum bag pressure, but thermoset fiber placement/autoclave curing, layer-by-layer E-Beam, and thermoplastic in situ consolidation can provide as much as 3.4 MPa (500 psi) compaction pressure.

Noting the extreme complexity and performance requirements of a composite cryotank to minimize RLV weight, and likewise the strength and stiffness requirements of other large aerospace parts like wing skins, the quality reproduced by any out-of-autoclave fabrication process would have to be exceedingly high. This rules out the four fabrication processes from Figure 1 not capable of at least what the autoclave provides: 0.69 MPa (100 psi) of radial compaction pressure during cure (those using a vacuum bag). Thermoplastic in situ consolidation and layer-by-layer E-Beam curing are cited as processes deserving development, owing to the use of a compactor to apply a normal force to the laminate during consolidation or cure.

1. OUT-OF AUTOCLAVE PROCESS TECHNOLOGY GAPS

There remains a substantial practical technology gap in current fabrication capabilities between components fabricated by layer-by-layer E-Beam and thermoplastic/ATP fiber placement fabrication, and complex aerospace structure. Layer-by-layer E-beam processing has resulted in the fabrication of wound rings [2]. Components fabricated by the thermoplastic in situ consolidation process include both unstiffened laminates and laminates stiffened by stringers or honeycomb core of cylindrical [3,4] or flat section geometry [4,5]. The fabrication of open section complex geometry panels with padups and ply details as would be required for very large aerospace part fabrication has not been demonstrated.

Figures 2 and 3 describe the process mechanics that result in inadequate microstructure when laminates are placed with a deposition head employing a compactor lacking sufficient conformability. In both examples, a rigid compactor was used. Both examples are of ply defects but are illustrative of what would happen if a tape or tow overlap occurs, such as in a ply addition or drop, at a location of macro-geometrical change (padup, pandown, joggle, double curvature), or if there were thickness variations in the incoming tows or tapes.

Figure 2 shows layers placed over a missing thermoplastic tow in the first ply. The layers placed over the gap did not fill the area introduced by the gap. The rigid compactor concentrates its force on the high spots, the low spots are not substantially compacted, and the time/temperature/pressure requirements for high-quality laminates are not fulfilled. The rigid compactor acts with displacement control. That is, the placement machine force is translated through the head to the highest points on the laminate. The rigid compactor doesn't conform to the laminate, and the high points are compressed, regardless of the force required. At low spots, the rigid compactor doesn't even touch the composite. In Figure 2, the deflection is indeed enforced at the edges of the missing tow because the force is reacted at the two edge pressure points. This results in favorable local microstructure at only the highly loaded areas. The rigid compactor cannot conform to the laminate, as would a vacuum bag pushed by autoclave gas pressure acting under the force control principle.

While the example above was for a rigid compactor, these maladies would occur with any non-conforming compactor processing a layered composite. In laminated composite materials, defects occur on a microstructural scale. If these defects are introduced within even one ply, they can compromise the microstructural load transfer from fiber to fiber and layer to layer, and have devastating consequences upon laminate properties.

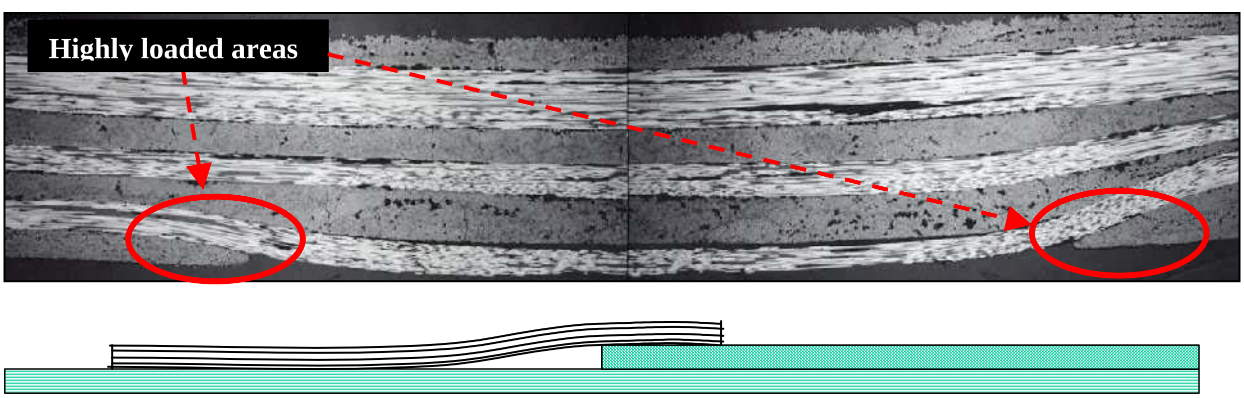


Figure 2 Photomicrograph of a laminate made with a missing ribbon illustrates the likely quality that would result should an overlap be consolidated with a rigid compactor.

Figure 3 shows two layers unintentionally placed over each other in the first ply next to the tool. When the thickness defect begins within a laminate, the defect will reproduce itself throughout much of the laminate thickness. The Figure shows the low void content in the center/right area obviously compacted. On both the left and right side of this laminate, the void content is elevated.

It can be seen from the preceding photomicrographs that intimate contact and consolidation was not achieved. A deposition head built around a rigid compactor preserves microstructural deficiencies and introduces new problems associated with intimate contact throughout the laminate. If intimate contact cannot be achieved, neither can healing and full stiffness and strength. It is postulated that this is the primary reason why thermoplastic laminates have not achieved full translation of autoclave properties for the various material systems evaluated.

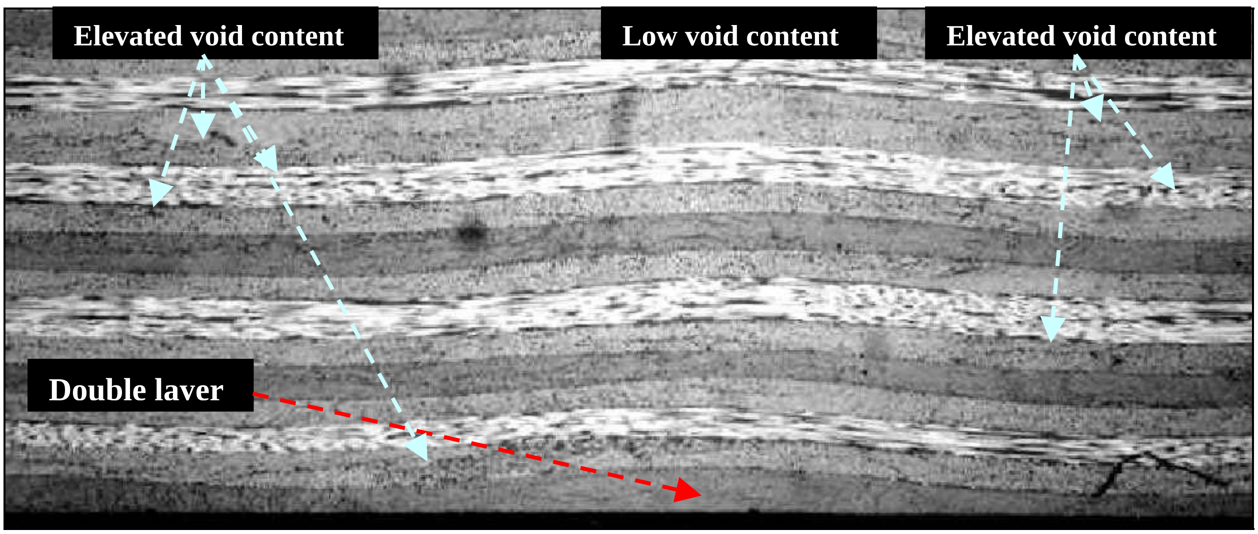


Figure 3 Photomicrograph of laminate with two tows placed directly over one another in the base ply. The ply undulation is reproduced throughout the laminate thickness.

Intimate contact will only be attained once a working conformable compaction system is developed, even for flat laminates (1). Deposition heads must be developed with conformable compaction systems so that the head force can create the type of laminate consolidation needed to manufacture the ultimate quality required. These compactors must utilize force control so that the head follows the material near a ply detail, near geometry transitions, or as the material loses height by compaction. Then perhaps thermoplastic ATP and layer-by-layer E-beam curing can be extended to curved laminates or to other complicated shaped structures. A conformable compaction system is thus the next logical step in the development of either out-of-autoclave process for fabricating RLV tanks or other large composite structure. Conformable compactor development is the focus of the Phase 2 SBIR.

5. OUT-OF-AUTOCLAVE FABRICATION PROCESS USING CONFORMABLE COMPACTION SYSTEMS

Figure 4 illustrates the integration of a process concept for a generalized deposition head that employs heated and chilled zones, and requires high forces over a small area or modest forces over a larger area. These process zones correlate to three compactor concepts, and are described in the context of thermoplastic in situ consolidation. However, a number of out-of-autoclave processes can be arranged by employing some or all of the compactors in any order. In the Figure, a feeder provides accurate deployment, starting, and cutting of tows or a tape. There may be a material or substrate heat source. In this process, two torches direct heated air to the material. The first heats the bare tool or previously laid composite, while the second trim heats the substrate and material feedstock. Three conformable compactors alternately heat and chill the composite. The first hot line compactor establishes the initial intimate contact between the lower surface of the incoming composite and the upper surface of the substrate, and initiates healing in those locations where intimate contact has been achieved. The second hot area compactor maintains the temperature long enough to complete healing of the longest polymer chains to develop interlayer strength. The third cold compactor combines the action of a cold line and a cold area compactor, and chills the material, re-freezing it in place and compressing the voids.

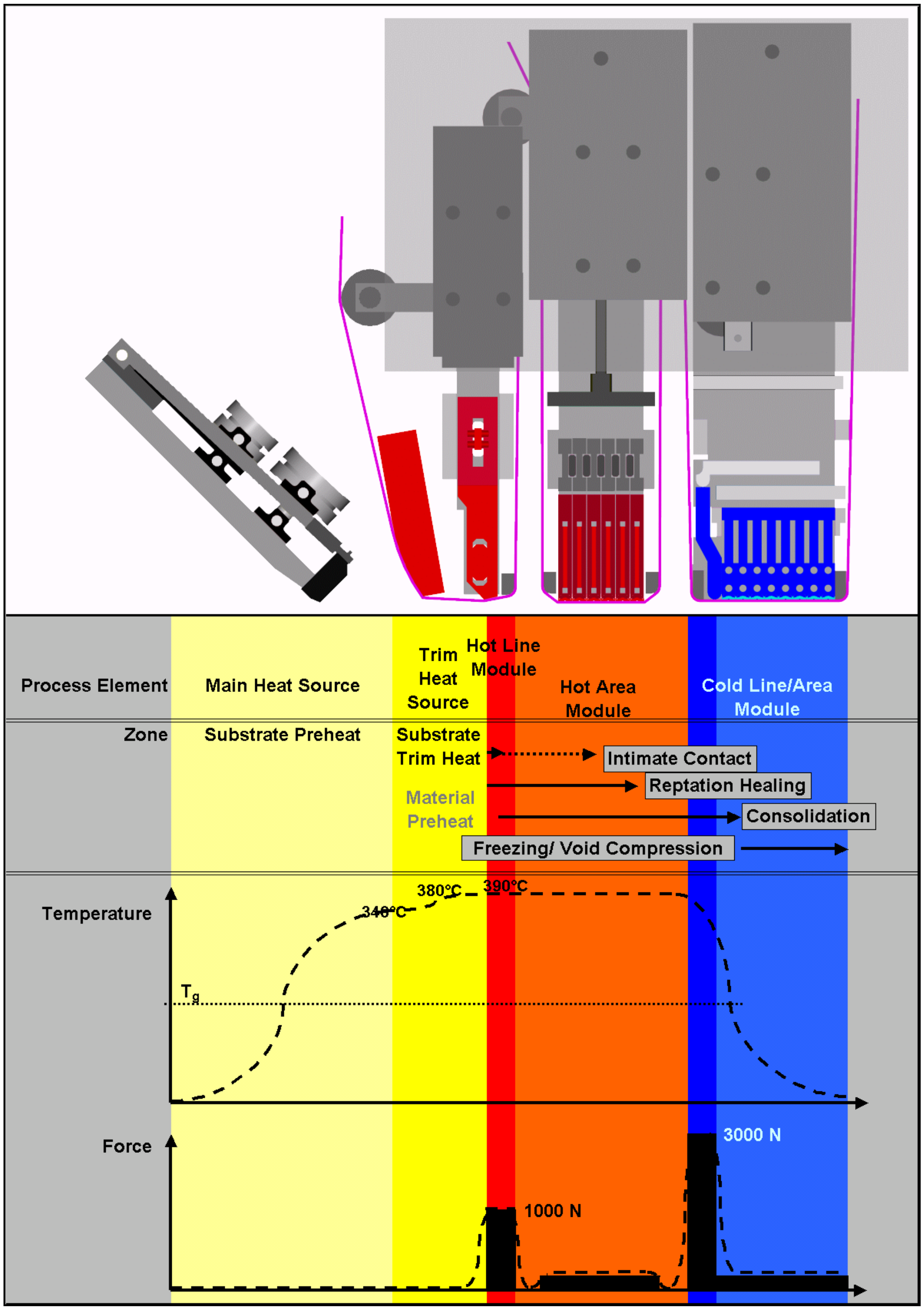


Figure 4 Fiber placement process zones and process parameters

6. CONFORMABLE COMPACTION SYSTEM DEVELOPMENT

The current NASA SBIR II program is directed towards developing both line and area conformable compactors. The designs were completed prior to the SBIR phase II and were guided by the following specification:

Specification
Two different surfaces over which conformance must be achieved have been defined. They are a general contour and a pad-up.

- Contour: The surface will have a minimum radius of curvature of 180cm (71-in).
- Pad-up: This is a rectangular pad on the surface of the part. The pad is a maximum of 2.5mm (0.1-in) tall and is blended into the surface using a ramp that is a minimum of 25mm (1-in) long (10:1 slope). A similar specification is applicable to a pad-down of identical dimensions.

Three modules were designed to incorporate the four process zones shown in Figure 4. The modules are the hot line compactor, the hot area compactor, and the cold compactor, comprising the cold line region and the cold area region

There is also a system design consisting of a frame, vertically articulating drawers that extend the geometry limits of the compactors to conform, and a shim drive apparatus to manipulate all of the shims, thereby achieving the process motions. Two of the three compactors are being fabricated and developed in the SBIR program: a line compactor and an area compactor. Their performance will be evaluated by placing tape in hot mode, and their conformance will be evaluated in cold mode as well. The line and area compactors are shown on their frame in Figure 5. These compactors will be described below.

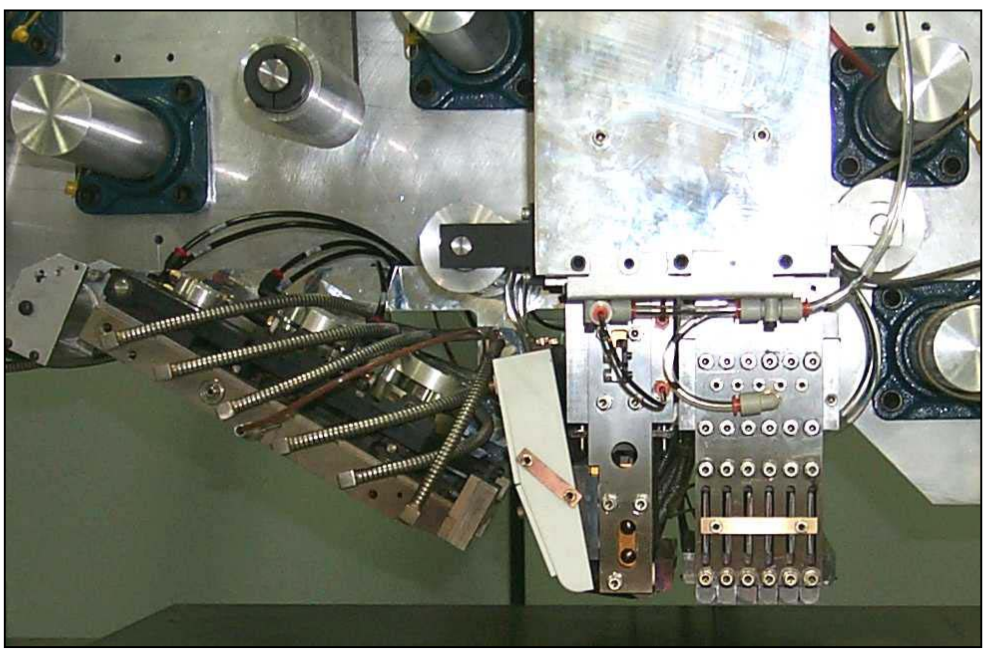


Figure 5 The hot line and the hot area compactors are integrated together with a feeder on an evaluation frame so that their conformability can be evaluated while placing composite tape

The Line Compactor

The line compactor is designed to provide a uniform short duration high force to the laminate. When heated, the "hot line" compactor provides a high temperature to initiate the in situ consolidation process. When chilled, the "cold line" compactor is designed to provide a high force and low temperature. Both versions feature a multiplicity of segments to allow the force to conform to the geometric details of the tool or laminate. The heated or chilled compactors have a different number of segments, as shown in Table 1. In the hot line compactor shown in Figure 6, there are seventy-six segments covering an 114mm (4.0-in) width, and the head is capable of compacting a 76mm (3-in) width. Thus, the hot line compactor is compatible with heads placing twelve 6.35mm (0.25-in) tows or one 76mm (3-in) tape. In either hot or cold mode, the segments are covered by a shim to protect the individual fibers in the tape or tow and also to integrate the segment forces. Shim thicknesses were chosen after substantial evaluation experiments proved the thickness requirements for robustness and conformance. A photograph of one of those tests is shown in Figure 7. A shim transport system is in place to index the shim so that it can be refreshed after each course, or less often, as required

The internal detailed parts of the line compactor enforce a constant pressure across the segments.

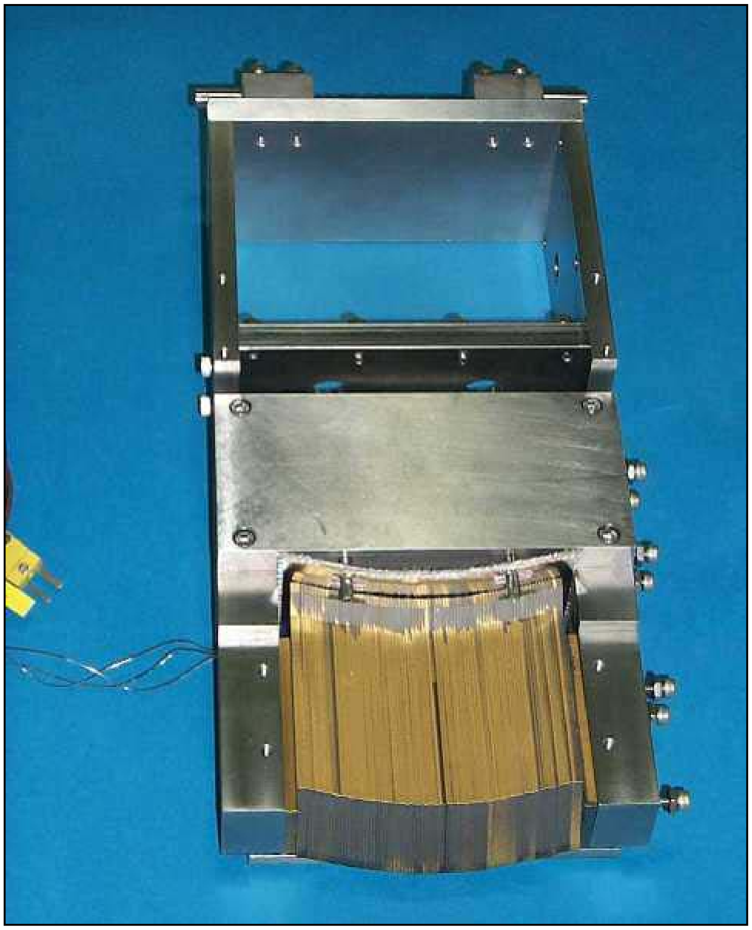


Figure 6 The hot line compactor features 76 heated segments. It is capable of transmitting a 1000N (250-lb.) conformable force at 450°C across a 102mm (4.0-in) width.

	Segments	Active Width, mm (in)	Active Length, mm (in)	Maximum Force, N (lb)	Temp, °C	Vertical Segment Conformance, mm (in)
Hot Roller		102 (4.0)	6 (0.25)	1000 (250)	450	0
Hot Line	76	114 (4.5)	6 (0.25)	1000 (250)	450	12.7 (0.5)
Hot Area	240	114 (4.5)	76 (3.0)	400 (100)	450	12.7 (0.5)
Cold Roller		127 (5.0)	6 (0.25)	2800 (700)	10	0
Cold Line	50	127 (5.0)	6 (0.25)	2800 (700)	10	12.7 (0.5)
Cold Area	400	127 (5.0)	102 (4.0)	1000 (250)	10	12.7 (0.5)

Table 1 Design features of hot line, hot area and cold line/area conformable compactors compared with rigid compactors used in the Cytec Engineered Materials thermoplastic ATP head

Figure 8a shows the ability of the line compactor to conform to a ball peen hammer. Figure 8b shows the line compactor in a drawer that allows air-pressurized cylinders to press the hot line compactor against the laminate, effectively increasing its stroke to 38mm (1.5-in).

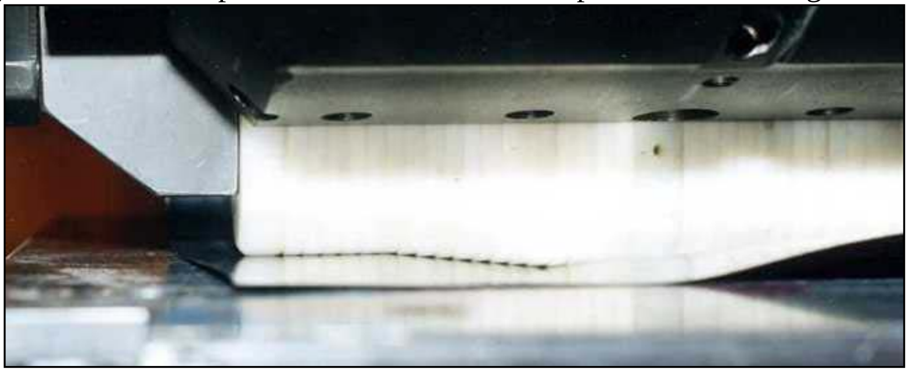
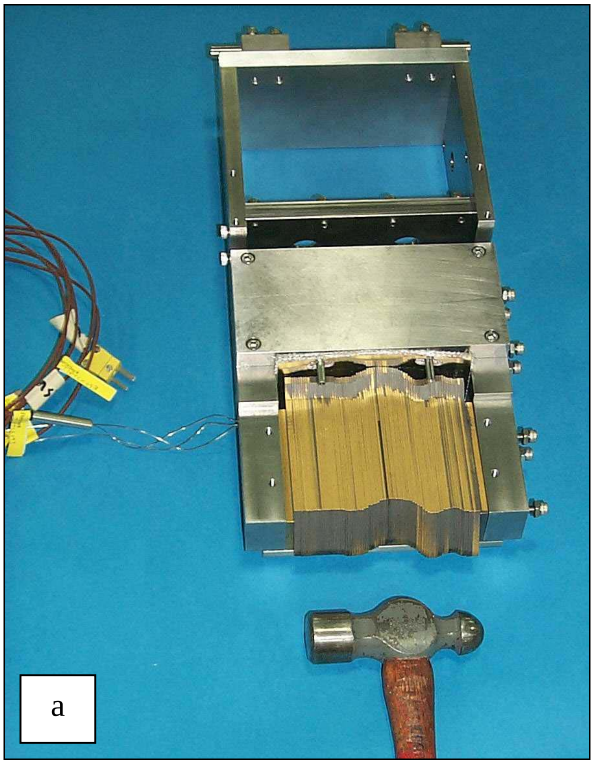


Figure 7 Conformance tests were completed to find shim thicknesses that would adequately conform to the specified geometry, protect the fibers from the segments, and have robust operation for a reasonable lifetime.



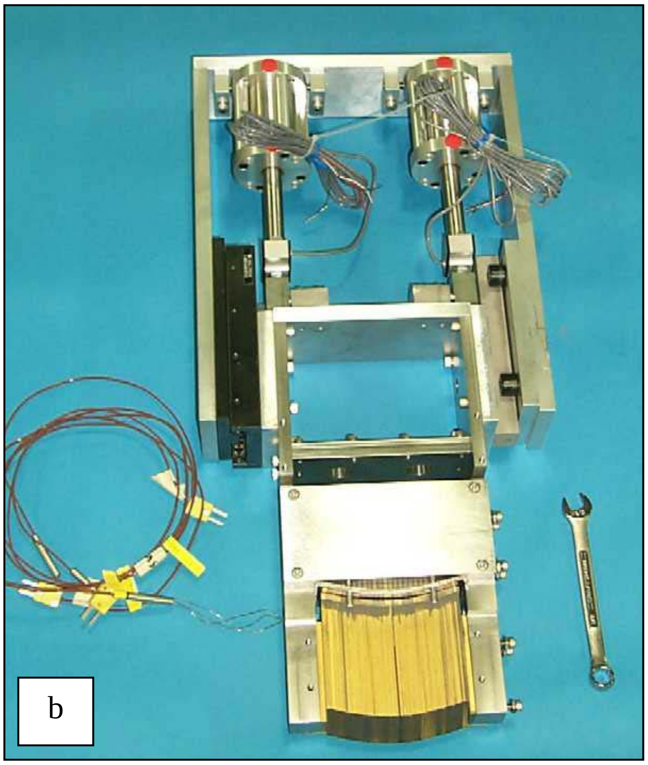
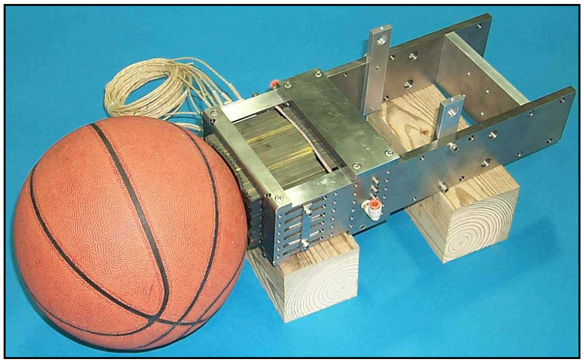


Figure 8 Hot line compactor has 76 segments, and can accurately conform to the shape of a ball-peen hammer. The hot line compactor is mounted in a drawer that provides an extra vertical articulation axis. When pressurized by air cylinders against the composite layers, the stroke is increased from the 6mm (0.25-in) available from the compactor itself to 38mm (1.5-in) overall.

The Area Compactor

The area compactor is designed to provide a light force over a longer process distance than the line compactor. As such, it has multiple rows of larger segments covered by a shim. All segments in the area compactor are tipped with remote center compliance feet. Table 1 shows that the area compactor has 240 segments if designed as a hot device and 400 segments if designed as a cold device. The segment widths are actually the same in the cold and the hot design. In the hot area compactor actually developed, there are six rows of forty segments, and the compactor is able to heat an area 114 mm wide by 76mm long (4.5-in by 3-in) while pushing with a 400N (100-lb.) force at 450°C. In the cold area compactor, there are eight rows of fifty



segments, and the compactor is able to chill an area 127mm wide and 102mm long (5-in by 4-in) while pushing with a 1000N (250-lb.) force at 10°C. Thus, the area portion of the cold compactor is essentially an extended version of the hot area compactor, with two extra rows of segments. In the hot area compactor, the shim can index after each course. Figure 9a and 9b show the hot area compactor's conformance to a basketball.

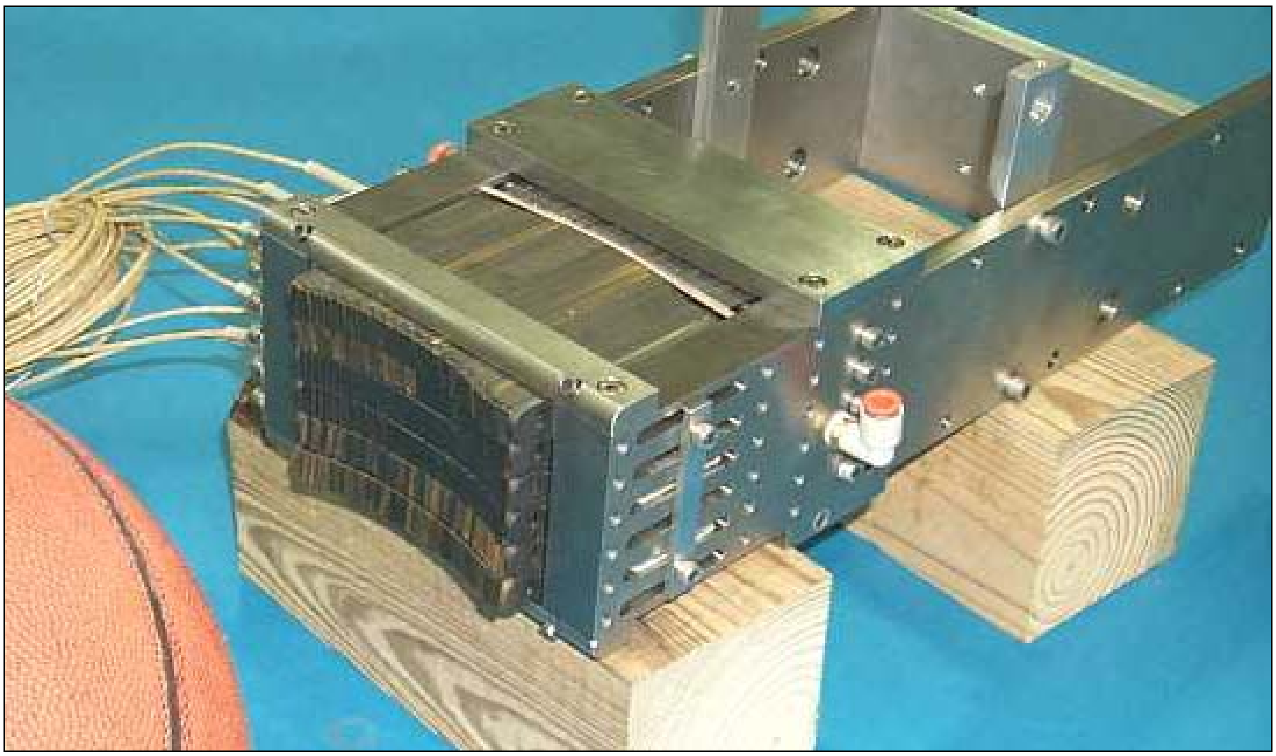


Figure 9 Hot area compactor's conformance to a basketball. The compactor pushes with a 400N (100-lb.) force at 450°C over a 114mm by 76mm area (4.5-in by 4-in).

7. SUMMARY

A trade study has been completed comparing the ATP/autoclave fabrication process with several out-of-autoclave processes for fabricating large composite structure like that found on the RLV tanks of other large aerospace parts like wing and fuselage skins. Ultimate properties like that available from ATP/autoclave fabrication are required, but autoclave processing of large tanks is very expensive. Four candidate out-of autoclave processes were rejected due to inadequate normal compaction force during cure. Thermoplastic in situ consolidation and layer-by-layer E-Beam curing were cited as processes deserving development, owing to the use of a compactor to apply a normal force to the laminate during consolidation or cure. E-Beam and thermoplastic in situ ATP fiber placement heads must be developed with conformable compaction systems so that the head force can create the type of laminate consolidation needed to manufacture the ultimate quality required. Without such a compactor, development on both processes for this application will not be successful. Conformable compactor development is the focus of a Phase 2 SBIR. The design of a series of conformable compactors has been completed, and include a hot line compactor capable of a 1000N (400-lb.) force at 450°C over a 114mm (4.5-in) width, a hot area compactor capable of a 400N (100-lb) force over a 114mm width by 76mm length (4.5-in by 3-in) at 450°C, and a cold compactor that combines the features of a line and an area compactor. The cold compactor's line segments act with a 2800N (700-lb.) force across a 127mm (5-in) width, while the cold compactor's area segments act with a 1000N (250-lb.) force over a 127mm by 102mm (5-in by 4-in) area. The hot line and hot area compactors have been constructed and are being tested in hot and cold modes to compact actual thermoplastic composite plies over undulating geometry.

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- Accudyne Systems – Steve Funck, Nan Gopez, Ross Hutter
- Enser – Eric Venskytis

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