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Recent Advancements in the Development of Inflatable Multi-Hull Boats Utilizing Drop-Stitch Fabric

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ABSTRACT

The development and use of drop-stitch technology has been around since the early 1950's when Goodyear and the U.S. Government began experimenting with inflatable airplanes. In 1991, CDI Marine (then Band Lavis and Associates) conducted a feasibility study for the U.S. Navy to develop a concept design for a 4-meter inflatable combat rubber raiding craft utilizing drop-stitch fabric. The purpose of this project was to determine if drop-stitch technology could be adapted to small inflatable boats to improve their performance, i.e., seakeeping and speed.

Over the past 20 years, the design of inflatable high-performance hullforms has expanded to include more sophisticated multi-hull hull forma that, for performance purposes, require rigid appendages of wood and aluminium to be attached to the hulls in order to achieve the proper hull shape. The initial design concerns raised with respect to the rigidity of the attachment points were resolved. Test results bore out the feasibility of such attachments to the degree that specific hard attachments can now be confidently employed in new designs. This development leads the way for future boats that are larger and with more powerful engines. Such past proposals to build large boats with composite after bodies, containing powerful Personal Water Craft (PWC) waterjet propulsion packages, are now within the realm of reality with minimal risk.

KEY WORDS

Inflatable Boats

Drop-Stitch Fabric

Multi-Hull Boats

Advanced Hullform

1.0 INTRODUCTION

Recent advancements in the design and testing of more "nontraditional" hullforms has advanced the knowledge of what can be done using drop-stitch technology. These advances have laid the ground work for larger, more capable inflatable vessels to be designed and built. By employing drop-stitch technology, the ability to carry two, or possibly more, USVs in the space of a traditional RIB increases the capability of U.S. Navy combatants such as the Littoral Combatant Ship (LCS).

This paper will describe drop-stitch technology, the history of its development, the history of CDI Marine's Internal Research and Development (IRAD) program, and recent technology advancements.

2.0 DROP-STITCH TECHNOLOGY

The basic technology employed for the boats described in this paper is generally referred to as drop-stitch technology. In its very simplest form, drop-stitch fabric can be compared to cored, composite structures, i.e., a core material with an outer laminate on both faces (Figure 1).

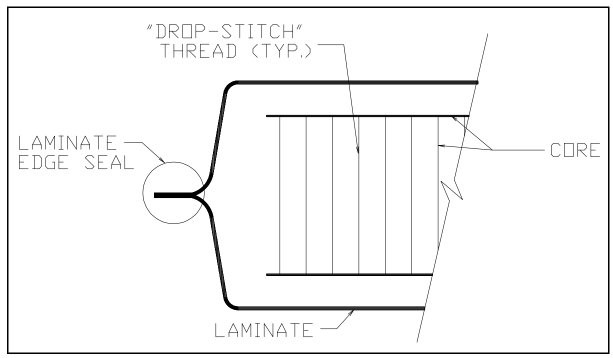


Fig. 1. Basic drop-stitch structural configuration.

The cored material in this case consists of two pieces of fabric that are connected, sandwich style, by a series of rows of "stitches". The "stitching" process leaves an excess amount of thread between the two pieces of fabric in such a manner that when the two pieces of material are separated, the faces of the panel are parallel to each other at a distance which is equal to the length of the excess thread (Figure 1).

2.1 Drop-Stitch Material

In actuality, the drop-stitch fabric is woven from Dacron or Nylon thread, not stitched, although it appears to be stitched, hence the name "drop-stitch". Upon close examination, it can be found that each thread used in the weaving process is woven several times in the warp direction, then up (or down) forming the "drop stitch", and then several times in the weft direction before running down (or up) again. This process assures that the fabric cannot unravel. The weaving process is such that there are approximately 50 "stitches" or threads per square inch (Figure 2). The thickness of this core can be as small as desired, but generally does not get much less than 2 inches. Maximum thicknesses are reported to be as much as 30 inches and are a function of the physical constraints of the weaving loom. Additionally, some looms are capable of varying the length of the threads linearly in one direction to form a wedge-shaped structure.

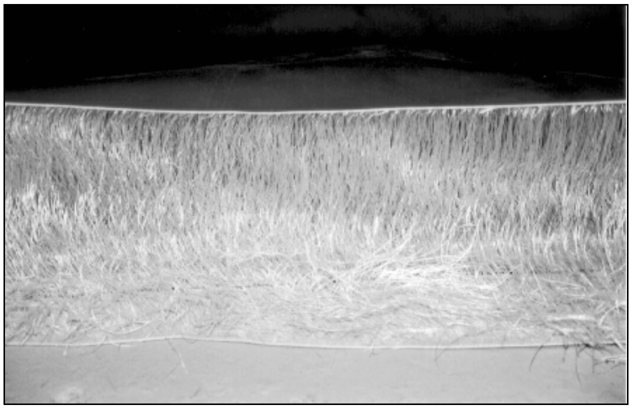


Fig. 2. Drop-stitch panel interior.

Drop-stitch fabric is also woven in two different grades – standard and heavy duty. The standard grade is generally rated for use up to 0.7 bar and the heavy duty to 1.0 bar. All of the boats discussed in this paper utilize the standard fabric but have routinely been inflated to 1.0 bar without any problems. In tests conducted by Maravia Corporation in 1992, a standard-grade drop-stitch fabric was used for a test panel that was pressurized to 3.5 bar before it failed.

The basic drop-stitch fabric is not air-tight and must be coated. The faces of the drop-stitch core are sealed by coating or laminating the faces with a non-permeable elastomer such as polyester, PVC, neoprene, urethane, Kevlar, etc. to make the structure air-tight. This material can be applied as solid sheets that are glued to the drop-stitch core or by a hot calendaring process where the drop-stitch core faces are actually impregnated with the coating material.

To form the final inflatable structure, the edges of the two outer laminates are sealed by welding the laminates or, in the case of panels that have been coated using the calendaring process, gluing a non-drop-stitch fabric tape around the perimeter (Figure 1).

Over the years, a number of names have been associated with this technology, e.g., Airmat, INFAB, drop-stitch and drop-thread. To further confuse the issue, these terms are sometimes taken to mean only the core fabric itself and sometimes the entire structure. For the purposes of this paper, the terminology “drop-stitch” will be used when referring to the entire inflated, coated structure.

2.2 Advantages of Drop-Stitch Technology

The advantages of drop-stitch technology are two-fold. The first advantage, as seen in Figure 3, is obvious. If a truly flat, rigid inflatable structure is desired, then something similar to a drop-stitch material is needed. As seen in Figure 3, a drop-stitch panel does not produce the typical “log raft” appearance so familiar in beach rafts. Drop-stitch structures are truly flat. The combination of the closely-spaced stitches and the thickness of the laminates prevents even localized bumps or spherical-shaped sections.

Fig. 3. Typical drop-stitch panel.

The second advantage of the drop-stitch fabric is that it demonstrates structural properties similar to plywood. A drop-stitch panel can withstand large loads, and associated large deflections, before failure. However, unlike plywood where the plys will delaminate at failure, a drop-stitch panel will generally collapse under large loads but rebound to its original shape when the load is removed. So, where there are surfaces that are largely flat with little twist in them, a drop-stitch panel can replace wood, metal or composite structure (Figure 4). The truly remarkable structural properties are still somewhat of a mystery and are currently the focus of an R&D program which will be discussed later in this paper.

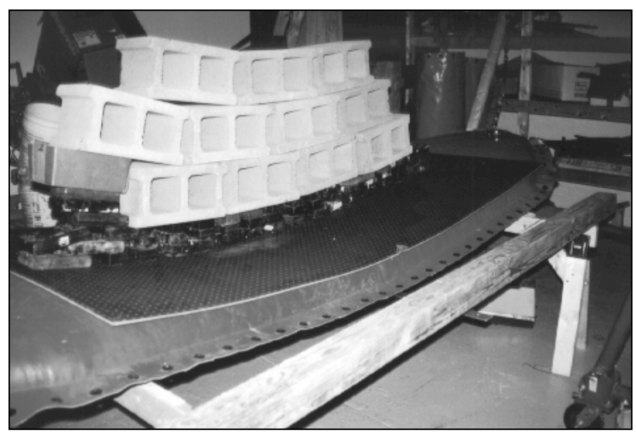


Fig. 4. Typical drop-stitch panel under load.

At this point, it is necessary to say that drop-stitch technology is not the answer for all inflatable applications. One reason is the cost of manufacturing the material. The looms are expensive and the demand for the fabric is somewhat limited. Another reason is that drop-stitch panels are not conductive to applications where compound curvature or spherical structures are required, nor is it conductive when fine, tapered edges or joints are required. Although some slight curvature can be employed with this technology, both the designer and the builder must be careful. An example of what can be done will be discussed in later sections of this paper.

So far, the discussion of drop-stitch technology has focused on boats and will remain the focus of this paper. However, it should be obvious to the reader by now that there are many other applications where this technology could be applied. In fact, drop-stitch technology is a byproduct of the aviation industry.

2.3 History

Drop-stitch fabric is not a new technology. In fact, it was developed nearly 60 years ago. In the 1950's and 1960's, NASA and the U.S. Air Force conducted considerable research that explored the use of drop-stitch technology for aerospace applications (Ross 1966).

Perhaps the most astounding drop-stitch accomplishment was a series of inflatable aircraft built by the Goodyear Corporation. During the 1950's, Goodyear Corporation was also conducting research with drop-stitch fabrics. At least two patents were granted to Goodyear (Ford 1958 and Mauney et al. 1956) describing drop-stitch technology. These patents may be the first describing this technology, at least in the U.S.

Six inflatable aircraft are known to have been built and flown, two of which were amphibious. The aircraft ranged in capacity from a single-seater to a six-passenger aircraft. Film footage of some of the flight tests conducted by Goodyear indicates that the aircraft was quite maneuverable and capable of handling considerable aerodynamic loads. The research for these aircraft was sponsored by the U.S. Government for use as air-deployable rescue vehicles.

During the 1960's, the U.S. Navy also showed some interest in the technology. A 1/20th-scale model of the bow section of a Mariner hullform was built using drop-stitch technology. Tests were conducted to determine the impact tolerance and shock absorption characteristics of the material (Chuang 1965). These tests were run in conjunction with the work Goodyear was conducting.

2.4 Rigid Inflatable Bottom Boats (RIBBs)

In the 1970's, the U.S. Navy small boat community also became interested in drop-stitch technology. Two patents (McCrory et al. 1981 and McCrory 1984) were granted to the U.S. Navy relating to the use of drop-stitch technology in small, inflatable boats. However, as seen in Luscombe (1976), other non-government patents pertaining to inflatable boats preceded these.

More recently, drop-stitch technology has been used for floors in both white-water rafts and inflatable boats. In both of these industries, a high strength-to-weight ratio, compact storage and ease of assembly are key design features.

Regarding the current program described in this paper, the first consideration for the use of drop-stitch was in 1991. At this time, a contract was let by the U.S. Navy for the design of a new inflatable combat rubber raiding craft under a government Small Business Innovation Research (SBIR) program. The objective of this program was to develop a new inflatable boat for the U.S. Navy SEAL Teams. This craft was known as the Combat Rubber Raiding Craft, Small (CRRC(s)). During the development of the design, drop-stitch technology was considered for use in the construction of the floor, but its potential for use in the construction of the hull was also recognized. However, the limited experience of the design team with this technology eventually led to eliminating it from consideration. Cost and technical risk were also factors in the decision to not use "drop-stitch" technology. Shortly after the completion of the initial design phase of this contract, this program was canceled.

Approximately four years later, this same program reappeared under the name Advanced Combat Rubber Raiding Craft, Small (ACRRC(s)). For this program, a new team was formed which included a white-water raft manufacturer, Maravia, who used drop-stitch technology. This particular manufacturer had, at the time, over ten years experience building white-water rafts with drop-stitch floors as well as considerable experience conducting white-water expeditions in some of the toughest rivers in the U.S. During the design phase of this SBIR program, a 16.5-ft proof-of-concept Rigid Inflatable Bottom Boat (RIBB) was built and tested.

Although both government programs were ultimately canceled, the results of the fabrication and performance tests of the 5.0-meter proof-of-concept RIBB were encouraging enough that an in-house R&D (IRAD) program was established to continue the development of the RIBB concept.

Ultimately, under this IRAD program, a 5-meter prototype boat was built and utilized for further testing and validation of the concept. The continued testing of this boat greatly enhanced our knowledge of, and confidence in, the technology, the design and the construction techniques. The culmination of this IRAD program led to further interest by the U.S. Navy. As a result of this interest, the boat was loaned to the U.S. Navy who conducted a series of independent tests. These tests were conducted in much more severe conditions and with instrumentation not available to our IRAD efforts. The results of the U.S. Navy tests were quite encouraging and eventually led to a contract to design and build two additional prototypes – a 5-meter boat and a 5.5- meter boat. These two boats underwent a series of tests by the U.S. Navy as well. From the design standpoint, the single most important finding of the tests was that at around 5.5-meters, the stiffness of the 1000 mm fabric was not sufficient to keep the boat stiff enough for the needs of a military application. Thus, the limited availability of the material was the biggest hindrance to the advancement of the technology.

Up to this point in time, these projects were focused on developing prototype boats designed to the same requirements as the U.S. Navy's standard Combat Rubber Raiding Craft. The key driver of these designs is the ability of the boat to be folded into a package that is no more than 500 mm in diameter and 1.3 m long. This requirement drives both the shape and size of the hull.

Table 1 shows a comparison of the characteristics of the 5-meter and the 5.5-meter boat to the basic Combat Rubber Raiding Craft. The boats can be seen in Figures 5 and 6.

Table 1. Comparison of principal characteristics.

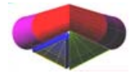
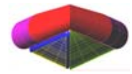
	F470	DS-500	DS-550
DESIGN SPECIFICATIONS			
O/A LENGTH	4.70 M	5.00 M	5.50 M
O/A BEAM	1.91 M	1.93 M	2.13 M
INSIDE LENGTH	3.30 M	3.61 M	4.21 M
INSIDE BEAM	0.91 M	0.91 M	1.22 M
DEADRISE	N/A	25 Degrees	22.5 Degrees
TUBE DIAMETER	0.51 M	0.51 M	0.46 M
AIR CHAMBERS	5+2+1 = 8	7+2+1 = 10	7+2+1 = 10
WEIGHT (EST.)	127 Kg	113 Kg	129 Kg

Fig. 5. 5-meter and 5.5-meter RIBBs inflated and folded.

Fig. 6. 5-meter RIBB.

2.5 Multi-Hulls

In the past five years, a number of inquiries have been received expressing interest in modeling an existing multi-hull design with the drop-stitch fabric. These projects are either classified or proprietary to the customer, so details of the design cannot be discussed. However, the fabrication techniques can be described here. This work has led to an understanding of how to:

- laminate two drop-stitch panels together to form a thicker panel,
- attach hard appendages such as skegs, nose cones, transom extensions and inboard waterjet propulsion systems, and
- build a shelter or cabin for the protection of the crew.

One of the most significant multi-hull projects was the design and construction of a 6-meter boat. It was evident early on that panels needed for the hulls of this boat would require much thicker drop-stitch fabric than was normally available from builders. These thicker panels would require a special run from the drop-stitch manufacturer. This would incur a special one-time setup fee plus an order for a minimum amount of fabric that was well in excess of that required to build the boat. This was obviously out of the question from both a schedule and cost standpoint. To resolve this problem, two panels of the builder's "stock" fabric were laminated together to approximate the required thickness. These panels were laminated together by placing them face-to-face and taping the edges around the perimeter of the assembly. This method was chosen over a process where the panel faces would be glued directly together. It was felt that this would minimize the distortion that might occur should one of the panels lose a bit of pressure and a differential develop between them. This could have been resolved by interconnecting the inflation system of the two panels. However, for this application, the added redundancy of having separate chambers was more important, so they were segregated utilizing independent inflation valves.

The lamination of two panels created another problem – a very blunt leading edge. To make them more hydrodynamic, consideration was given to staggering the leading edge of the panels so that one panel would be offset from the other. When taped, this would create a beveled edge of sorts. However, with each panel itself being relatively thick, this left large radiused edges that were still quite blunt. Ultimately, it was found that the best solution was to attach a composite or wooden appendage that was shaped more like a conventional boat bow, but the issue was how to attach such an appendage. Simply gluing and taping an appendage to the drop-stitch panel would not have a strong enough joint to withstand the lateral hydrodynamic loads. It was felt that to be successful the loads would have to be carried well into the inflatable structure beyond the joint. To accomplish this, longitudinal stringers were built into the appendage, in this case a wooden appendage, and designed so that they would slip in between the laminated panels. In this manner, the lateral loads seen by the bow appendage would be transferred in a more global manner to the panels. When fully assembled and inflated, this long 6-meter structure was quite stiff and, by all appearances, acted as a single structure. Unfortunately, systematic engineering tests were never conducted, so the actual failure point and mechanism are still unknown. However, it was reported that the boat did perform its mission.

The lamination of these large panels makes for quite a bulky package. Fortunately, this particular boat was only required to fit in a container and did so quite easily. However, it was fairly heavy due to the added fabric of the multiple panels and the appendages.

A second multi-hull that was modeled was a smaller boat with a considerable amount of compound curvature. In this instance, laminating multiple panels was done not for strength or adding appendages, but to assist in replicating curved surfaces via a series of straight sections. The key to this design was to not add so many panels that the boat became heavy and bulky and unable to perform its mission. This hullform also required the use of laminated panels. For this application, the panels were glued together and provided with a common port for filling both panels simultaneously. This filling port also provided a free communication between the panels which enabled them to maintain the same pressure at all times. This provided a much simpler fill system than would otherwise have been needed. In addition to providing the required hull shape, the laminated structure made for an extremely stiff hull. Again, this boat proved very successful, closely replicating the performance of the parent hull that was constructed of composite material.

3.0 STRUCTURAL PROPERTIES

As mentioned throughout this paper, the technical details of the structural properties of drop-stitch are still somewhat of a mystery. Early on in the IRAD program, some very simple load tests were conducted utilizing a 4-foot by 14-foot, 6-inch drop-stitch white-water raft floor (Figure 4). An unsupported section approximately 4 feet by 8 feet was loaded with weights and the deflection at midspan measured. This was done both with a point load at midspan and with a distributed load. These tests, plus our experience with the drop-stitch, showed that (Figure 7) (Bagnell 1998):

- As the pressure increases, the panel gets stiffer,
- As the thickness increases for a given pressure, the panel gets stiffer,
- A panel can withstand a significant load and deflection right up to the point of collapse, and
- The structural properties of the drop-stitch panel are not only dependent on the actual drop-stitch fabric, but also on the type and thickness of the coating.

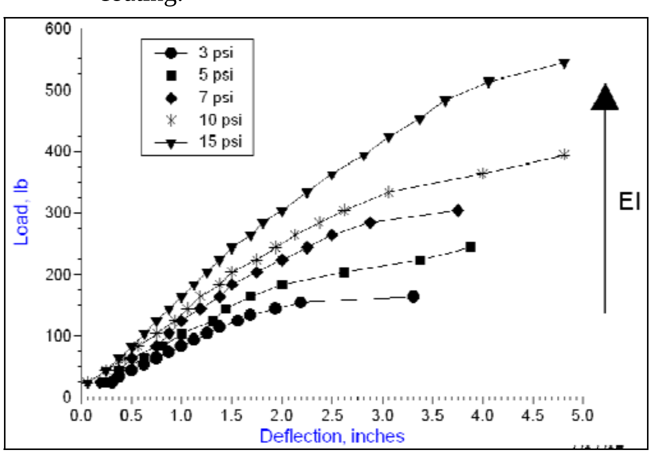


Fig. 7. Load versus deflection (Bagnell 1998).

These observations are obvious, but the objective of the tests was to at least take the first step in trying to identify the crossover points between pressure and thickness so that the designer can select the optimum combination of thickness and pressure. As with all tests like this, it is a costly effort to cover the whole range of variables – thickness, pressure, coating, sealing process, etc. However, a small but important step was taken in this direction recently. Under funding from the U.S. Navy Office of Naval Research T-Craft program, the U.S. Naval Academy conducted a limited series of engineering tests to quantify the load and deflection characteristics of a series of drop-stitch panels. This included testing two different sets of panels, one set being twice as thick as the other, and then gluing two of the thinner panels together and comparing the results to the single panel of equivalent thickness. Initial findings of these tests continue to confirm the experiences and lessons learned from field tests (Waters 2010). Specifically:

- A laminated panel can withstand, on average, a 30% greater load before collapsing compared to a single panel of the same thickness and pressure (Figure 8) (Waters 2010).
- Prior to buckling, the upper surface of a panel begins to wrinkle. For the laminated panel, it appears that the upper surface of the lower panel may be prevented from wrinkling by the glued joint. This could explain part of the ability to handle higher loads.
- The snap-back load, the load at which a deflected panel recovers from being loaded, is approximately the same as a similar single panel (Figure 8) (Waters 2010).
- The bending stiffness of an inflated panel is approximately 18% greater than what would be predicted by classical beam theory.

The final report for this project is expected to be released soon.

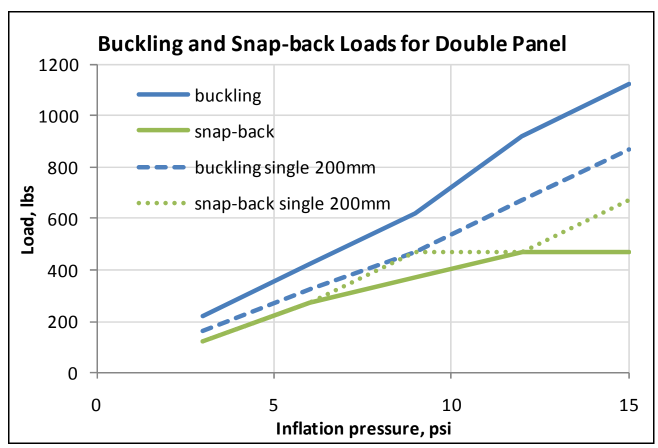


Fig. 8. Buckling versus inflation pressure (Waters 2010).

There has always been a concern that the structural quality of a glued-on coating was not as reliable or as strong as a calendared coating. This is in part due to very early tests in the 1980s when drop-stitch was only coated by gluing neoprene sheets of fabric to the drop-stitch. In those panels, failure occurred when the glue failed and the entire sheet of coating separated from the drop-stitch. The glue technology has matured so that, if applied properly, gluing a laminate to drop-stitch fabric is not a real concern any more. Failures we have seen on old panels have been around the inflation fittings. In tests conducted by Maravia Corporation in 1992, a standard-grade drop-stitch fabric was used for a test panel that was pressurized to 3.5 bar before it failed. This particular failure originated not in the drop-stitch fabric, but the welded seam around the perimeter.

4.0 CONCLUSIONS

Recent advances in the understanding of the structural properties of drop-stitch fabric and, more importantly, manufacturing processes have now provided the necessary information to make the leap to designing and building inflatable, high-performance boats in sizes larger than 5.5 meters with accompanying good structural qualities. Of particular significance is that the techniques are now available for building an inflatable boat with an inboard waterjet propulsion system. This provides the opportunity to build a USV that can be stowed in a package significantly smaller and lighter than a conventional RIB. This will allow large combatant craft to save space or carry additional USVs in the space of a conventional RIB.

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