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Orthotic Devices Using Lightweight Composite Materials

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FINAL REPORT

CONTRACT NAS1-15477

ORTHOTIC DEVICES USING LIGHTWEIGHT COMPOSITE MATERIALS

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1. INTRODUCTION

This final report is submitted within the requirements of NAS1-15477. It presents the results of all the projects and tasks undertaken during the entire contract period. Section 2 of this report contains a description and detailed discussion of each of these projects and tasks. In those cases where specific hardware has resulted from the individual projects, photographs and documentation are given. More detailed descriptions of two of the major projects completed under this contract are contained in Appendices A and B.

Appendix A is a Disclosure of Invention of the "Connector System for Joining Tubes, Pipes, Rods, and Other Regular Cross-Section Structural and Nonstructural Members," as submitted to the NASA Langley Research Center, Office of Assistant General Council for Patents. A patent has been filed on this invention, but it is felt that, for purposes of understanding the specific applications covered under this contract, the Disclosure of Invention is easier to understand than the patent document itself.

Appendix B is a paper describing the graphite walker developed under this contract. This paper was presented at the International Conference on Rehabilitation Engineering, Toronto, Ontario, Canada, June 16-20, 1980.

2. PROJECT DOCUMENTATION

In the following paragraphs each of the projects undertaken under Contract NAS1-15477 are described in detail.

2.1 Shoe Plates

The first project was the fabrication of shoe plates using graphite composite material. The objective was to obtain shoe plates lighter in weight and stiffer than those currently available. Shoe plates in the orthotic field are generally fabricated from metal. In most cases, the metal is a mild steel plate. The plate is inserted between the inner and outer sole of the shoe to provide rigidity to the shoe sole. The shoe plate is used in conjunction with short leg braces for a variety of applications but primarily with short leg braces designed to correct foot drop.

The shoe plates made from steel are in many cases quite heavy. For some of the larger patients, steel plate as thick as 6.35mm (0.25 inch) is required, and fracture of such plates is not an unusual circumstance. As a result, lighter weight and high strength are very desirable in this application. A graphite composite shoe plate was felt to have the potential for achieving both the necessary rigidity and the lighter weight. Three standard foot plate contours are normally employed, depending upon the height of the heel of the shoe. For this application, the median height was selected as the appropriate contour for the shoe plate.

Molds were required for fabrication of the shoe plate. Because of limited machine shop capability in our lab, the first mold attempt was made using a multi-segment wooden top and bottom plate faced with a thin aluminum sheet. Difficulty was encountered with this segmented mold, and after several attempts, it was decided that the variation of the wood with repeated temperature cyclings was sufficient to render the material unsatisfactory for a mold unless fabrication of a solid wooden mold could be achieved. As a result, it was decided to make a new mold using solid aluminum plate. This mold was constructed in four pieces: a top and bottom plate and two angled plates which fitted together to form the curvature. These were fabricated using a horizontal milling machine.

Using the new all-aluminum mold, a shoe plate was fabricated. The layup procedure used 27 plies. Twenty-five of the plies were Narmco Rigidite 5213-C6000, 30.5cm (12 inch) pre-pregged unidirectional fiber tapes. The top and bottom plies were Fiberite HMF-330C-34 fabric. The layup was as follows: 1 fabric, 4 parallel, 1 transverse, 4 parallel, 1 transverse, 5 parallel, 1 transverse, 4 parallel, 1 transverse, 4 parallel, and 1 fabric. Airtech A-4000, 0.0254mm (1 mil) release film was used between the mold surfaces and the graphite pre-preg. General Sealants GS-100 dam material was used around the layup.

The mold was assembled sandwich-fashion with a 2.54cm (1 inch) blanket of Dapcocast 15 rubber between the upper mold half and a reinforcing plate. Twelve 3.81cm (1.5 inch) square steel tubes were used to distribute the force of compression evenly. Six of the bars were drilled on each end to accept a 12.7mm (0.5 inch) bolt. The bolts holding the mold together were uniformly torqued. The material was cured in an oven. The cure cycle was: room temperature to 98.9°C (210°F) at 1.7°C (3°F) per minute, hold 98.9°C (210°F) for 50 minutes, heat to 135°C (275°F) at 1.1°C (2°F) per minute, hold at 135°C (275°F) for 90 minutes, and then oven cool to room temperature.

The fabricated graphite shoe plate blank was of excellent quality. The finish was very good, and the overall variation in thickness was less than 0.305mm (0.012 inch). Figure 1 is an overall view of the shoe plate blank. Using the graphite shoe plate material, several orthoses were fabricated. Results were excellent, and no failures have been experienced to the present time. Figure 2 shows the molds for a custom-fitted shoe sole. The rough cut insert is shown in the lower right, and the graphite shoe plate is in the upper right.

2.2 Walker

The second project addressed was the improvement of existing commercially available walkers. Walkers, as presently configured, are essentially small, three-dimensional space-frame structures that are used by patients with minimal gait difficulties or pain to aid in ambulation. Most of the currently available walkers are constructed of steel and aluminum tubes. Most fold to a relatively compact volume to permit storage in automobiles. Present units weight from 2.5 kg

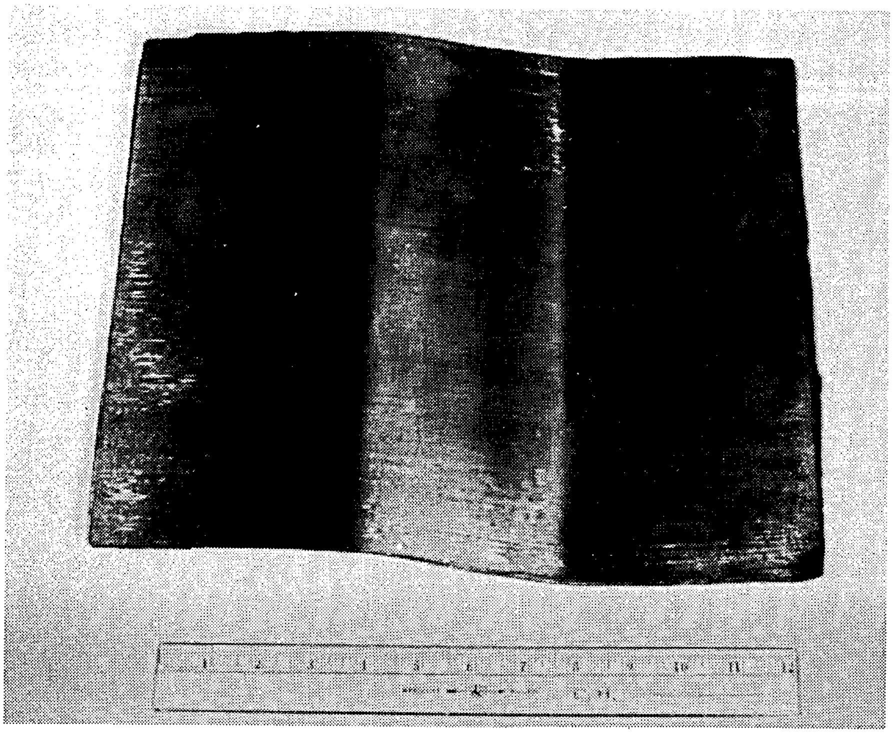


Figure 1 - Shoe Plate Blank

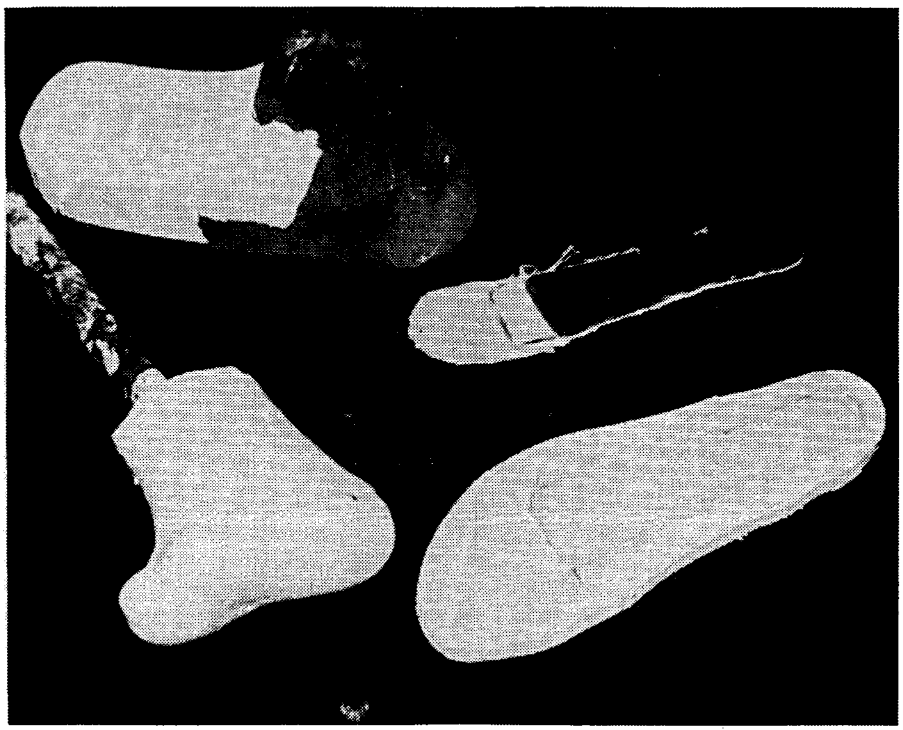


Figure 2 - Shoe Plate Cut for Insertion into Shoe Sole

(5.5 lbs.) to 3.4 kg (7.5 lbs.). The primary area for improvement in these walkers would be a reduction of weight.

There is a large population of patients requiring walkers who have some form of infirmity in their arms and shoulders. In order to use the walker, one must move the walker forward with the arms and shoulders and then step forward into the walker frame. This process is repeated to obtain ambulation. People with arthritic pain in the arms and shoulders frequently experience difficulty in using currently available walkers because of the weight which must be lifted for each step taken. This particular population is the population having arthritic involvement in the legs sufficient to impair ambulation and also having arthritic involvement in the shoulders and arms so that pain is experienced in lifting. A significant reduction in weight of the walker would permit these patients to use the walker more frequently and in many cases would allow people who are presently wheelchair-bound to use walkers for ambulation. This population, primarily the arthritic elderly female, is one of the rapidly increasing segments of the American population.

Various methods of fabrication were investigated to implement a lighter weight walker. Such a walker must be stable, strong, lightweight, and easy to fold into a compact unit for transport in automobiles. From a strength-to-weight standpoint, tubular structures are attractive. In addition, the presently constructed walkers are also of tubular construction so that patients accustomed to walkers made from aluminum tubes would find less difficulty in acceptance of new walkers if they had a general resemblance to present-day walkers. As a result, it was decided that efforts should be expended to develop a walker design employing graphite composite tubes.

2.2.1 Assembly Methodology

The methods used to assemble the currently available walkers are not appropriate to the assembly of walkers made from composite materials. This is true because of stress concentration in the current design. While metal tubes can withstand the stress concentration relatively easily, composite tubes must have the stress distributed over a larger area. Many of the tubular graphite structures built in the aerospace program have used individually machined connectors of aluminum. This approach would satify the requirements from a functional and a strength consideration. However, machined connectors would pose a problem in eventual large scale manufacture of such units because of the high cost involved. As a result, this particular method of joining tubes was eliminated because of the cost consideration. Other types of commercially available fastening systems are available in the commercial market, but none seem particularly suited to the problem of joining composite tubes. Consequently, it was decided that an attempt would be made to design several simple connectors that could be used with graphite tubing. Discussion of this effort is detailed in Section 2.2.3. Connector Problems and Solutions.

2.2.2. Search for Graphite Tube Fabricator

Once the decision was made to fabricate the walker using graphite composite tubes, it was, of course, necessary to obtain a source of such tubes. The problem was approached in a two-pronged effort: first, to examine the relative cost of inhouse fabrication of the tubes and, second, to solicit the fabrication of tubes from commercial fabricators. A number of fabrication facilities were contacted. Hercules Incorporated, who in the past had developed a pultrusion facility to market structural shapes in various composite materials, was contacted. Unfortunately, they had closed that particular operation, and were no longer making standard structural shapes in graphite. We were directed by them to a company in California named Composite Technology Engineering who might be able to supply fabrication of standard structural shapes. This company was contacted and, again, they did not have standard structural shapes of any kind available for sale.

Finally, the Graftek Division of Exxon Enterprises Incorporated in Raleigh, North Carolina, was visited after preliminary telephone discussions had indicated that this company might be able to furnish us with the graphite tubes required. Graftek has, inhouse, a pultrusion machine that they were currently using to make fiberglass tubing. In addition, they have wide experience in graphite fabrication. After discussion of our problem, Graftek offered to furnish graphite epoxy tubing in sufficient quantity to construct several walkers without charge. Specifications for the tubes were developed, and Graftek began layup of the tubes, thus solving the problem of availability of graphite tubes.

2.2.3 Connector Problems and Solutions

Since no commercially available connectors existed, it was necessary to design appropriate connectors to assemble the tubular graphite components of the proposed walker. Several considerations were deemed important. First, the connector should solve the problem of preventing stress concentration on the graphite tubes. Second, the connector should be as simple as possible and should require as few molds as possible for fabrication. Third, the assembly of the tubes with the connectors should be straightforward so that any semi-skilled person could easily perform the fabrication. With these overall guidelines in mind, the physical configuration of the proposed tubular graphite walker was examined to specify the connectors required for this fabrication.

The side frames are the major components of this particular space-frame structure. They support the patient's weight during weight bearing. The structure associated with attaching the two side frames together must provide stability and steadiness to the two side frames. The two side frames can basically be fabricated using only two types of connectors: a right-angle connector and a "tee" connector. The other connectors necessary to provide the spacing between the two side frames and the stability and stiffness are basically special purpose devices or variations of the other two types. As a result, it was decided to initiate design of general purpose connectors for joining tubes: first, the right-angle connector and second, the "tee" connector. Again, the use of as few pieces as possible in accomplishing the joints was a prime consideration.

Following these guidelines, a two-piece right-angle connector of graphite composite was designed. Each of the two pieces forming the connector are identical so that only one mold is required to make both pieces of the connector. The "tee" connector was also designed using the two components employed in the right-angle connector. Two additional pieces were required to achieve assembly of the "tee" connector. Both of these pieces were also identical so that the "tee" connector and the right-angle connector could be fabricated using only two molds.

Subsequently, the connector design was found to be sufficiently unique as to warrant a patent application. A detailed description of the physical and mechanical characteristics of these two connectors is given in Appendix A which is a copy of the Disclosure of Invention.

In the following discussion, only the actual physical characteristics of the connectors fabricated for use with the graphite composite walker are discussed. Figure 3 shows all of the mold components required to fabricate the right-angle connectors. This particular mold permits fabrication of enough material for two complete right-angle connectors. Figure 4 shows the mold after it has been disassembled, following cure of the graphite pre-pregged material. As can be seen, the graphite composite connector pieces in this photograph still have the internal cylindrical mandrels and the flat spacer bars in place. The connectors are fabricated using graphite fabric and unidirectional graphite tape prepreg. The layup consists of the following: 1 layer of fabric followed by 10 layers of unidirectional tape with alternating right-angle fiber directions, followed by an additional fabric cover. Figure 5 shows the graphite epoxy composite blank with the cylindrical mandrels and flat spacers removed. Figure 6 demonstrates the connector components after the first cuts are made, i.e., the graphite epoxy blank from the mold is cut into four pieces using a tungsten carbide bandsaw. Figures 7 and 8 indicate the manner in which the tubes of the two right-angle connectors interleave. Figure 9 shows the final cut that is required with the bandsaw to achieve the right-angle connector. Figure 10 shows the same connector with the tubes inserted in place. Figure 11 is an end view of one component of the right-angle connector. Figure 12 shows the manner in which the two tabs of the two connector halves interleave in forming the joint. Figure 13 shows the two tubes inserted in the two connector components with the tabs partially interleaved. Figure 14 shows the right-angle connector assembled, together with the two tubes, in the configuration in which they are finally bonded together. All of the right-angle joints in the said frames of the walker are made using this connector.

The "tee" connector uses two of the right-angle connector components plus two additional components. Figure 15 shows the mold necessary to make the two additional components for the "tee"

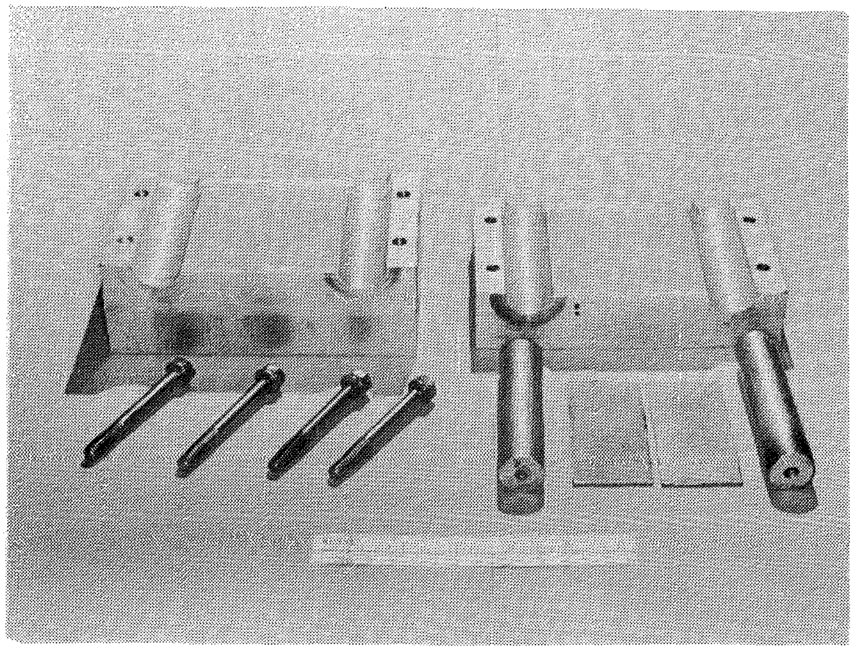


Figure 3 - Right-Angle Connector Mold Components

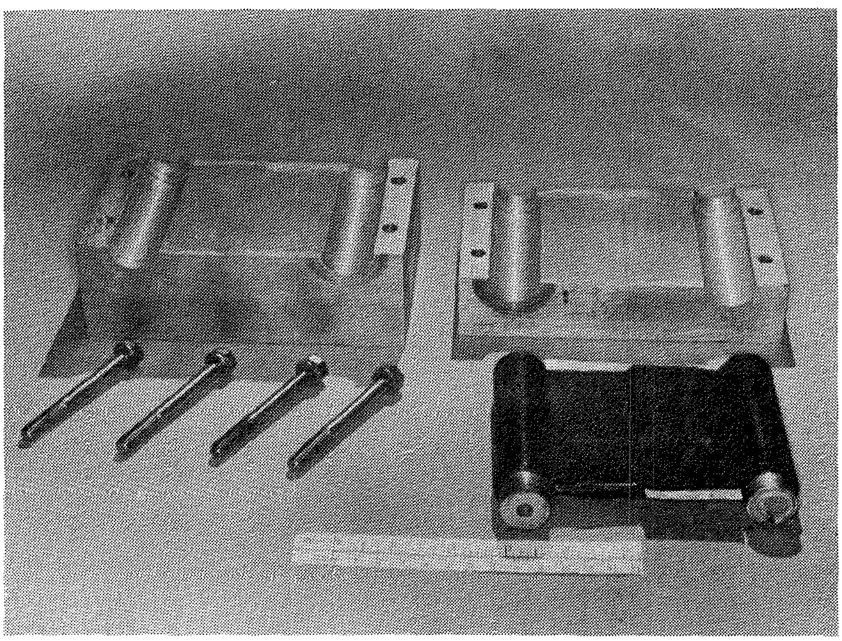


Figure 4 - Connector Blank as Removed from Mold

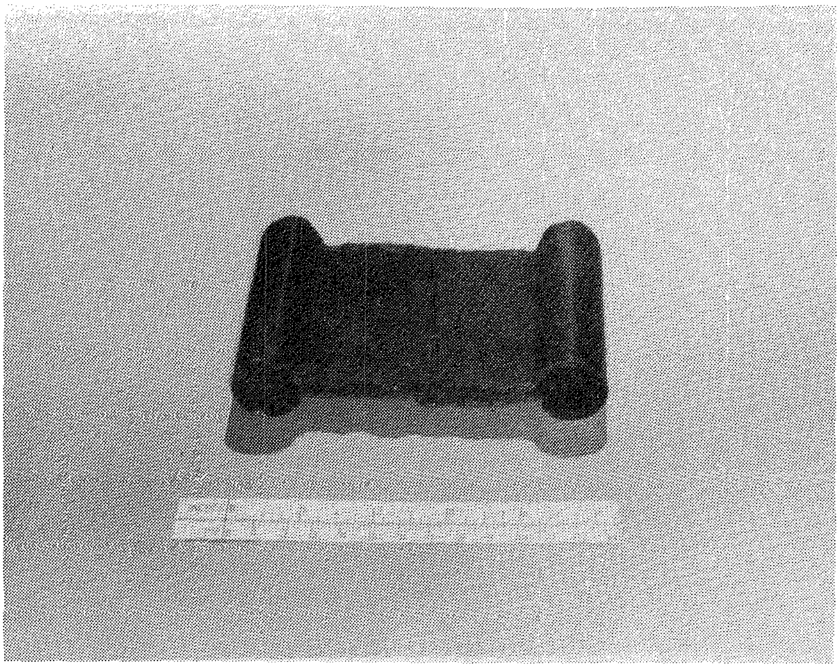


Figure 5 - As-Fabricated Connector Blank

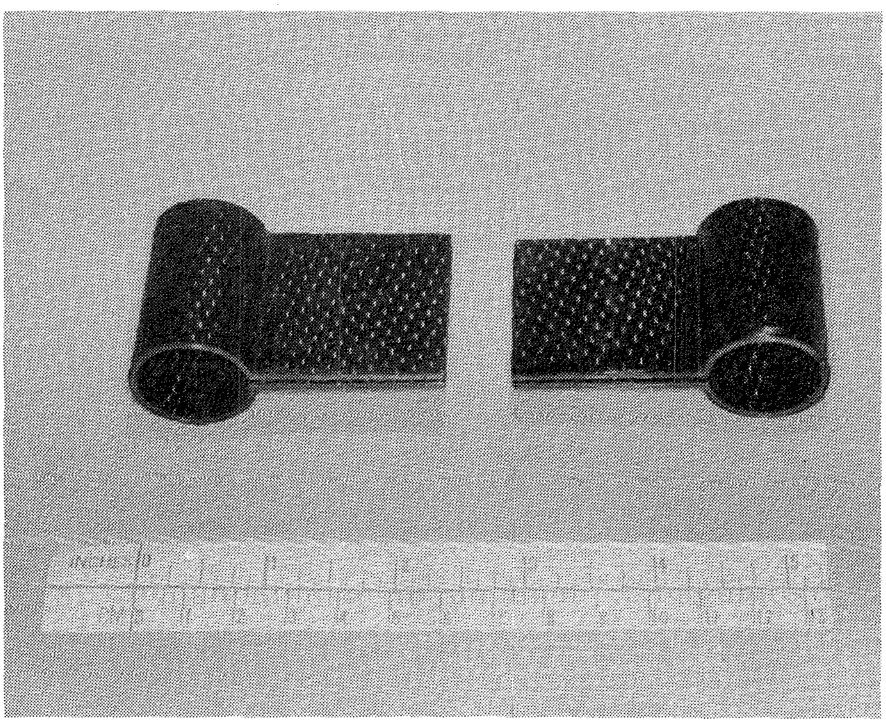


Figure 6 - First Dimensioned Cuts on Connector Blank

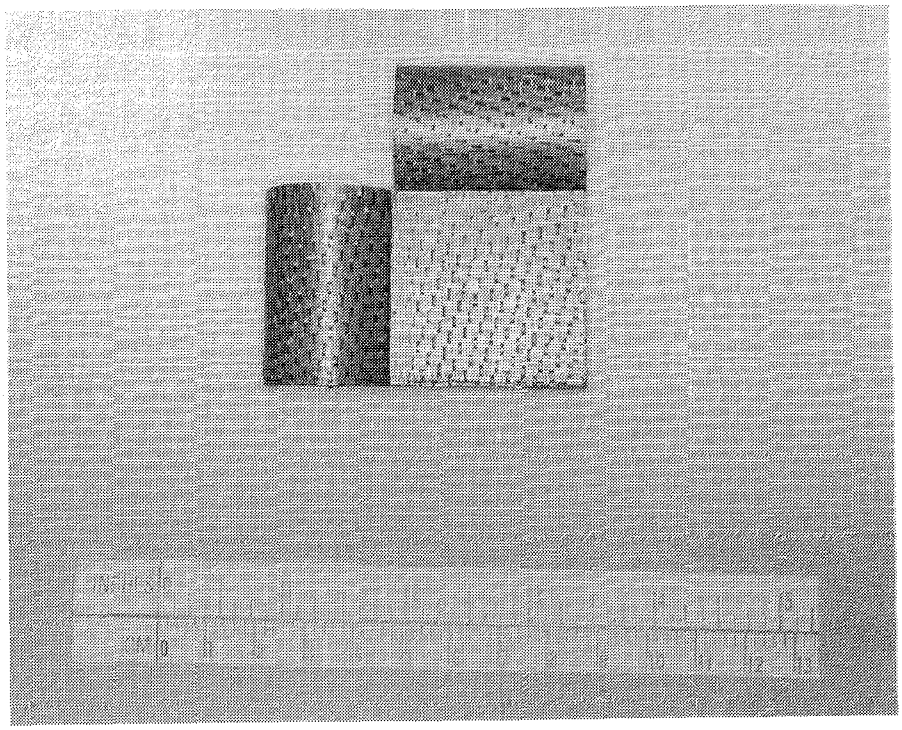


Figure 7 - Two Connector Components Interleaved

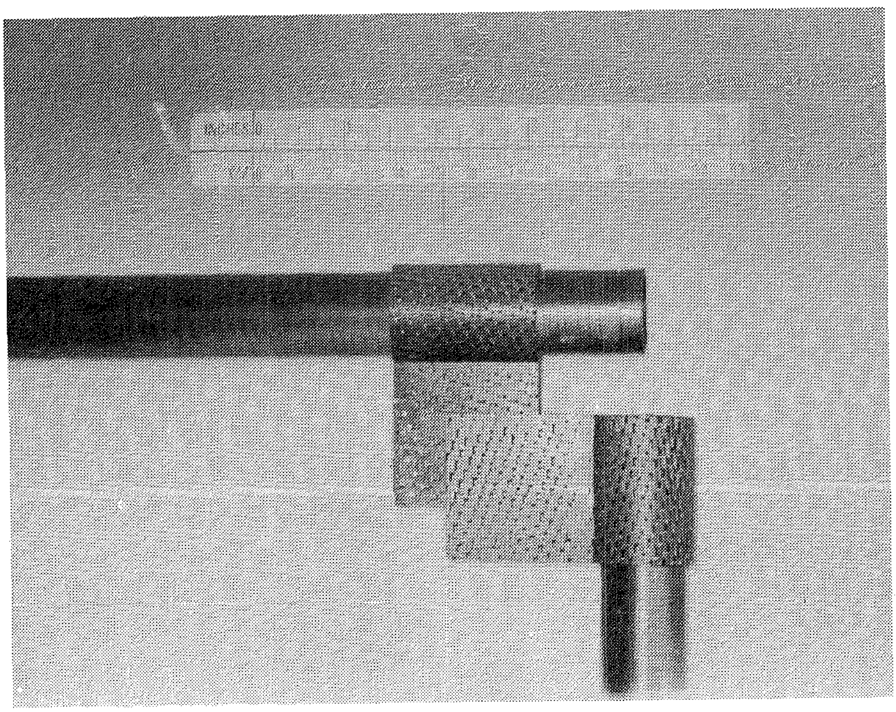


Figure 8 - Two Connector Components Interleaved with Tubes

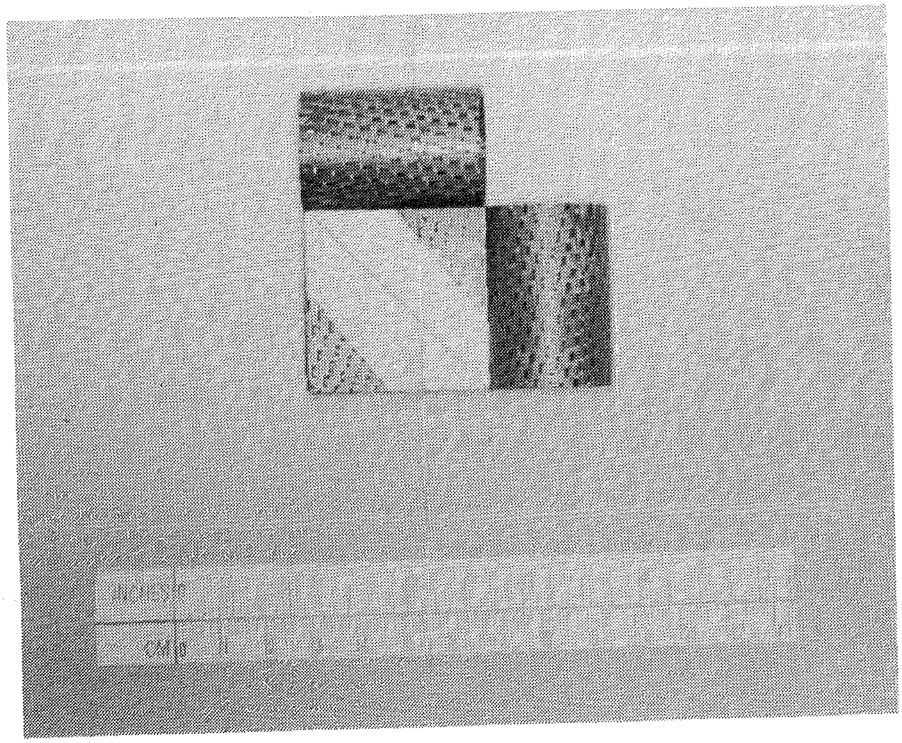


Figure 9 - Final Cuts Required on Right-Angle Connectors

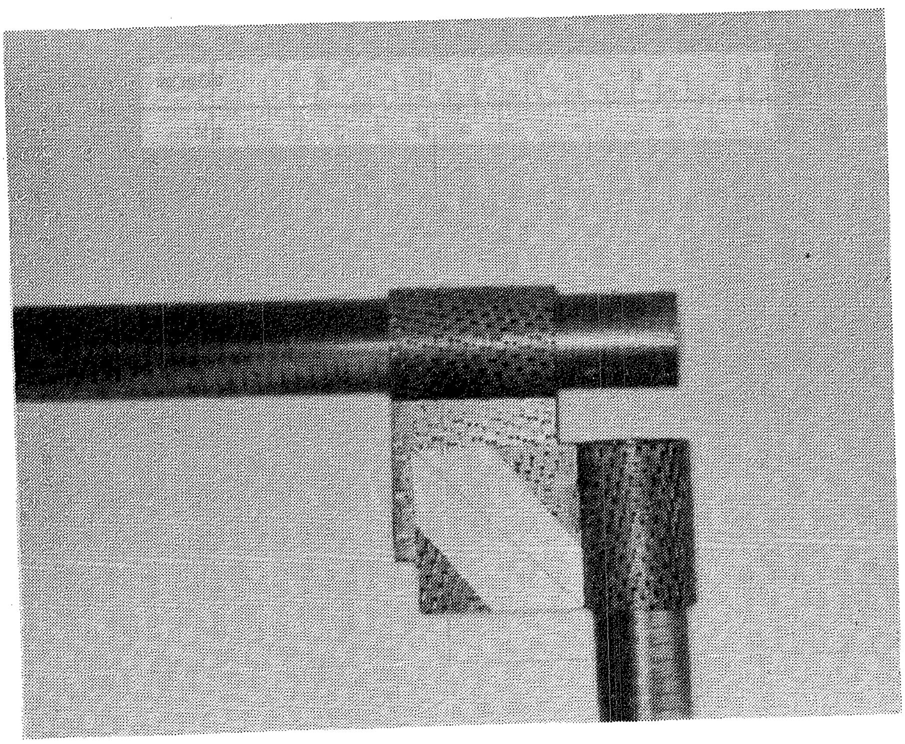


Figure 10 - View of Fig. 9 with Tubes Inserted

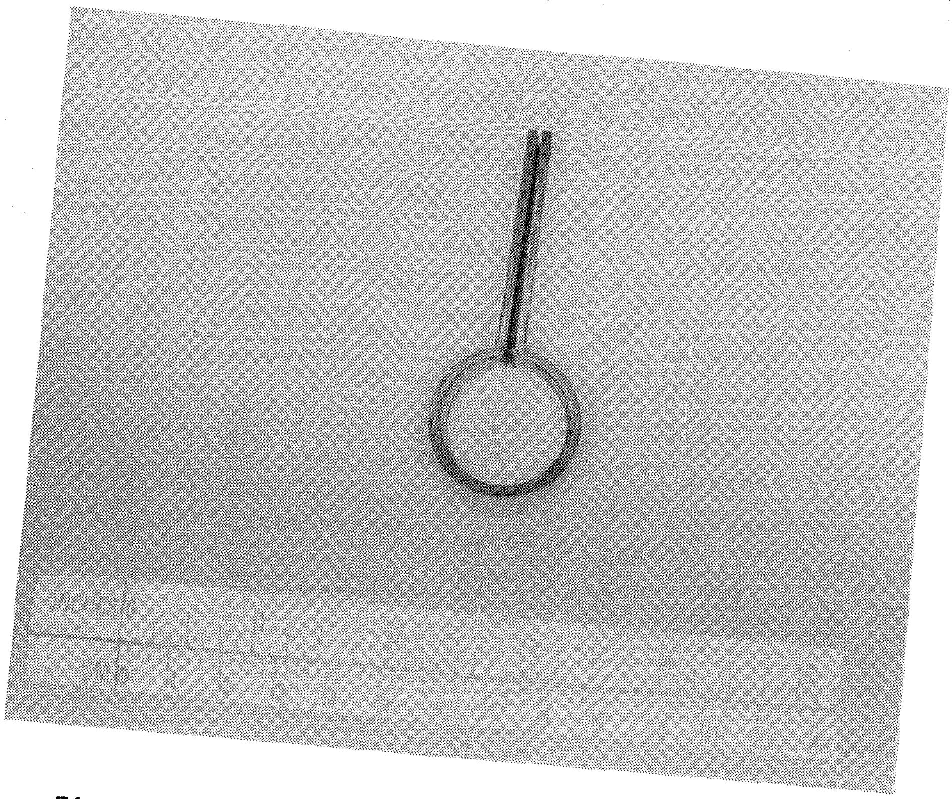


Figure 11 - End View of One Component of Connector

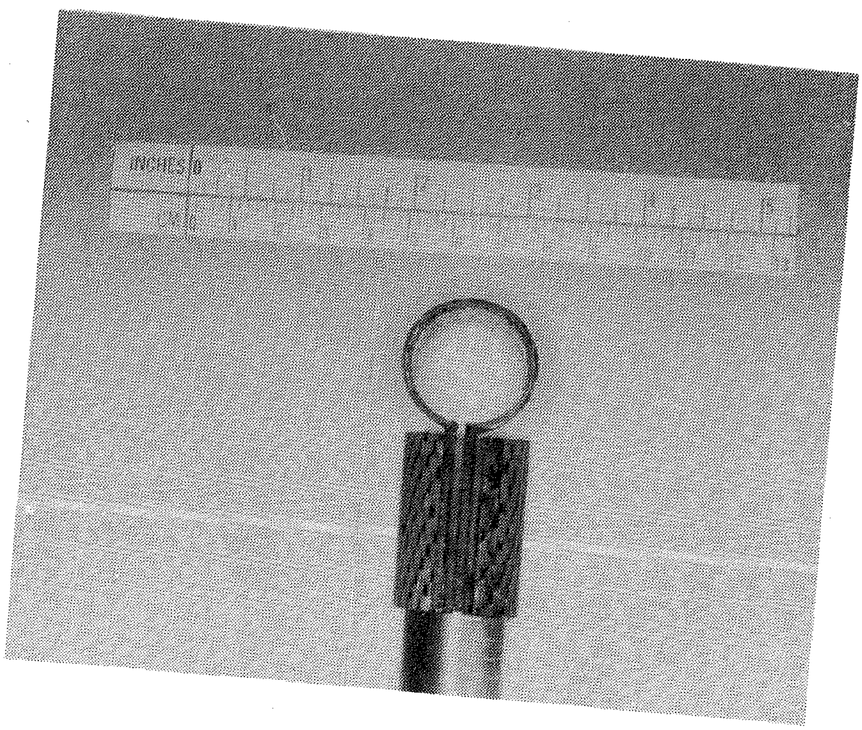


Figure 12 - End View of Connector Showing Interleaving of Tabs

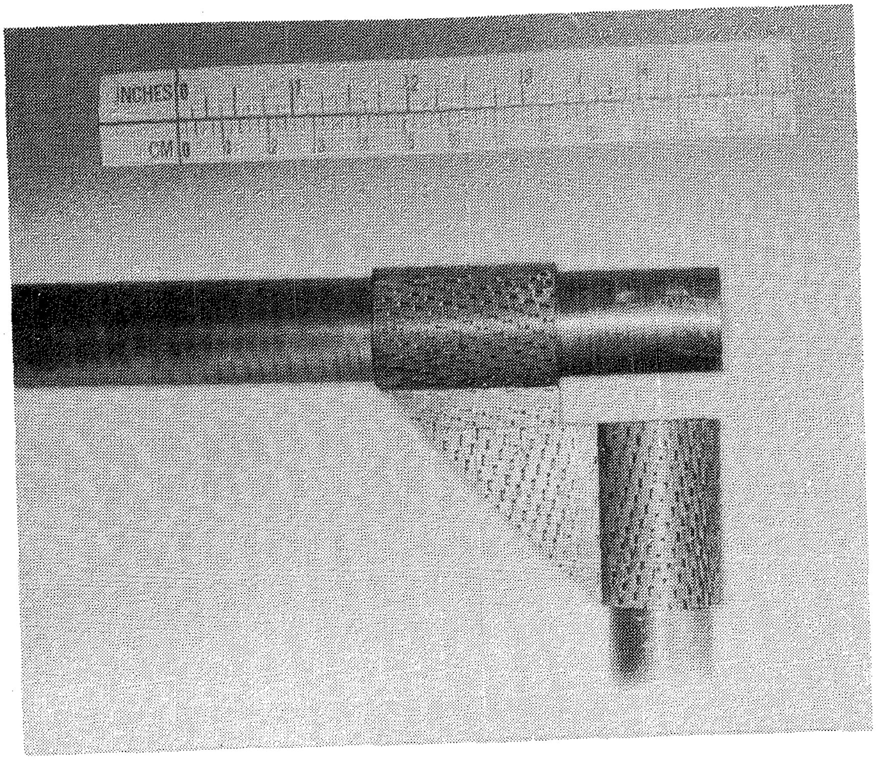


Figure 13 - Connector and Tubes Ready for Assembly

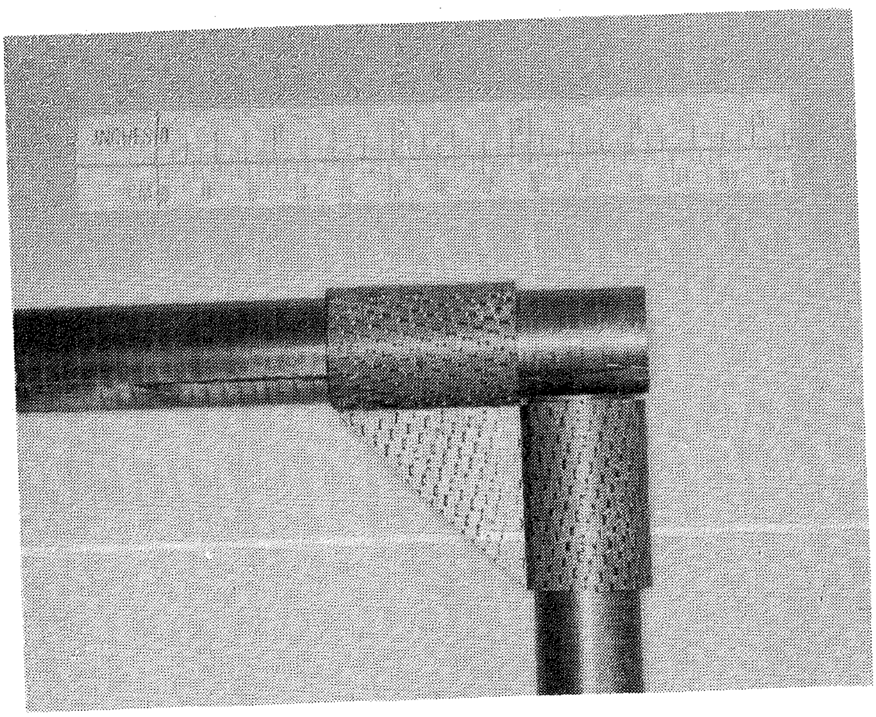


Figure 14 - Finished Right-Angle Connection

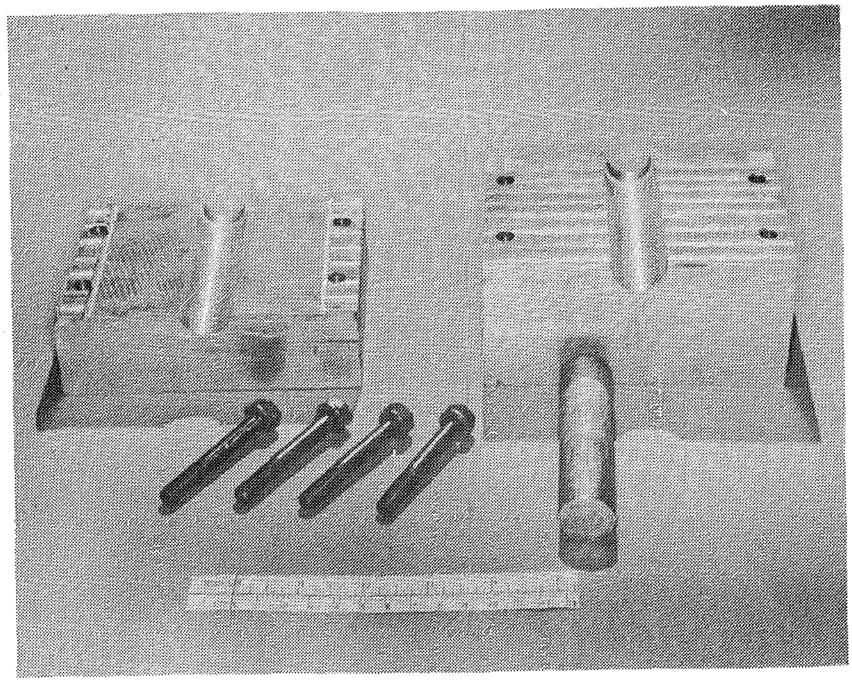


Figure 15 - "Tee" Connector Web Mold

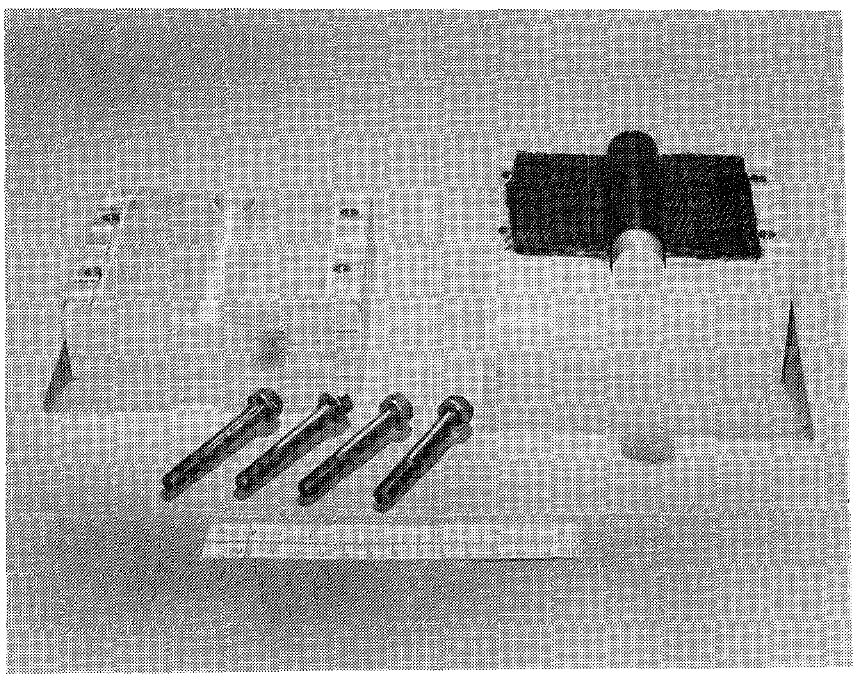


Figure 16 - "Tee" Connector Web Blank Prior to Removal from Mold

connector. Figure 16 shows the mold as it has been disassembled following cure of the graphite components in the oven. The top is taken off of the mold revealing the graphite in place on the bottom half of the mold with the tubing mandrel still in place. Figure 17 shows the two pieces removed from the mold. It should be noted that these two pieces are not exactly identical in that they are slightly offset with respect to the center line of the tube axis. Figure 18 shows the webs after they are cut to size with a tungsten carbide bandsaw. The graphite epoxy layup for each of the two components is as follows: 1 layer fabric, followed by 2 layers of unidirectional tape with alternating right-angle fiber directions, followed by 1 layer fabric. Figure 19 shows two right-angle connectors in place on the upper tube. The two additional components of the "tee" connector are around the lower tube and interleaved with the tabs of the right-angle connector components. The interleaving of the tabs is shown in the photograph. Figure 20 shows the final cuts to be made by the bandsaw to complete the physical configuration of the "tee" connector. Figure 21 shows the two "tee" connector components that fit into the right-angle connectors as they are used in their final form. Figure 22 is an end view of the "tee" connector joint with all components assembled, but before insertion of the tube to be joined to form the "tee". A completely assembled walker side frame is shown in Figure 23.

In order to complete the walker, it is necessary to provide some means of attaching the two side frames together in a stable and strong

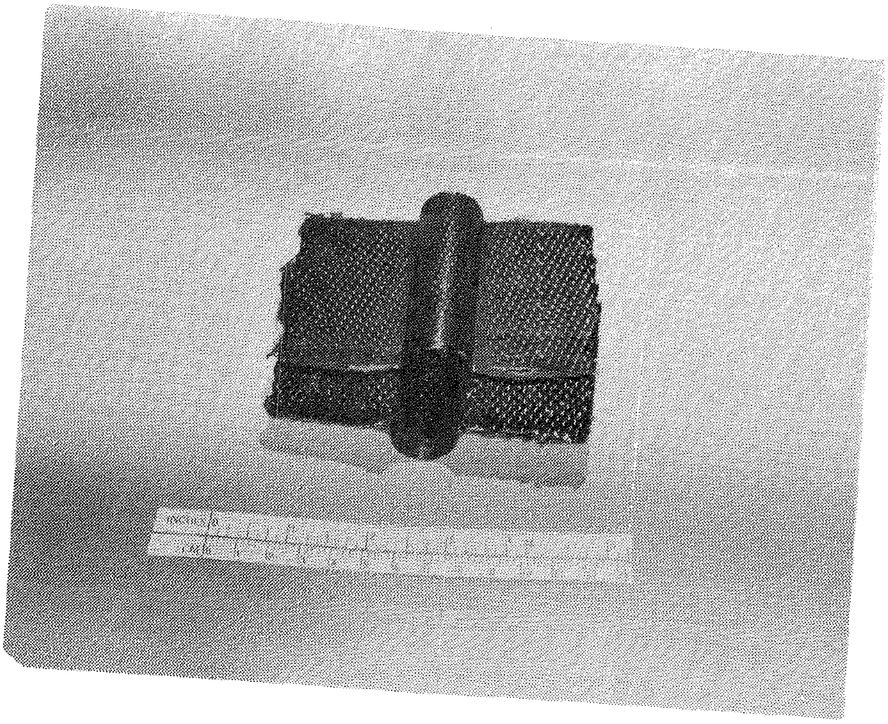


Figure 17 - Two "Tee" Connector Web Blanks As Removed From Mold

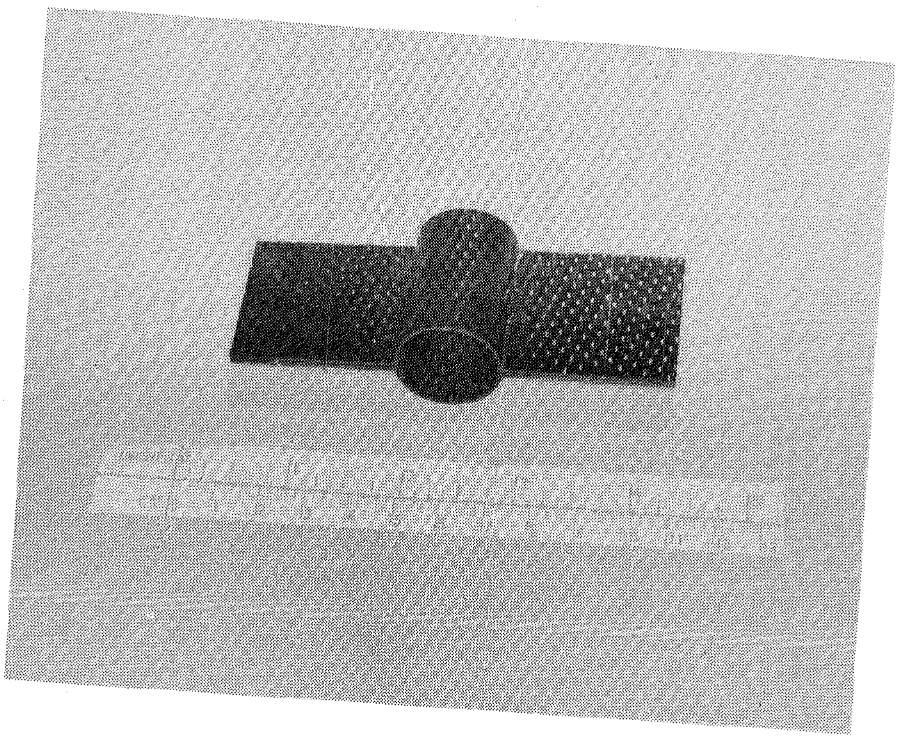


Figure 18 - Two "Tee" Connector Web Blanks After First Cuts

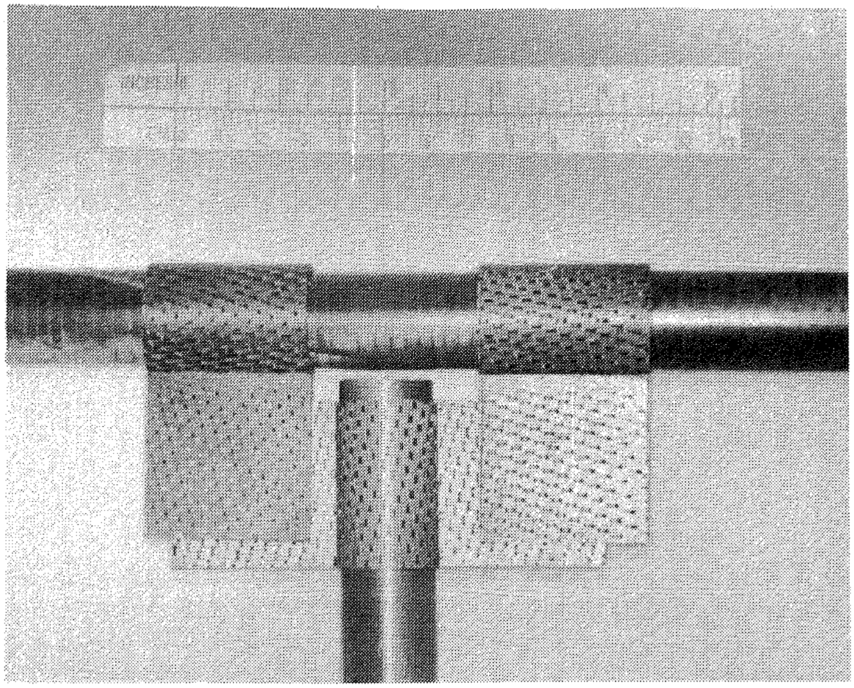


Figure 19 - Method of Assembly of Complete "Tee" Connector for Assembly of Two Tubes

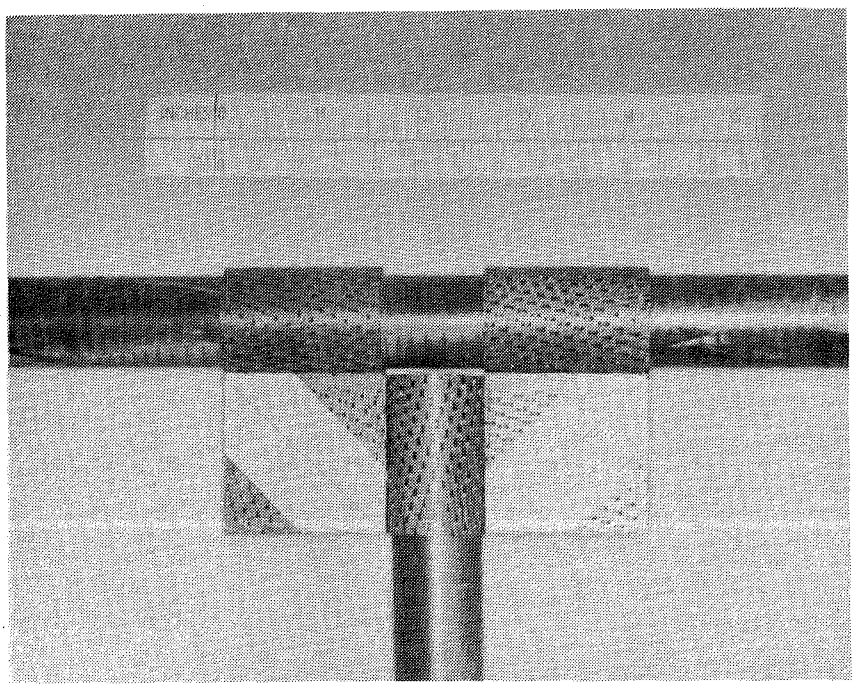


Figure 20 - Final Cuts Required on "Tee" Connector

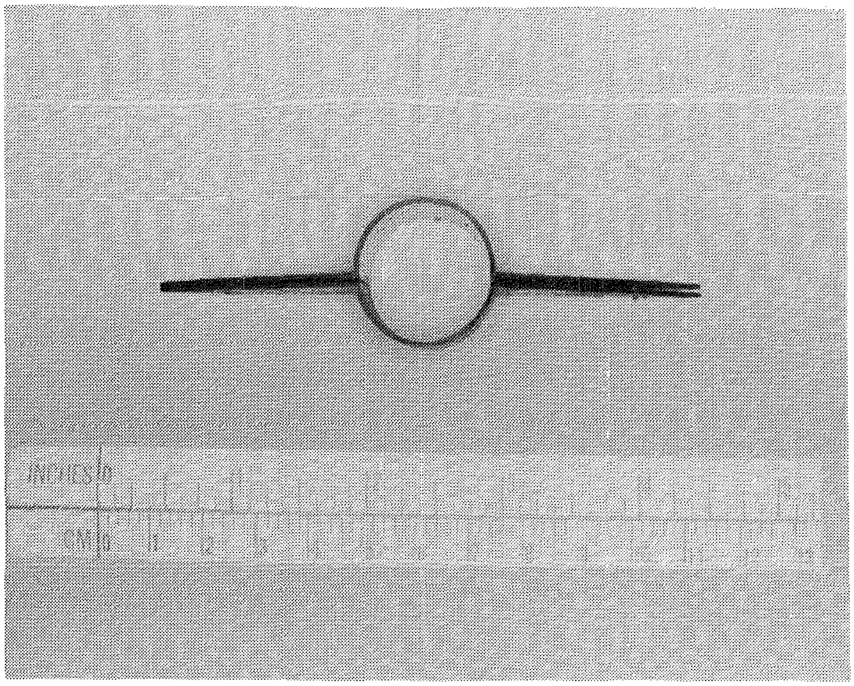


Figure 21 - Finished "Tee" Connector Web Pieces

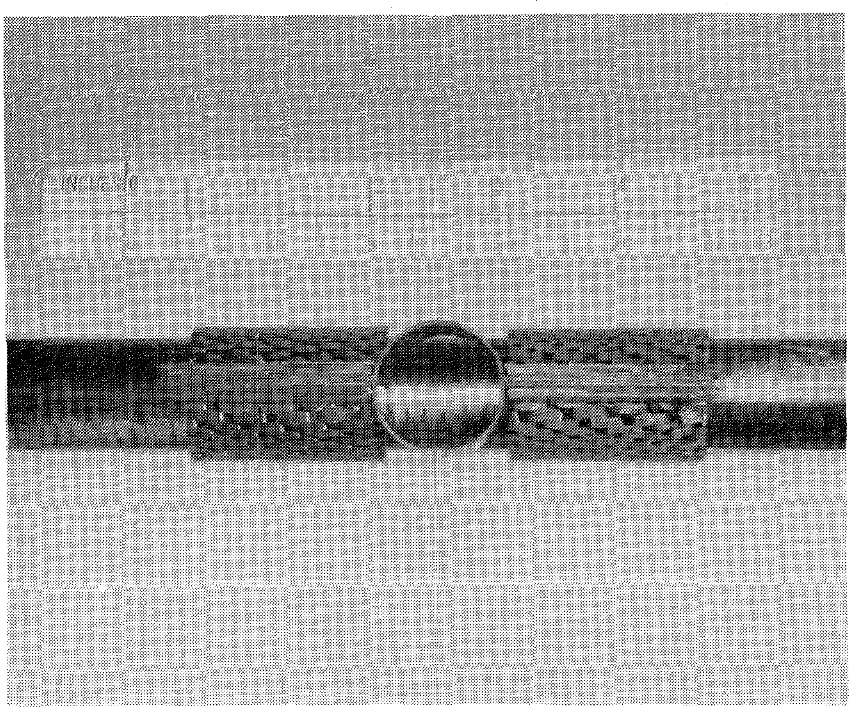


Figure 22 - End View of Complete "Tee" Connector
Prior to Insertion of Final Tube

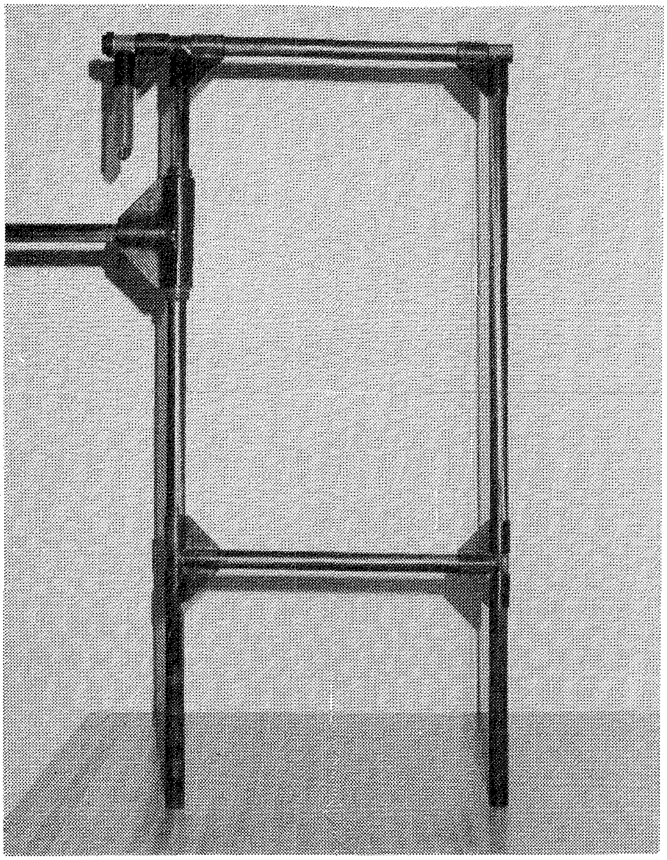


Figure 23 - Walker Side Frame

fashion, while at the same time permitting the walker to be folded for storage in automobiles. Two horizontal tubes (of the same type as used in the side frames) are used to provide the structural connection between the two walker side frames. Both horizontal tubes are on the front of the walker. The top tube actually consists of two separate short pieces. Each piece of tube is connected to a side frame along the top by means of a right-angle connector. In this case, however, the right-angle connector is only bonded to the two tube pieces between the two side frames. The portion of the right-angle connector around the top horizontal bar of each side frame is not adhesively bonded so as to permit pivoting of that joint. A thin heat-shrink teflon tubing is placed between the connector and the tube to provide a bearing surface. A third tube segment, whose inside diameter is slightly larger than the outside diameter of the two top horizontal bar pieces, is used to entrap the two ends of the top horizontal bar, providing structural rigidity for the frame.

The lower horizontal bar is constructed in a slightly different configuration. Both of these joints can be seen in Figure 24 which shows an overall view of the walker in its deployed configuration. The bottom horizontal bar, connected between the two side frames, uses a larger right-angle joint than in the side frames because the strength requirements are greater in this area. This horizontal bar connector consists of three pieces: two halves which mate together entrapping the vertical bar of the side frame and the horizontal bar plus a third component that is configured to the external cylindrical

Figure 24 - Assembled Graphite Walker

shape of the clam shell joint over the vertical bar. The horizontal bar connector holds the cross bar to the two side frames while permitting the side frames to pivot. It is constructed basically as a clam shell with the two halves fitting together. The two pieces are assembled by adhesive bonding of the two stiffening tabs and the third cylindrical segment which overlaps the join line where the two halves meet. Again, heat-shrink teflon is placed over the vertical tube underneath the horizontal bar connector as a bearing material.

The two halves of the horizontal bar connector are fabricated from graphite epoxy composite using the following layup: 1 layer of fabric followed by 20 layers of unidirectional tape with alternating 90-degree fiber directions, followed by 1 layer of fabric. The third element of the horizontal bar connector is laid up using the following sequence: 1 layer of fabric, 8 layers of unidirectional tape, and 1 layer of fabric.

Locking rings are required to hold the lower horizontal bar at the proper height. These locking rings are attached to the vertical bar of the side frames at the top and bottom of the horizontal bar connector. These are merely graphite epoxy tubes fabricated with an inside diameter equal to the outside diameter of the graphite tubing of the vertical component of the side frame structure. The locking rings are sliced off from the cylinder using a bandsaw and are adhesively bonded in place. Two other locking rings are required. One each is required on the top horizontal tube of the side frame to prevent the top horizontal bar from sliding off. These are of the same size and construction and are attached in the same manner.

2.2.4 Walker Configuration

Using the components discussed in the preceding paragraphs, the graphite epoxy walker was fabricated and delivered to NASA Langley Research Center,Technology Utilization Office. A paper was presented at the International Conference on Rehabilitation Engineering, June 16-20, 1980, in Toronto, Ontario, Canada. This paper is included in Appendix B of this report. For additional description of the walker, the reader is referred to Appendix B.

2.3 Eastern Virginia Medical School Tasks

In May of 1979, the Technology Utilization Office at NASA Langley Research Center received inquiries from Dr. Joseph T. McFadden, Professor and Chairman of the Department of Neurosurgery of Eastern Virginia Medical School, about the possibility of using materials developed in the NASA Space Program in several medical applications. This inquiry was referred to the Mississippi Methodist Rehabilitation Center and a conference was arranged. In June, 1979, Ernest Harrison, Jr., Director of Biomedical Engineering at the Mississippi Methodist Rehabilitation Center, and Richard Scearce, Ph.D., of the Research Triangle Institute met with Dr. McFadden at the Eastern Virginia Medical School, Norfolk, Virginia. In these discussions, Dr. McFadden outlined three problem areas in which he felt that NASA might be able to provide assistance: (1) Radiolucent aneurysm clips to replace those of his design made from stainless steel. He felt that composite materials might be a good candidate for this problem. (2) A composite that can be used to replace missing portions of the human skull. (3) A controlled, iso-pressure method of retracting portions of the human brain to reduce trauma to the brain during those procedures in which the brain must be displaced to gain access to a particular area.

After discussion of these problems with Technology Utilization personnel at NASA Langley Research Center and Dr. Scearce of the RTI Biomedical Application Team, it was agreed that problems 1 and 2 were worthy of additional investigation under this contract. Specifically, it was agreed that MMRC would investigate the possibility of fabricating an aneurysm clip from a graphite epoxy composite based on Dr. McFadden's design and, if feasible, to fabricate three clips. With respect to problem 2, it was agreed that MMRC would investigate various composite fabric-resin systems to determine if a molding technique simple and easy enough to use in the operating room can be devised. Both of these problems were recognized to be very difficult: problem 1 because of the small size of the device and the peculiar set of installation constraints, and problem 2 because of the necessity to fabricate the required shape in the operating room using medical personnel while at the same time conforming to the operating room environment.

It was agreed that bio-compatibility of the composites would not be considered as a part of this project. Any devices developed under this contract would be for experimental purposes only, and any bio-compatibility testing required would be obtained from other sources. With respect to problem 1, a number of preliminary paper designs were devised. When subject to critical analysis, each had serious difficulties which mitigated against success in the proposed application for the aneurysm clips. Discussions were held with the technical representative and with Mr. Bob Baucom of the Materials Division, NASA Langley Research Center concerning the difficulty of fabrication of these designs. It was agreed that we were stretching the limits of the material in attempting to use graphite in this particular application. However, it was also agreed that one more final attempt should be made to devise the successful clip.

One of the problems associated with fabricating a suitable aneurysm clip is the fact that the currently available prepregged plies of graphite are quite thick. These unidirectional fibers yield a cured per-ply thickness of approximately 0.0177cm (0.007 inch). Because of the sharp bends required in the aneurysm clip, this thickness of material rendered fabrication virtually impossible. It. was thought that reduced ply thickness might alleviate this problem.

There are three factors involved in successful fabrication of an aneurysm clip if one omits the problems of bio-compatibility. These factors are:

1. Design must incorporate a jaw structure (which actually is the part in contact with the aneurysm, i.e., the clip part).
2. A means of loading the jaws so as to force them together must be provided.
3. A suitable structure for transmitting the loading force to the jaws and for achieving and maintaining the jaws in proper alignment to each other must be provided.

The jaw structure, as currently employed in the stainless steel aneurysm clips, is entirely adequate and can be easily replicated using pre-pregged unidirectional graphite fibers and/or graphite epoxy fabric. This particular factor is not an unsurmountable problem with respect to replication in composite materials.

The structure for transmitting force to the jaws and achieving and maintaining jaw alignment is almost entirely dependent on the means of loading the jaws. It will be easy or difficult depending on the design selected to achieve factor 2. Factor 2, the means of loading the jaws, is perhaps the most difficult part of the problem with respect to implementation and fabrication. Most present aneurysm clips use a spring of stainless steel having a modified "V" configuration. This spring element is loaded by compression applied at the tips of the "V" and applied so as to move the tips toward each other. The compressed spring, when released, applies force so as to cause the jaws to close. With this configuration, the spring is essentially a ribbon of stainless steel, and the structure transmitting the load to the jaws, as well as the jaws themselves, are merely extensions of the stainless steel spring material configured so as to achieve the desired results.

Because the width of the spring element is much greater than its thickness, the force required to compress the spring a unit distance is significantly less than the force required to offset the jaws the same unit distance. The current stainless steel aneurysm clips receive, as their final assembly, a manipulation of the jaws in an offset direction so as to clear each other as they are crossed and the spring element compressed. Given the significant anisotrophy of the unidirectional graphite fibers and the added anisotrophy of the geometric form of the leaf spring, the offset necessary to clear the jaws to permit crossing of the jaws (and the consequent loading of the spring) is difficult if not impossible to achieve without failure of the spring when using stiff brittle materials such as graphite epoxy. It was therefore decided to look at a design based on fabrication of two separate jaws having a flexible structure to transmit the loading force to the jaws. The jaws would be separately assembled to the flexible structure.

It was thought that the preload on the aneurysm clip jaws could be obtained by placing a piece of elastomer within the spring elements so that compression of the spring also compresses the elastomer. A clip was designed and fabricated using this principle. Two problems were encountered. First, the flexible material used to connect the two jaw support structures failed to maintain alignment of the jaws. Second, the range of compressibility of the elastomer was insufficient to provide, simultaneously, an effective force preload of the jaws and adequate jaw opening distance. These compound problems rendered the clip unusable. Several other variations of the spring element of the aneurysm clip were considered and mockups constructed. However, none were felt promising enough to pursue.

A new design of the aneurysm clip was proposed, and design of the mold was begun. Basically, this clip design involved the use of separately fabricated jaws with a spring element in the form of a "W". With this design, the spring element could be compressed during the time that the jaws were bonded to the spring element so that pre-loading could be achieved. This has been the most significant problem in development of an aneurysm clip, and the proposed design appeared to offer the most promise.

Molds for the jaws were made, along with molds for the spring elements. Figure 25 is a photograph of one of the spring elements as it is removed from the mold. This is before any trimming has taken place. Figure 26 is a photograph of two of the jaws of the aneurysm clips as they come from the mold, again before any trim. Figure 27 is a photograph of one of the completed aneurysm clips.

The graphite epoxy aneurysm clips were delivered to the Technical Representative of the Contracting Officer, May 28, 1981. The aneurysm clips were designed to demonstrate the extent to which graphite epoxy materials can be configured and fabricated to emulate the physical characteristics of stainless steel clips while providing the desired reduction in radiopacity.

Problem 2, involving the replacement of missing portions of the skull with a composite material, was investigated and several candidate materials were discussed with the problem originator. None of the materials were found to have appropriate characteristics as defined by the problem originator, and the problem was considered to not be feasible at the present time.

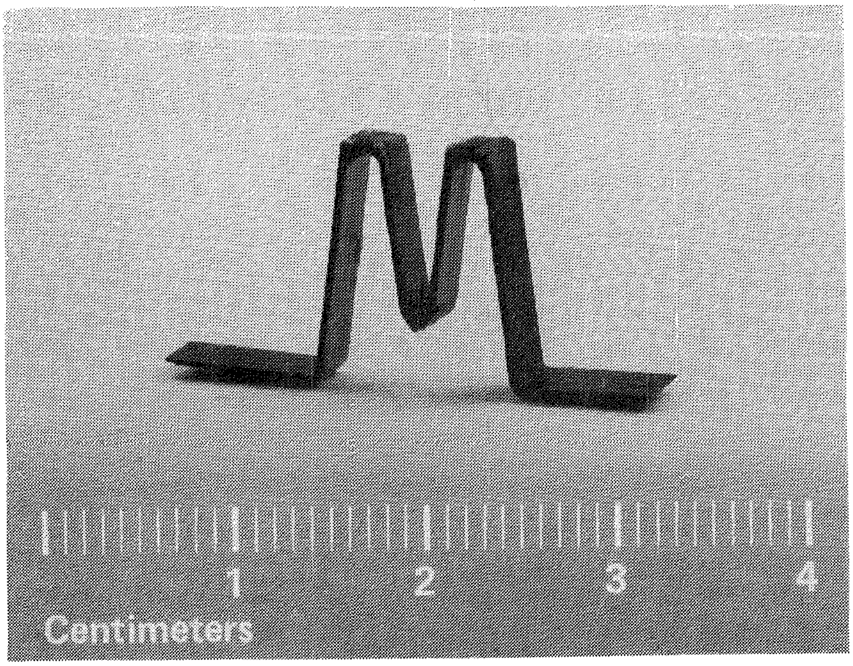


Figure 25 - Aneurysm Clip, Spring Element

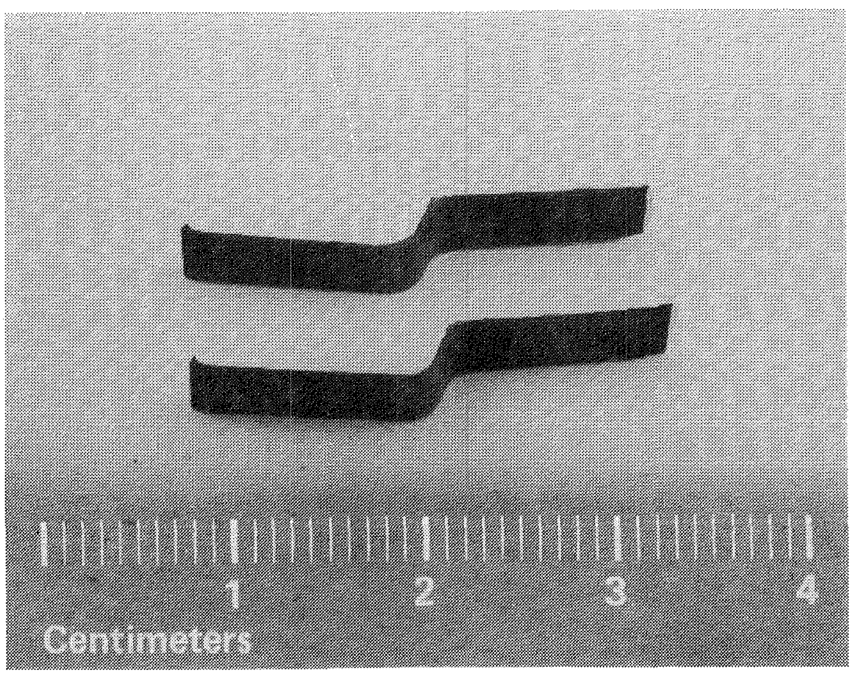


Figure 26 - Aneurysm Clip, Jaw Elements

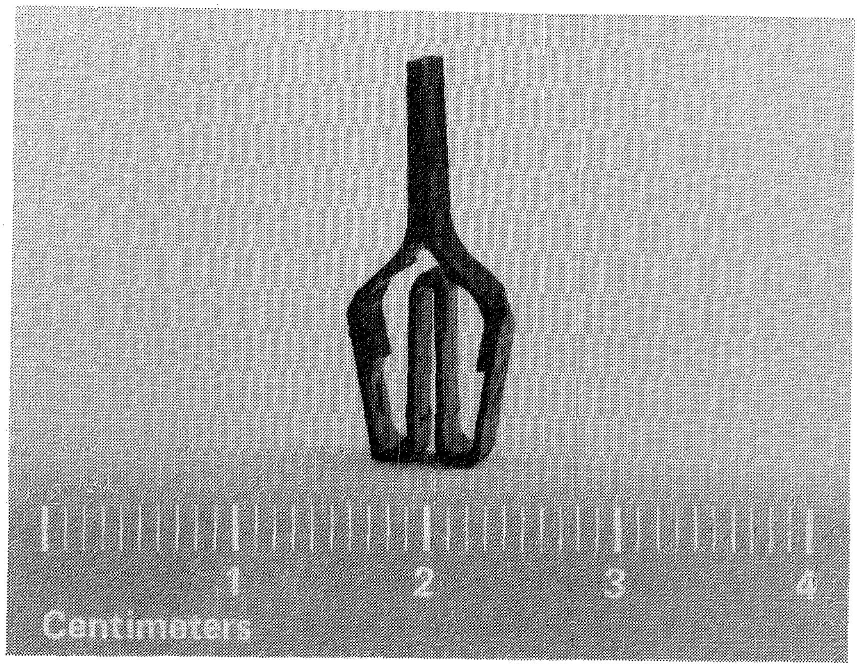


Figure 27 - Completed Aneurysm Clip

2.4 Composite Wheelchair

The construction of a wheelchair using lightweight, high strength composite materials was an addendum to the contract. Wheelchair configurations were studied, and analysis was made of the weight of the various components of a currently existing popular wheelchair. Preliminary ideas were discussed with respect to using a tubular structure much as is presently used in conventional wheelchairs. However, consideration of the wheelchair problem led to the conclusion that replication of existing wheelchair designs using composite materials might not be the wisest approach. The existing designs are based on a tubular frame and the best existing designs are very functional. However, since the use of new materials affords the opportunity for totally new structural arrangements, it was felt that novel structural approaches to wheelchair design should be considered. Indeed, they should be given high priority since significant progress is more likely to result from a fresh approach to the problem which may be possible through the use of new materials. A number of potential overall approaches were considered, most involving some sort of molded structure deriving part of its strength from curvature induced for strengthening purposes. Graphite, Kevlar, and fiberglass were all considered as candidate fabrics for the material of fabrication.

Sandwich construction, which employs a lightweight structural core that is faced with high-strength fabrics or fibers in an appropriate resin binder, was considered a very good candidate for use in the wheelchair project. In addition to the use of structural foam, aluminum honeycomb structures are widely used in this type of sandwich construction.

It was felt after weighing the advantages and disadvantages that sandwich construction techniques offer the greatest promise for construction of a composite wheelchair. It was therefore decided to base initial considerations on the composite sandwich structure method of fabrication. In order to reduce the time of fabrication and the cost of prototype fabrication, it was proposed to construct some individual wheelchair components using aluminum honeycomb and fiberglass. The use of fiberglass greatly simplifies fabrication, so that full scale prototype components can be made rather quickly for analysis and study. The results from the fiberglass components can be easily scaled for graphite or Kevlar construction, if additional weight reduction and strength are required.

The first item selected for fabrication was the wheelchair seat. The seat in a conventional wheelchair is made of canvas and vinyl and is already light in weight. In fact, first impressions were that no weight reduction was possible in the seat design. The seat is easily made - not requiring complex molds - so it is a logical first choice component. In addition, if a significant weight reduction could be demonstrated in this already light component, it would provide great encouragement for the other components.

The first seat was fabricated using 12.7mm (0.5 inch) thick, 9.5mm (0.375 inch) cell diameter aluminum honeycomb. The honeycomb was clad on all sides with two layers of fiberglass impregnated with polyster resin. The resulting seat was tested to 227 kilograms (500 lbs.) loading on a 323 cm^2 (50 $inch^2$) foot without failure. The seat weighed 627 grams (1.37 lbs.). The corresponding heavy duty canvas/vinyl seat used in wheelchairs at MMRC weighed 1.14 kilograms (2.5 lbs.). A net weight saving of 45% was achieved.

A lighter weight aluminum honeycomb material was obtained from the Hexell Corporation, and an additional wheelchair seat was fabricated. The seat was fabricated using Hexcel ACG 3/8-.003 hexagonal honeycomb and commercial fiberglass with polyester resin. The honeycomb was cut to dimensions of 40.6cm x 40.6cm x 1.3cm (16 inches x 16 inches x 0.5 inches). It was then cleaned and clad with two plies of fiberglass impregnated with polyester resin. The two plies (top and bottom) were allowed to cure. The seat was then trimmed on a bandsaw, and an edge fiberglass tape with 2.5cm (1 inch) overlap top and bottom was applied.

Following fabrication, the seat was weighed and tested for strength. The fiberglass honeycomb seat weighed 620 grams (1 lb. 6 oz.). The fiberglass honeycomb seat was tested for weight bearing capacity in the following manner. It was supported on its two sides by wooden timbers, 3.8cm (1.5 inches) wide. A 323cm^2 (50 $inch^2$) plywood foot was used to load the seat in its center. A load of 272 kilograms (600 lbs.) was sustained without failure. These tests verified that weight reduction could be achieved using these techniques.

With this encouragement, it was felt appropriate to evaluate the available structural foam materials that might be used in fabrication of the composite wheelchair. The structural foam offers two advantages over aluminum honeycomb. First, the structural foam is significantly lighter in weight. Second, some of the foams available can be contoured while in sheet form to reasonably complex contours merely by heating. This is an advantage not found with the aluminum honeycomb except for very expensive types of honeycomb. Consequently, it was decided to purchase structural foam core materials for evaluation.

After discussion with personnel in the Materials Division and the Technology Utilization Office at NASA Langley Research Center, it was concluded that a testing program should be undertaken to evaluate the mechanical properties of the structural foam core materials with various types of cladding including Kevlar, graphite and fiberglass, using both fabrics and unidirectional fibers. As a result of these discussions, it was agreed that MMRC would fabricate test blanks of the abovementioned materials and that NASA Langley Research Center would provide mechanical and physical tests to permit MMRC to calculate mechanical and physical characteristics of the composite sandwich structures.

The test blanks for this program were made using conventional vacuum bagging techniques. Additional study showed that end-grain cut balsa, which is used extensively in the boating industry and corrosive liquid tank industry, has significantly higher core shear strength than the structural foams currently available. It was felt useful to include a testing program on the sandwich construction using end-grain balsa as the core material as well, in order to compare the relative strengths and weights of these two different core materials. A small test run of balsa core samples was made. In this run, only fiberglass was used, since it was anticipated that results could be easily extrapolated to the other materials based upon the test data of the structural foam cores.

At this particular time, the Technology Utilization Division, which had been pursuing a project with the University of Virginia, decided to change its program emphasis with respect to construction of a composite wheelchair. A "total wheelchair" project using composite materials for construction was initiated involving the University of Virginia and NASA Langley Research Center. In order to avoid duplication of effort, the decision was made to modify the direction of this contract. In a conference at the NASA Langley Research Center in February, 1982, with the Technical Representative of the Contract Officer and Technology Utilization Office personnel, it was agreed that MMRC should participate in the NASA-UVA "total wheelchair"project as fulfillment of the remaining MMRC obligations under Contract NAS1-15477. It was specifically agreed that MMRC would fabricate the seat of the "total wheelchair" using sandwich construction techniques. The design of the seat would be furnished by NASA. It was also agreed that calculations on the sample test blanks would be completed. As a result of this action, this part of the task was then concluded, and efforts were re-directed toward the sandwich construction testing program and the "total wheelchair" project.

2.5 Sandwich Construction Testing Program

Sandwich construction was seriously considered as the probable material of choice for construction of the composite wheelchair. Because of the fact that there is a paucity of data regarding the physical characteristics of sandwich construction using Kelvar and/or graphite facings on structural foam, a decision was made to embark on a testing program for guidance on this project. To this end, discussions were held with the Technical Representative of the Contract Officer at NASA Langley Research Center regarding the possibility of instituting such a program.

It was proposed that MMRC prepare a number of samples for testing and that the testing facilities available at NASA Langley Research Center be employed to obtain the physical testing data. This proposal was accepted,and arrangements were made to have the physical testing performed in the Materials Division of the NASA Langley Research Center. A variety of samples were prepared for testing including the following facing materials: fiberglass fabric, unidirectional fiberglass, unidirectional graphite, and Kevlar fabric. These facing materials were applied to two different types of structural foam. One was a 72 g/m^3 (4.5 lb/ft^3) density structural foam manufactured by the American Klegecell Corporation. The second foam was a General Plastics Manufacturing Company foam known as Last-a-Foam. It was available in three densities of 128, 161, and 241 g/m^3 (8, 10, and

15 lb/ft^3). The resins used were of three types. Some of the graphite and Kevlar fabrics were purchased with epoxy pre-preg. The remainder of the fabrics were bonded using either commercial Shell Epon room temperature curing epoxy resin #8132 or commercial grade polyester resin.

Samples were fabricated using foam thicknesses of approximately 6.35mm (0.25 inch). The length of all samples was approximately 35.6cm (14 inch), and the width of all samples was approximately 63.5cm (2.5 inch), except for those samples employing unidirectional fiberglass. The samples using unidirectional fiberglass were cut to a nominal width of 4.4cm (1.75 inch) because of the unavailability of unidirectional fiberglass materials in wider widths.

The samples were each prepared according to the recommended cure cycle for the resin used. In all cases the samples were vacuum bagged on aluminum platens with aluminum caul plates on top of the samples. Sample uniformity achieved with this technique was excellent. Following fabrication, the samples were shipped to NASA Langley Research Center for testing. Testing was requested in accordance with the American Society for Testing and Materials Specification C-393-62. "Standard Method of Flexure Tests of Flat Sandwich Constructions." The tests were performed at the NASA Langley Research Center, and the raw data were returned to MMRC where the calculations were performed. The tests methods and the equations used are those outlined in ASTM C-393-62. The reader is referred to this standard publication for details of the test method and the calculations involved. The results from this testing program are given in Table 1 below.

In industrial applications where large fiberglass tanks and other such structures have been required, sandwich construction has been employed extensively. One of the primary core materials used in this type of sandwich construction has been end-grain cut balsa. This material is widely used in large structures as well as in the boating industry. The primary feature that renders it so useful is its high core shear modulus. The core shear modulus for end-grain balsa is significantly greater than that of most all commercially available structural foams. In order to compare performance of the structural foams with this industry-standard material, it was felt that a series of tests should be run using end-grain balsa as the core material. To this end, the Technical Representative of the Contracting Officer was contacted and the matter discussed. It was concluded that a small series of tests using fiberglass as the facing material was warranted.

End-grain balsa was obtained from a commerical supplier in the minimum thickness of commercial grade. This was 0.953cm (0.375 inch) thick. A series of samples were made using polyester resin and fiberglass facing materials. For half of the samples, the facing material in contact with the balsa core was fiberglass mat. In the other six samples, the fiberglass material in contact with the balsa was fabric. Test blanks were fabricated using vacuum bag techniques in the same manner as the previous test samples. Test specimens were

Table 1: Foam Core Sandwich Construction - Physical Test Results

Facing	Resin	Foam	Flexural Stiffness kg m^2	lb in^2
1 FF	Epon	K-75	.3183	1088
3 FF	Epon	K-75	.6560	2242
4 FF	Epon	K-75	.4638	5003
5 FF	Epon	K-75	.6610	5677
1 FF	Polyester	K-75	.3649	1247
2 FF	Polyester	K-75	.7713	2636
1 FF	Epon	FR-8	.2259	772
2 FF	Epon	FR-10	.6978	2385
1 FU	Epon	K-75	.8432	2882
2 FU	Epon	K-75	.1885	4062
1 FU	Polyester	K-75	.7666	2620
2 FU	Polyester	K-75	.1531	3941
3 FU	Polyester	K-75	.4419	4928
1 KF	Epon	K-75	.2025	692
2 KF	Epon	K-75	.3485	1191
3 KF	Epon	K-75	.5074	1734
1 KF	Epoxy Prepreg	K-75	.2730	933
2 KF	Epoxy Prepreg	K-75	.7765	2654
1 KF	Epoxy Prepreg	FR-15	.5074	1734
2 KF	Epoxy Prepreg	FR-15	.9910	3387
1 GU	Epon	K-75	.9541	3261
2 GU	Epon	K-75	.3526	4623
1 GU	Polyester	K-75	.1039	3773
2 GU	Polyester	K-75	.9677	6725
1 GU	Epoxy Prepreg	K-75	.7660	2618
1 GU	Epoxy Prepreg	FR-8	.9562	3268
1 GU	Epoxy Prepreg	FR-10	.8748	2990
1 GU	Epoxy Prepreg	FR-15	.1431	3907
1 KF/1 GU	Epon	K-75	.2274	4195
1 KF/1 GU	Polyester	K-75	.2853	4393
2 KF/1 GU	Polyester	K-75	.3146	4493
1 KF/1 GU	Epoxy Prepreg	K-75	.0516	3594
1 FU/1 KF	Epon	K-75	.9471	3237
1 FU/2 KF	Epon	K-75	.8520	2912

FF - Fiberglass Fabric

FU - Fiberglass Unidirectional

KF - Kevlar Fabric

GU - Graphite Unidirectional

cut to approximately 38.1cm (15 inch) in length and 7.62cm (3 inch) in width. The finished samples were then delivered to the Materials Division, NASA Langley Research Center, for physical testing. The raw data was returned to MMRC and calculations were made. The test methods and the equations used for calculations are those outlined in ASTM C-393-62. The results of this testing program are given in Table 2 below.

2.6"Total Wheelchair"Project - Seat Assembly

In March, 1982, in a conference at NASA Langley Research Center with the Technical Advisor and NASA TUD personnel, the direction of this contract was modified. At that time, the work toward a composite wheelchair under this contract was cancelled, and a new approach was taken to the overall problem of fabrication of a lightweight composite wheelchair. NASA Langley Research Center had begun a project to design a "total wheelchair" using lightweight materials with the University of Virginia. In order to avoid duplication between these two projects, it was decided at this meeting that it would be inappropriate to pursue the current direction under this contract. As a result, the goals and tasks of this project were redefined. At this point, it was agreed that the remainder of this contract would be devoted to support of the NASA Langley Research Center-University of Virginia "total wheelchair" project. That support, specifically, was the fabrication of the seat of the "total wheelchair" using sandwich construction techniques.

Table 2: End-grain Balsa Core Sandwich Construction - Physical Test Results

Fiberglass Facing		Flexural Stiffness	
Mat	Fabric	kg m^2	lb. in^2
1		0.8073	2,759
1		0.7982	2,728
1	1	1.3108	4,480
1	1	1.5162	5,182
1	2	3.6957	12,631
1	2	2.5528	8,725
	1	0.0591	202
	1	0.0679	232
	2	1.4998	5,126
	2	1.2894	4,407
	3	2.5262	8,634
	3	2.5125	8,587

A core material (Rohacell foam) was selected at NASA Langley Research Center Materials Division for use in fabrication of the "total wheelchair" seat. The facings for the "total wheelchair" seat chosen by the Technical Representative were graphite fabric and Kevlar fabric. Drawings of the component parts of the wheelchair were obtained from the Technical Representative, and an analysis of the seat design was undertaken at MMRC. All questions concerning the construction and fabrication of the seat were resolved with the technical representative, and mold design and fabrication was begun.

The seat was produced in two steps. First, the side rails were separately fabricated using vacuum bagging techniques. The Rohacell structural foam was used as the core material. All dimensions were made according to specifications provided by NASA Langley Research Center. The Rohacell foam was milled in areas of stress concentration to remove sufficient foam to permit two layers of graphite to be inserted as reinforcing material. Two layers of graphite fabric were placed in each of the reinforcing areas. Next, two layers of graphite were placed on the top and bottom sides of the core. This was followed with a final layer of Kevlar fabric. Using Shell Epon resin, the layup was made employing vacuum bag techniques. Following vacuum bagging, the blank was cut to size with a bandsaw using a tungsten carbide blade.

The seat of the wheelchair was constructed using the same techniques. Core, resin, and facings were of the same materials. Flanges were molded in place on each end of the seat to permit attachment to the seat side rails. The seat was then vacuum bagged using a complex, seven-piece mold as shown in Figure 28. Figure 29 shows the seat blank as removed from the mold. The seat blank was then cut to size using a tungsten carbide bandsaw. The seat was bonded to the side rails using Shell Epon resin. Following completion of assembly, the entire seat assembly was sprayed with a urethane paint to reduce "dusting" from the cut edges of the foam core material. The finished seat assembly was then delivered to the Technical Representative at NASA Langley Research Center.

2.7 Simes Prosthesis Reinforcement

An ancillary task was also completed on this project. The Prosthetics/Orthotics Department at MMRC found it necessary to fabricate a Simes prosthesis (used when the front protion of the foot has been amputated). This prosthesis receives heavy weight bearing and shock loads. It is conventionally fabricated using multiple layers of fiberglass (8 to 14 plies) and is therefore quite heavy. The director of the Prosthetics/Orthotics Department requested that assistance be given to reduce the weight of the prosthesis using the lightweight, high strength techniques employed under this project.

Calculations were made, and a spine running from the sole of the prosthesis up the back of the calf using unidirectional graphite was recommended. Nylon stockinette (2 layers) was placed over the mold as a substrate, followed by a layer of fiberglass. Next, eight plies of 226 gram (8 ounce) unidirectional graphite, 5cm (2 inch) wide were laid in place as the structural spine for the prosthesis. This was

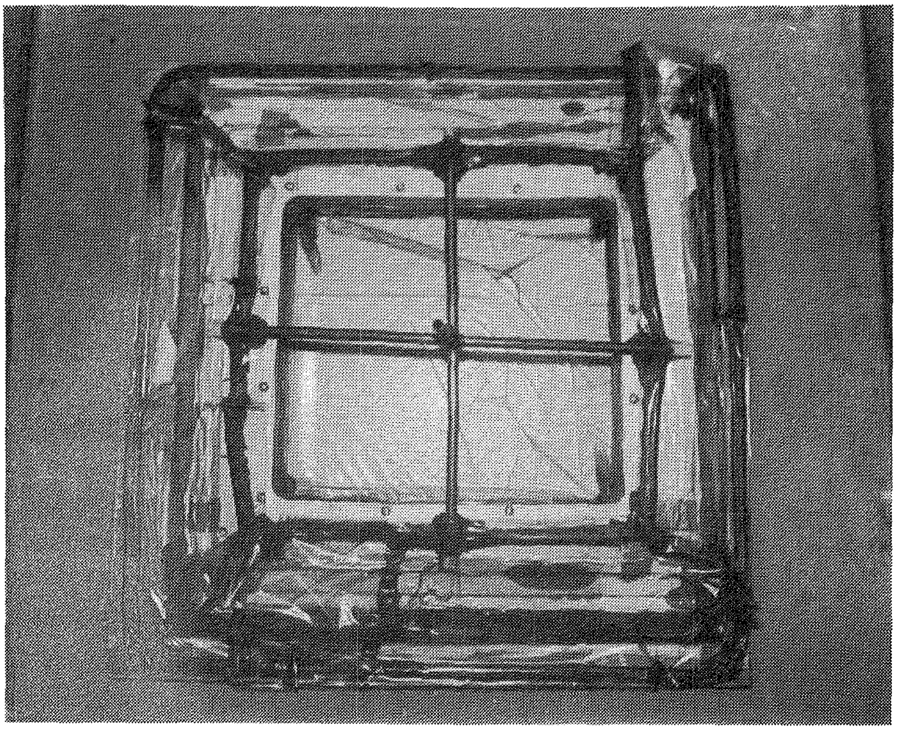


Figure 28 - "Total Wheelchair" Seat Mold and
Vacuum Bag Assembly

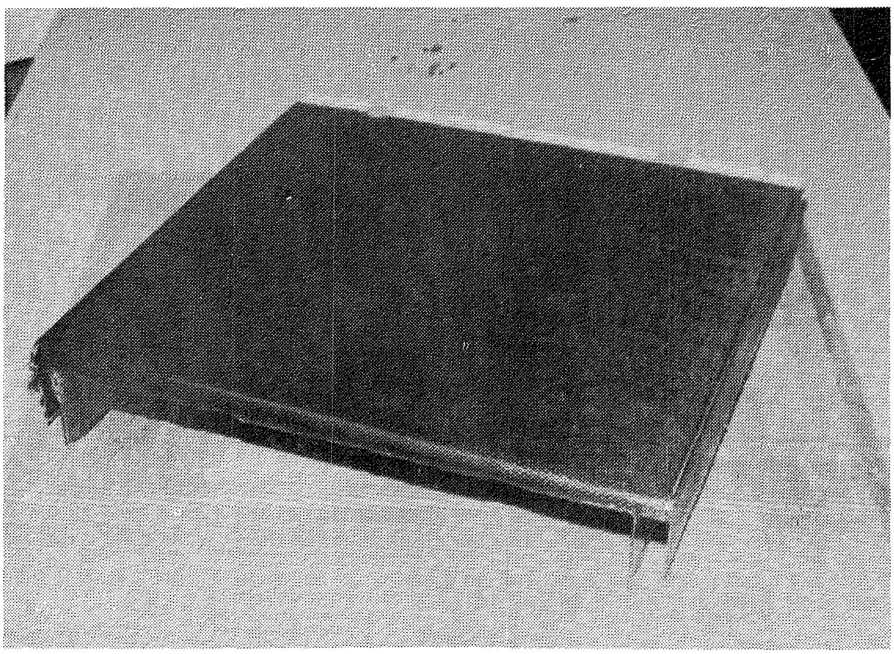


Figure 29 - "Total Wheelchair" Seat Blank

overlaid with two layers of fiberglass approximately 15.24cm (6.0 inches) wide to reduce localized stress concentrations. Two more layers of nylon stockinette were placed over the mold, and the entire unit was vacuum bagged. Epoxy resin was introduced, and the unit allowed to cure.

The net result was a graphite-reinforced prosthesis fabricated using essentially the same procedures as would have been used with an all fiberglass unit. This is probably the most important point with respect to transferability of graphite reinforcement technology to prosthetics/orthotics. It is not necessary to use unfamiliar techniques or fabrication methods that would require re-training of the prosthetist/orthotist. After making only one prosthesis, during which I provided encouragement and advice, the prosthetist/orthotist could fabricate others without supervision. The only additional information he would need is the amount of graphite required for the application. A series of "rule-of-thumb" calculations could easily be made to develop a table showing the amount of graphite needed to replace multiple fiberglass and nylon stockinette plies. This particular prosthesis has functioned without failure and was significantly lighter than a conventional unit.

APPENDIX A

Disclosure of Invention: "A Connector System for Joining Tubes, Pipes, Rods, and Other Regular Cross-Section Structural and Non-Structural Members"

A CONNECTOR SYSTEM FOR JOINING TUBES, PIPES, AND RODS AND OTHER REGULAR CROSS-SECTION STRUCTURAL AND NON-STRUCTURAL MEMBERS

The general purpose of this invention is the development of a means of constructing three-dimensional structural space frames. Particularly, when high strength, lightweight three-dimensional space frames are required, it is necessary to use advanced materials and fabrication methods such as composite technology. The problem of fabricating such space frames from composite materials is difficult because of the limited techniques of joining structural elements made from composites. Present joining techniques primarily employ machined metallic connector parts to which are bonded the composite structural components. Aluminum is frequently used. These connectors are expensive of fabrication, difficult to interface with composites because of their differing physical characteristics (primarily stiffness) and not as strong as required in many applications. Further, they frequently impose a weight penalty because the connector material has a lower strength-to-weight ratio than the composite structural elements being joined.

The invention is basically a connector design which permits the making of 90^{o} joints and "tee" connectors as well as obtuse and acute angles using composite materials. The 90^{o} joint uses two identical elements. The same two elements can be used for acute and obtuse angle joints. Large obtuse angles may require a flat plate stiffner as well. "Tee" joints are assembled using the same two identical elements as in the 90^{o} joint plus two special web components (also fabricated from composites) that structurally lock the base of the "tee" to the cross-piece.

The special feature that permits the basic connector component to be used for all the above-described joints is a special interleaving design providing great web strength and rigidity while at the same time having a large area bonding surface to the tubes being joined. Because the connector is fabricated from the same materials as the tubes being joined, a strong bond between the two is easily achieved without special surface preparation. Further, since both tube and connector are fabricated from the same materials, the problems associated with differing physical characteristics between the tube and connector are significantly reduced.

The cross-sectional configuration of the basic connector element is as shown in Figure 1. As can be seen, it is basically cylindrical with two tabs on either side of a longitudinal slit. The tab and wall thicknesses are exaggerated in the figure to demonstrate geometric features more effectively.

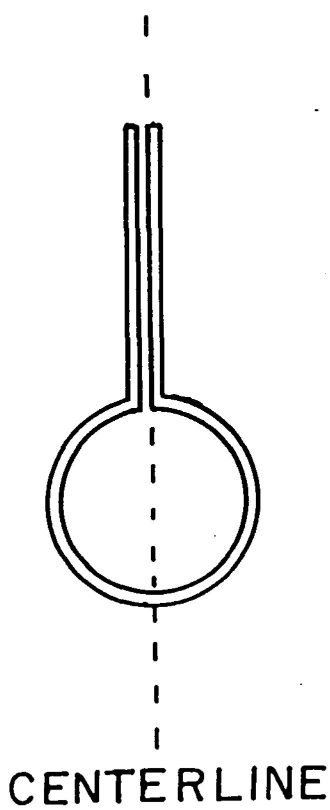


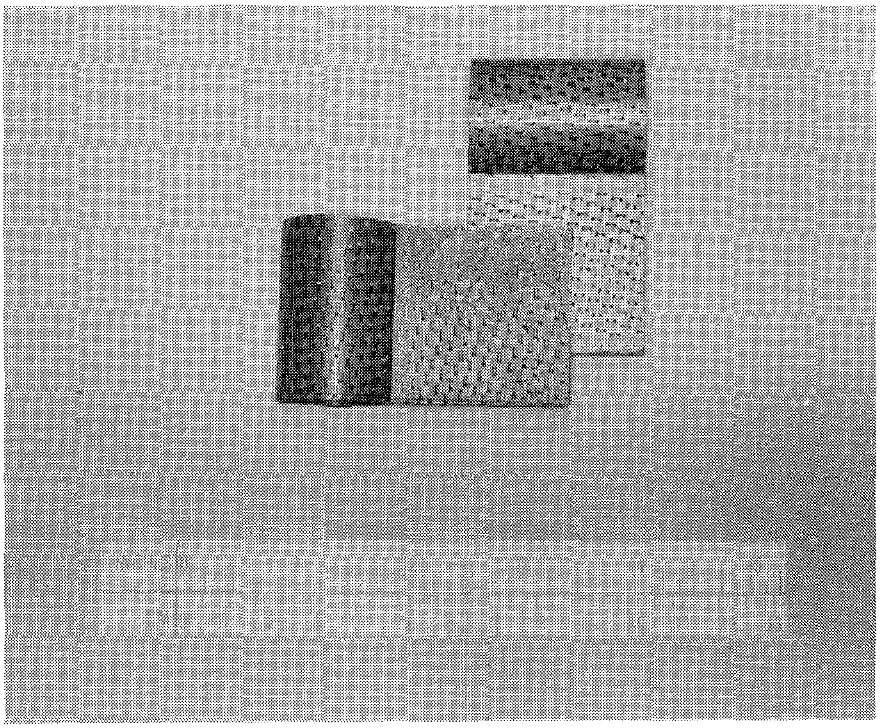
Figure 1.
Basic Connector Element - Cross Section

The inner surface of one tab lies on the center line of the cylindrical section. The inner surface of the other (offset) tab is parallel but displaced from the center by an amount equal to the tab thickness. The connector can be made in relatively long lengths so that multiple connector elements can be cut from a single length. The fabrication process involves layup of multiple plies of pre-pregged fibers and fabric. Magnitude and direction of the connector strength is determined by the number of plies of fiber and/or fabric and their orientation. The inner diameter of the cylindrical section is equal to the outer diameter of the tube, rod, or pipe to be joined plus 0.005" to 0.010" clearance as required for the adhesive to be used in joining. It should be noted that different diameter rods, tubes, pipes can be joined by using two connector elements with the appropriate inner diameters. For maximum uniformity, the tab thicknesses should be the same.

Using 12 inch tape or fabric, a single layup will yield 8 connector elements and, with a two mandrel mold, 16 connector elements can be made from one layup for joining rod, tubing, pipe having diameters in the range 0.75 inch to 1.25 inch. Following layup, the material is cured in an oven at the appropriate temperatures using vacuum bag molding or pressure molding as desired. The 12 inch long piece is then sliced in sections as desired. The tab is sliced so that the length of the tab protruding from the cylindrical section is equal to the width of element, i.e., the tab sides are all equal. The tabs are further trimmed depending on the type joint to be formed.

A right-angle connector is formed by taking two identical connector elements oriented in exactly the same fashion, then one of the elements is rotated 180^{0} about an axis perpendicular to the longitudinal axis.

The connectors are then interdigitated (Figure 2) so that the inner surface of the tab which lies on the center line of one connector mates with the inner surface which lies on the center line of the other connector element. This simple juxtaposition allows the same element to be used on both tubes and, most important, insures that the center lines of the two tubes being joined lie in the same plane.



Right-Angle Connector Components

For right angle joints, one-half the tab is removed, the cut being made along a diagonal of the tab (Figures 3 and 4). To achieve proper alignment of the tube center lines, the tabs on the two elements must be cut on opposite diagonals. For angles, other than 90 degrees, the tabs must be cut to correspond, depending on the angle desired. For angles significantly greater than 90°, a supplementary tab may be required.

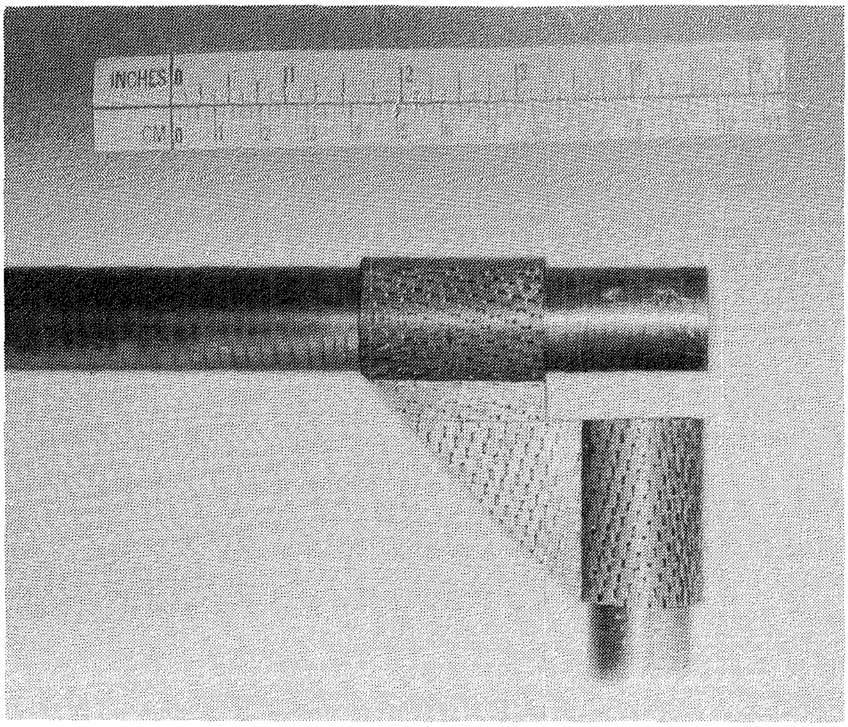


Figure 3 - Right-Angle Connector Assembly

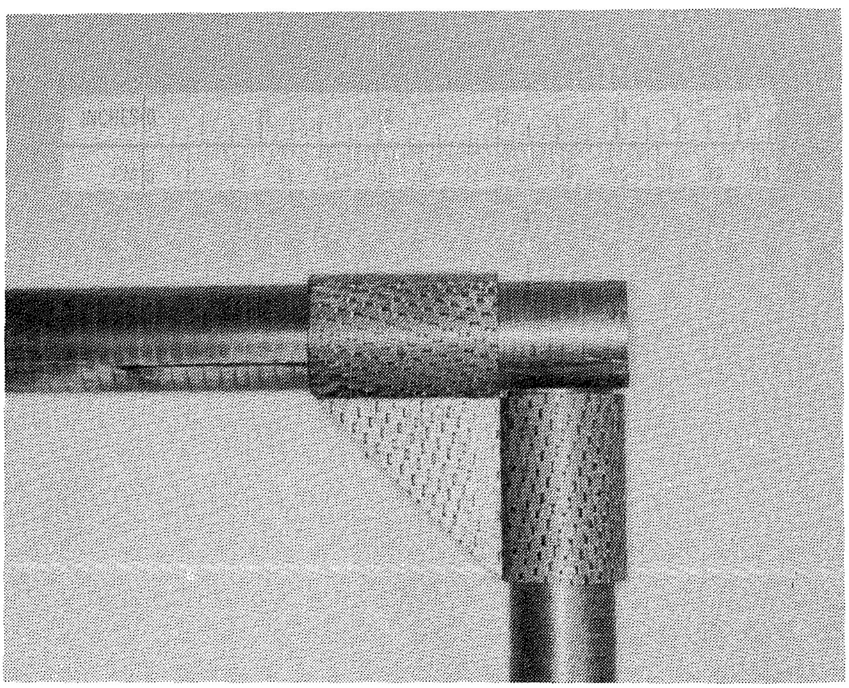


Figure 4 - Right-Angle Connector Assembly

Two additional elements are required to form "tee" joints. To assemble a "tee" joint, two of the basic connector joints are placed over a length of tubing, one on either side of the point where the other tube will be joined to the first tube. In this joint, however, both basic connector elements are aligned so that the space between the two tabs of each connector element are aligned in the same plane. The two additional web elements required are illustrated in Figure 5.

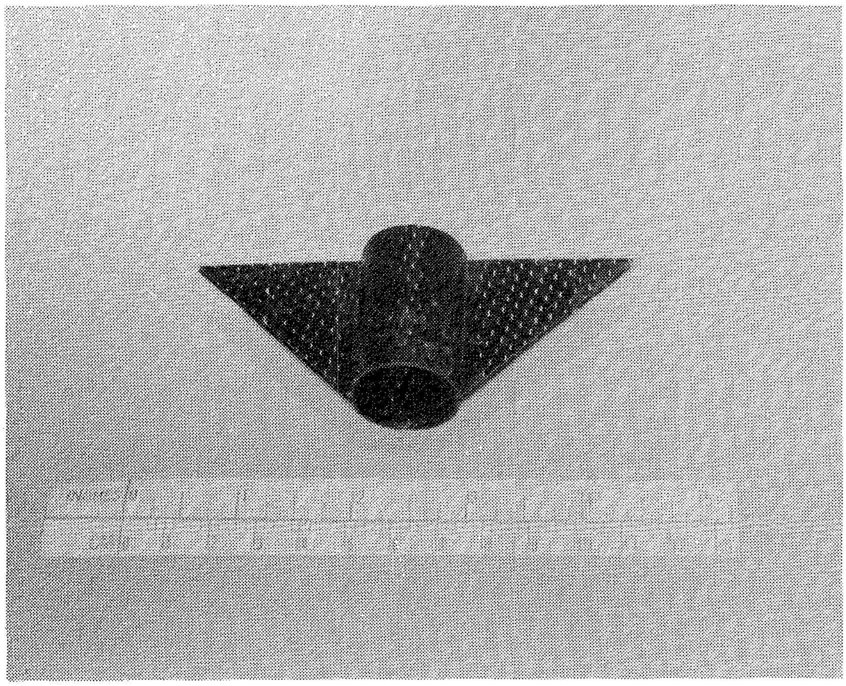


Figure 5 - Web Element for "Tee" Connector

The thickness of each element is equal to one-half the space between the two tabs on the basic connector element. The webs of these two elements fit between the tabs of each basic connector element with the end of the tube being joined between the two web elements as shown in Figure 6. The two web elements are different because they must be offset with

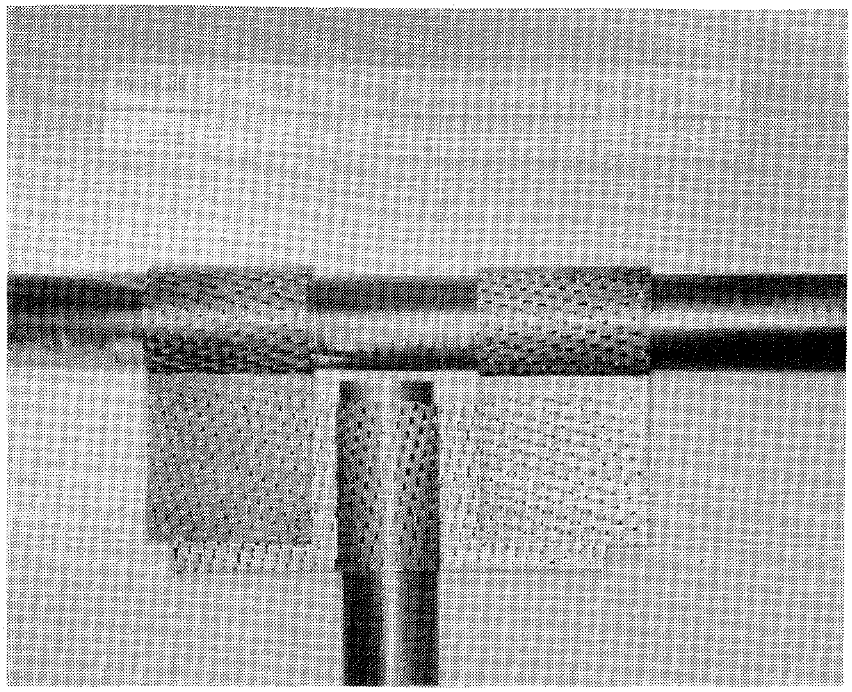


Figure 6 - "Tee" Connector Assembly Details

respect to the plane formed by the center lines of the two tubes comprising the "tee" so as to fit correctly into the two basic connector elements. Since the two web elements fit one on top of the other when assembled, one must be offset more than the other. In essence, the outer surface of one web element mates with the inner "center-line" surface of the basic connector element tab; while the inner surface of the second web element mates with the inner surface of the first web element. Figure 7 shows the relation of the tubes to the "tee" joint elements in a completed "tee" joint.

The advantages of the new invention over prior techniques have been discussed above. The configuration and design of this connector system is felt to be a new and improved method of joining tubes, pipes, rods and other regular cross-section structural and non-

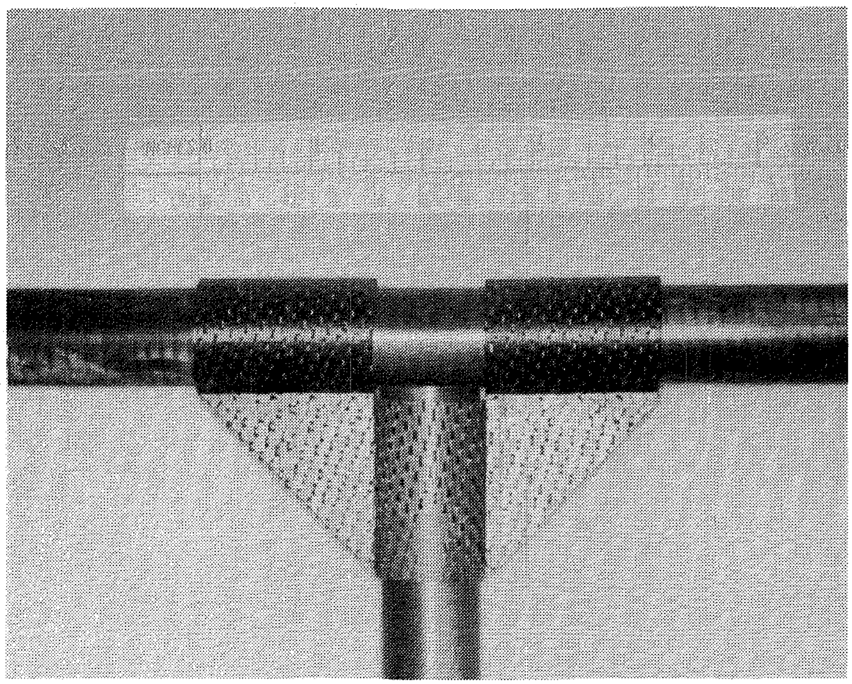


Figure 7 - Assembled "Tee" Connector

structural elements. This connector system is particularly applicable to composite materials and other "difficult-to-join" materials. The design virtually eliminates the stress concentrations experienced when metal fastners or connectors are used to join such materials. The use of oriented fibers and/or fabrics permits the design of joints with anisotropic strength characteristics so that strengths can be optimized in those directions in which stress on the joint is likely to occur.

It is only necessary to stock two elements: (1) the basic connector element and, (2) the web element to achieve 90^{o},acute, obtuse angles and "tee" connections for any given size of structural members being connected.

APPENDIX B

AN APPLICATION OF COMPOSITE TECHNOLOGY TO ACHIEVE A LIGHTER WEIGHT WALKER

A Paper Presented at:

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AN APPLICATION OF COMPOSITE TECHNOLOGY TO ACHIEVE A LIGHTER WEIGHT WALKER

1. INTRODUCTION

There are a variety of ambulation aids available for the mobility impaired. These aids vary from simple canes to quad canes, crutches, and various types of walkers. Most of these assistive devices for ambulation are fabricated from aluminum and steel. Various components of these aids are also made of rubber for specific cushioning effects. The steel used in such devices is used sparingly in those places where maximum strength is required.

As a general rule, patients who only require canes as ambulation aids have reasonably good control and strength in their upper extremities. Canes require only a small amount of material and consequently, most are sufficiently light as to not require any additional weight reduction. In addition, because of their relatively small initial weight, significant gross weight reduction is difficult to achieve. Crutches are several times heavier than canes and are required by persons with less functional ambulatory capability. Again, however, the overall weight of a pair of crutches is not very much. For most persons requiring crutches, the aluminum crutches are sufficiently light in weight for the needs of the patients. The maximum weight reduction that could be achieved, merely by the substitution of lightweight materials, is somewhere on the order of one pound. For most patients, this is a marginal decrease in weight and would require a significant increase in cost because of the expense of the fabrication and raw materials involved inlightweight processes. Crutches, therefore, are not particularly appropriate candidates for lightweight, high strength materials. It could be argued that for some patients who ambulate a great deal and who do a lot of tranferring to and from automobiles, a small weight reduction could be significant enough to warrant fabrication of such lightweight crutches. Overall, however, it is clearly a marginal situation since the cost of the crutches themselves would increase.

For those more severely disabled in their ambulatory capability, a family of aids called walkers have been developed. These generally consist of a four-legged, three-dimensional space frame within which the patient stands. This frame is used both for support and steadiness and also to permit ambulation using arm strength much as in the manner of arm crutches. Most of these walkers are fabricated from aluminum with steel tubing employed at points of stress. Most are designed to permit folding so that the patient can store the walker in the back seat or in the trunk during transportation by automobile. Nominal weights of such walkers are in the range of 2.7 to 3.6 kilograms (6 to 8 pounds). These basic walkers have been modified in numerous ways to provide additional structural support for specific patients having more severe disabilities. For example, forearm rests have been added and, in some cases, even the upper portion of crutches have been added to permit weight bearing at the shoulder.

Again, for a large segment of the population of patients who employ walkers for ambulation, the aluminum and steel walkers presently on the market are entirely adequate. The occasional user of a walker who has reasonable upper arm strength and upper body control experiences little difficulty with the weight of the currently available walkers. There are two classes of patients, however, in which the weight of the walker itself poses somewhat of a problem.

First, the very active patient with good upper body strength but with significant functional loss in the legs tends many times to have a lifestyle in which he seeks to live a relatively normal life, going from place to place, holding down a job, and seeking not to compromise his mobility to any significant degree. Such patients do a lot of ambulation and may be in and out of an automobile a large number of times each day. For such patients, a significant weight reduction in the walker would be a positive benefit and would reduce their daily energy expenditure. A weight reduction would also produce greater convenience in handling, particularly in the process of transferring the walker to a vehicle after which the walker must be folded up and then stored by the patient while he is seated in the driver's seat of the vehicle. This group of highly active patients, who require a walker for functional ambulation, could benefit from a reduction in weight of the walker itself.

The second category of patients who would benefit from a reduction in weight of the walker is the patient suffering severe disability; so severe that ambulation is impossible or extremely difficult with walkers of conventional weight. Most of these patients are, of course, not frequent ambulators but would ambulate more frequently if use of the walker itself were not such a chore. In addition, there are patients whose disability is sufficiently severe as to preclude the use of walkers at the present time because of the weight of present walkers. Most of these patients fall into a particular pattern. They are usually arthritic patients having multiple joint involvement. Frequently, these patients require additional structures on the walker to permit ambulation. Further, they usually have little strength, or little ability to exercise strength without severe pain. These are the classic "little old ladies" with multiple joint involvement arthritis. These patients with severe pain and motion impairment in multiple joints (including arms and shoulders) would benefit from a significant reduction in the weight of the walkers.

2. MATERIAL AND FABRICATION CHOICES

It is with these two classes of patients in mind that we have attempted to develop a lighter weight walker than is presently on the commercial market. We have chosen to opt for the strongest, lightest-weight materials available in order to achieve maximum weight reduction. This involves the use of composite structures. We have selected a graphite fiber-epoxy resin material for this application. Composite materials generally suffer from two distinct disadvantages in the marketplace. First, the fabrication of composite materials is frequently expensive. Second, the materials used in fabrication are also quite expensive. The use of graphite epoxy in applications such as the one which we have addressed has been greatly hindered by the cost added by the technology when compared to that of units made from conventional materials. Both factors, the cost of fabrication and the cost of materials have contributed to this problem. I might hasten to point out that this has not been a significant deterrent to the use of graphite epoxy and other composite materials in recreational devices. For example, it is not at all uncommon to find the fisherman using a graphite epoxy fishing rod. Skis, tennis rackets, golf club shafts, and other applications too numerous to metion are continually being developed employing these expensive technologies. This says something about the value structure of our society; however, such is not the subject of this paper. The point is that while not everyone who fishes with a fishing rod buys a graphite epoxy rod, there are those who feel that the marginal benefits to be gained are worth the additional cost. In considering the patient population using walkers, we feel that the two categories of patients discussed will realize sufficient marginal benefits to warrant the additional cost of these walkers.

In addition, there have been several encouraging developments which promise to reduce the cost of items fabricated from graphite epoxy and other composite materials. These factors are: (1) As graphite epoxy and other composite materials are used in more and more applications, and as they find their way into the mass market, the relative cost per pound of such materials is decreasing. (2) The recent development of a particular fabrication process offers the promise of significant reduction in fabrication cost. This process is called pultrusion. The pultrusion process permits the continuous forming of specific cross-sectioned shapes from composite fiber resin systems. For example, using the pultrusion process, it is possible to make continuous bar stock, right angle, "U" and other shapes, including tubing. The advent of the pultrusion technique promises to reduce the cost of graphite tubing.

3. DESIGN PHILOSOPHY

With the promise that these costs will be reduced, we have felt encouraged to embark on a design and fabrication study using these materials in the fabrication of a walker. We have chosen to develop a design based upon the use of straight tubes of graphite epoxy which can be pultruded. In order to construct a three-dimensional space frame from straight tubes, it is obvious that methods of joining these tubes in a reliable fashion must be found. In this program we have concentrated on methods of joining straight graphite epoxy tubes so as to achieve the three-dimensional space frames required. Anyone who has played with an erector set or tinker toys knows that it is necessary to have connectors which will permit, at the very minimum, "Tee" joints and right angle joints if rectangular frames are to be constructed and assembled to form three-dimensional space frames.

In most respects, the weight of the graphite walker, as designed, is greater than necessary in that most of the structural components are overdesigned. The use of stronger components than necessary contributes to the overall rigidity of the walker itself. High rigidity will contribute, we feel, to ready patient acceptance of the units.

4. DESCRIPTION OF GRAPHITE EPOXY WALKER

The first slide shows an oblique view of the graphite walker. Note that all components of the walker are of graphite epoxy material with the exception of the rubber foot caps on the bottom of each leg. One item not visible is the bearing material used in the joints involving the front horizontal connector bar. The two upright side panels rotate in each end connector of the front horizontal bar. This connector is essentially of a clam shell design, as can be seen, with two pieces glued together with epoxy adhesive to form a "Tee" joint. The horizontal bar is securely attached with adhesive. The front vertical member of the side frame has a piece of heat-shrink teflon tubing over it in the area of the joint. The front vertical member is not glued to the connector so that the side frame is free to rotate in the tube formed by the two halves of the "Tee" joint. The teflon covering of the vertical tube in this area permits easy rotation and eliminates wear on the graphite epoxy material itself. Two graphite rings are epoxied in place above and below the joint to hold it at its proper height. These are essentially stop rings.

In this prototype, two measures are employed to ensure rigidity of the walker when it is in its operational configuration. The top horizontal tube between the two side panels is made in two sections to permit folding. Each section of the horizontal tube is attached to the upper horizontal tube of each side panel using a modified right angle connector which is free to rotate on the horizontal tube of the side panel. The two sections are rotated until horizontal as the walker side panels are deployed to the operational position. At this point, the two sections butt together when the walker is correctly deployed. Teflon bushings are employed over the mating ends of the horizontal bar sections. A larger diameter sliding graphite epoxy tube is then slid into place, locking the two-piece horizontal bar into a rigid unit, which in turn locks the walker in its operational configuration.

The second means of providing additional stiffness to the walker involves the use of a U-shaped structure consisting of three straight pieces of graphite epoxy tubing and two right-angle joints. This U-shaped member remains suspended in front of the walker when not in use. When in use, it is rotated up and over the walker and locked into the two clips, one on each side on the rear vertical member of each side panel. Coupling to the front horizontal connector bar is achieved by means of two components formed in such a fashion as to provide a clamp around the horizontal connector bar with a stand-off and a sleeve which fits over the horizontal section of graphite tubing at the base of the "U". This permits swiveling of the "U" so that the walker can be folded. When the "U" is rotated up and over into its operational position and locked into the two clips at the lower portion of the rear vertical member on each side panel, the "U" bracket provides additional resistance to spreading of the rear portion of the walker. This additional structural reinforcement was provided in the first prototype because of the desire to achieve a very rigid structure. Initial evaluations indicated that such a structure will probably not be necessary. Use of the upper tube will provide all of the locking and rigidity necessary for functional use of the walker. This will permit abandonment of the "U"-shaped reinforcement. The net result is that approximately 325 grams (0.75 lb.) of additional material can be eliminated resulting in both a weight saving and a cost saving.

The next slide shows the walker in a folded configuration as it would normally be carried. Most conventional walkers on the market today have a telescoping bar which holds the two side panels at a specified point. To fold the walker, a catch is released and both of the side panels are folded in toward the middle, one lapping over the other to achieve a folded structure. With the graphite walker, a thinner package can be achieved by folding one leg of the walker inward and by rotating the other one completely around to the front. This results in a thickness reduction of the folded walker of several inches. The present walker is unfolded in the following sequence.

The side panel (folded to the front) is rotated around to the 90^o position with respect to the front horizontal connector bar. The other side panel (folded to the rear) is opened up to the 90^o position. The U-bracket is rotated up and over the walker, and lowered until the rear ends are engaged in the two stops, one on the either side of the rear vertical member of the side frame. Next, the two-sectioned top spreader bars are rotated up into position and the graphite epoxy sleeve is moved to the left stop, thus locking the horizontal spreader bar into a rigid unit. This completes deployment of the walker.

This slide shows the assembled walker in the normal position for use. It will be noted that no hand grips are apparent on the top horizontal bars of the side panels. These were not shown so as to reveal the graphite structure more clearly. In actual use, rubber hand grips will be cemented in place on the walker.

In the second prototype, the U-shaped bracket was eliminated, and assembly of the walker was simplified as shown in the last two slides.

The walker, as shown in the photographs, has a weight of approximately 1.93 kilograms (4.25 lbs.). This represents a 1.25 - 1.47 kilogram (2.75-3.25 lbs.) reduction over that found in conventional walkers fabricated out of aluminum and steel. The net result is an extremely lightweight portable walker.

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16. Abstract

A study was conducted of potential applications of high-strength, lightweight composite technology in the orthotic field. Several devices were designed and fabricated using graphite-epoxy composite technology. Devices included shoe plates, assistive walker devices, and a Simes prosthesis reinforcement. Several other projects having medical application were investigated and evaluations were made of the potential for use of composite technology. A seat assembly was fabricated using sandwich construction techniques for the NASA "Total Wheelchair Project."

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