Permanent Press, No Wrinkles: Reinforced Double Diaphragm Forming of Advanced Thermoset Composites

by

Samuel B. Truslow

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ABSTRACT

Structures made out of advanced composite materials have significant advantages over those made from metals. The chief advantages are high strength-to-weight ratio, the ability to tailor mechanical properties, high fatigue resistance and good corrosion resistance. The manufacturing methods used to produce these materials are different from those used to produce metal parts. Composite structures are made from numerous layers of fibrous material which must be prevented from wrinkling during manufacturing to maintain optimal mechanical properties.

Manufacturing composite parts without wrinkling can be very difficult when the part has double curvature. In these cases there will be a tendency for the parts to wrinkle as they are shaped. Due to these difficulties many parts are made by hand. This method carries two penalties in that is much slower, and therefore more expensive, than automatic methods and it involves significant hand manipulation of the material resulting in the potential for serious repetitive stress injuries in the workers.

The double diaphragm forming process was developed to allow parts of significant double curvature to be made faster and with little hand work. The process involves creating a flat stack of all the layers of material and then forming it into shape between two rubber diaphragms in one step.

This process was adapted to a family of structural composite parts, called rib chords, in the Boeing 777 airliner vertical fin and horizontal stabilizer. These parts have considerable double curvature and so present opportunities for large improvements in production rate and ergonomic suitability. Development of a reinforced version of double diaphragm forming has created significant cost savings for manufacturing these parts. A production machine was designed and built to match this process to the production environment for the rib chords. Use of the machine reduces the part flow time by 70% (Boeing's figure) which translates to significant direct cost savings. The process also reduces the potential for worker injuries dramatically. Not only is the processing improved but significant factory floor space and fabricating equipment are freed up since the one machine can make production quantities easily. Finally the process is very well suited for use in an automated production system creating the opportunity for even more savings in the future.

Thesis Supervisor: Dr. Timothy G. Gutowski
Professor, Department of Mechanical Engineering

Acknowledgments

Many people contributed to this thesis and my research in general. Most had a direct impact in help or consultation, others provided an equally critical service by tolerating unending streams of complaints, thoughts and general musings on the matter of "the machine". This phrase must now be purged from my vocabulary lest I stretch the seemingly infinite reserve of my family and friend's tolerance.

Crucial to all that has gone into this thesis are the efforts of my advisor Professor Gutowski whose wisdom and belief in me provided enormous assurance to a stressed and uncertain mind. Without your help and support this would not have been possible. Thank you.

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For my family whose love and support have meant so much to me throughout my life I thank you. You're the best and were instrumental in getting me through this. I promise I'll stop droning on about "the machine" and "the project". At least until the next one. Thank you for everything.

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1 Introduction

1.1 Composite Materials

Composite materials offer great benefits over traditional materials. They are so useful in many applications that materials such as carbon fiber and Kevlar™ have become household terms and are involved in everything from spacecraft to automobiles to golf clubs. The key to their widespread use is the remarkable mechanical properties they exhibit. Chief among these properties is their very high strength-to-weight ratios. This factor is the main driving force behind their use in most applications.

Composite materials are a combination of two or more constituents that combine into one structure and the characteristics of each contribute to the character of the whole. In most instances the materials are made up of a reinforcing fiber and a matrix, or resin, that holds the fibers in place and transfers loads between them. There are two classes of resins used: thermoplastic and thermoset. Thermoplastics are solid materials at normal temperatures but can be heated and softened to a flexible state for shaping then cooled down to maintain the new shape. This heating and processing can be performed repeatedly. In thermoset systems, the resin goes through a non-reversible chemical change called curing after which it can no longer be processed. This thesis is concerned with thermoset resins.

The most common reinforcing fibers are fiberglass, aramid (e.g. Kevlar™) and carbon fiber. These are paired with resins that match their properties. Fiberglass is used typically for its low cost and so uses a polyester resin that is inexpensive. Aramid and carbon fibers are much higher performance so they are matched with higher performance resins, typically epoxies.

The resins are a mix of two materials that react to form chemical bonds that solidify the material and so can be dependent on accurate mixing of the two components. The ratio of resin to fiber affects the strength-to-weight ratio of the final part. Excess resin beyond what is needed to transfer the loads among the fibers only adds undue weight and does not add significant strength. Therefore, the resin-to-fiber ratio is an important factor in maintaining the high-strength, low-weight properties of the composite material.

For this reason many composite materials, and especially those used for high performance applications, are made out of "prepreg" material. This is where the fibers have been pre-impregnated with the mixed resin prior to being shaped into the final part. They are then frozen to prevent the curing reaction from continuing. The end user of the material simply thaws the prepreg, lays it up on the mold, applies a vacuum bag and cures it at the appropriate temperature. The use of prepreg materials eliminates the mess and inconsistency of mixing and impregnating the resin at the manufacturing stage.

Prepreg material for structural applications typically comes in one of two forms. The first is as a woven fabric, which can be of many different weaves depending on the properties required. The second fiber type is known as unidirectional material. This is where the fibers are collimated without any weaving at all. Unidirectional materials can come as a tape or as tows. Tape material has the fibers collected on backing paper. Tows are generally wound onto spools.

One of the important properties of composites is that the strength of the fiber is highly dependent on its angle to the applied load. This has two implications. The first is that the part must be made with material oriented in all the directions of the loads. This is usually accomplished by adding many layers or "plies" of material together at certain angles to develop strength in those directions. Given the high dependence of strength on fiber direction it is necessary to keep the fibers straight. If the fibers wrinkle, the strength of the material is greatly reduced. The main criterion of successful manufacturing therefore, is that the material not wrinkle.

For most composite manufacturing processes, the material is placed on the mold, or tool as it is called, as a combination of many plies. This means that the manufacturing of composite parts is a sequential process of laying down individual plies. Each of these plies must be shaped to the contour of the tool without wrinkling. Since the prepreg material is very sticky, and this stickiness is highly dependant on temperature, it is difficult to get a machine to apply it reliably. For this reason many highly contoured parts are made by hand. Most machine methods do not work well for small or highly curved parts.

While composite materials far out-perform other materials in terms of mechanical properties, they have always suffered from high costs which has restricted their use in many applications. This is due in large part to the fact that the materials themselves are expensive. This is unlikely to change because some of the materials such as carbon fiber can only be made by inherently expensive methods. To manufacture the parts the material has to be laid down one ply at a time with each step involving careful shaping of the ply to the part shape, it can be a very slow process. This is particularly the case if the part has many layers. The manufacturing of the parts more so than material development is the area where the overall cost of the parts can be reduced most.

To speed up the process of laying down this material, and thereby lower the cost of these parts, either the time to shape a single ply must be reduced or more than one ply must be shaped at one time. The latter approach is the one used in the forming process. The term "forming" covers a wide range of processes that vary somewhat depending on what part is being made out of what material. The generic forming process involves using a machine for shaping a number of plies simultaneously rather than sequentially as with hand methods. The process is characterized by laying up all, or most, of the plies in their flat state and then shaping them to the final part configuration. Since a flat layup involves no shaping of the individual plies, the time to lay it up is minimized. These factors contribute to the main advantage of the process, which is that it has a very low cycle time translating into manufacturing cost savings by eliminating the need for hand labor.

Much work has been accomplished at the Laboratory for Manufacturing and Productivity in the area of forming processes for composites. The work in this thesis builds upon the foundation laid by Professor Gutowksi and the students in the lab. The people who paved the way for this work are Professor Gutowski, Dr. Greg Dillon working in a Post-Doctoral position and Dr. Haorong Li as a PhD student.

1.2 Background

This thesis is concerned with a specific version of the general process of diaphragm forming. The general process is very similar to thermoforming or vacuum forming thermoplastics in that the material is shaped over a tool by means of a pressure difference. In vacuum forming the material itself becomes the barrier across which the pressure difference is applied. In diaphragm forming, however, the pressure difference is applied to an elastic diaphragm that is used to shape the material by stretching over the tool.

In the specific version of diaphragm forming investigated in this thesis called double diaphragm forming, there are two diaphragms that sandwich the stack of material. This stack is known as a preform. The two diaphragms are used to provide support to the material as it is being formed to prevent it from wrinkling. Once the part has been formed to the tool shape, the pressure difference is removed and the diaphragm taken off, leaving the part shaped to the tool. The part is then removed and placed on a cure tool for curing into its final state.

1.3 Forming Issues

Forming processes in general work very well when only simple bends are involved, a straight fold in a sheet for example. However, for more complicated parts with severe double curvature, problems with wrinkling can occur. In forming the flat material into a doubly curved shape there will be regions where the material will wrinkle due to “bunching”. Wrinkles are a very undesirable feature in a composite part since the loads in a composite material are taken by the fibers. If the fibers are not straight then the strength of the final part is significantly reduced.

As with any process there are limiting factors that determine the processes’ applications and effectiveness. The biggest influence in establishing the limits of what parts can be successfully formed is this tendency of a part to wrinkle due to its geometry. This wrinkling comes about during the transformation from the flat preform, into a doubly curved surface since there will be areas of the part that will be in compression. If this compression is great enough then the part will buckle causing wrinkling. One can imagine this problem by thinking about draping a cloth napkin over various objects. If it is draped over the edge of a table it will form a smooth 90 degree bend. If it is laid on top of a round or doubly curved object like a bowl, it will wrinkle. In order to solve this problem something in the forming process must resolve this compression and prevent the part from buckling.

1.4 Double Diaphragm Forming

The goal of double diaphragm forming is to provide a mechanism whereby this compression can be overcome. The process came about through a research effort aimed at forming thermoplastic part not thermoset ones. The process involved forming parts using two aluminum diaphragms as a means of supporting the part and suppressing wrinkling. To get the required formability out of the aluminum the diaphragms were heated to the superplastic temperature range where they could be stretched to many times their original size without tearing (so-called superplastic extension). This prevented the use of this process with many composite materials since they could not either withstand such extreme heat or would not cure correctly at such temperatures. Since the parts were made from thermoplastic material there was no second curing step needed but rather they just needed to be brought to processing temperature at which they could be formed. Once the part cooled the diaphragms could be removed and the parts would be hardened.

The superplastic temperature range of aluminum diaphragms is far beyond what thermoset materials can be exposed to however, meaning that some other material must be used for the diaphragms. This requirement has led to the use of rubber diaphragms.

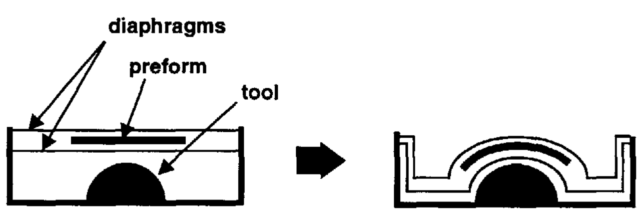


Figure 1-1 Schematic of the double diaphragm forming process

In this very schematic view of the process, one can see that the preform is set in between the two diaphragms and above the tool which is inside a vacuum chamber.

When a vacuum is applied between the diaphragms they come into contact with the preform. Vacuum is then applied inside the chamber and both diaphragms are formed over the tool shaping the preform in between. This process resulted in U.S. Patent # 5,648,109 by Professor Gutowski et al.

The rubber diaphragms are the key to forming thermoset materials since they provide support to the preform by transmitting tension to it as they stretch. Compressive forces are relieved by pulling the material into shape during forming rather than allowing it to bunch up due to compression. Since heat is generally applied to the material to make it less viscous and easier to form, the rubber diaphragms must be of a type that can withstand the temperatures needed for forming. In general silicone rubbers are used as they have a very high temperature capability and are also very durable.

The thickness and hardness of the rubber is generally selected on the basis of the forming parameters. Since the pressure difference for most forming process is generated by means of a vacuum for simplicity's sake, the total pressure is limited by ambient atmospheric pressure and reasonable cost vacuum pumps to about 14 psi. This limiting pressure difference and requirement that the diaphragm be able to form completely to the tool provide the two criteria for selecting the diaphragm material. In general, the thicker and harder the material is, the more support it will provide to the part, but the harder it will be to stretch. The selection process must take all these factors into account.

Chapter 2

2 Boeing 777 Rib Chord Forming Project

The research contained in this thesis is based on applying the double diaphragm forming process to the manufacturing of structural carbon fiber parts, called rib chords, used in the empennage the Boeing 777 airliner. The empennage consists of the vertical fin and the horizontal stabilizer. The rib chords connect the flat ribs to a series of I-beams that run along the inside of the outer skins, called stringers. The structural scheme for the fin and the stabilizer is the same. The rib chords have an L-shaped cross section with one flat flange connecting to the ribs, and the other flange connecting to the tops of the stringers so that it is curved to follow the airfoil shape of the skins.

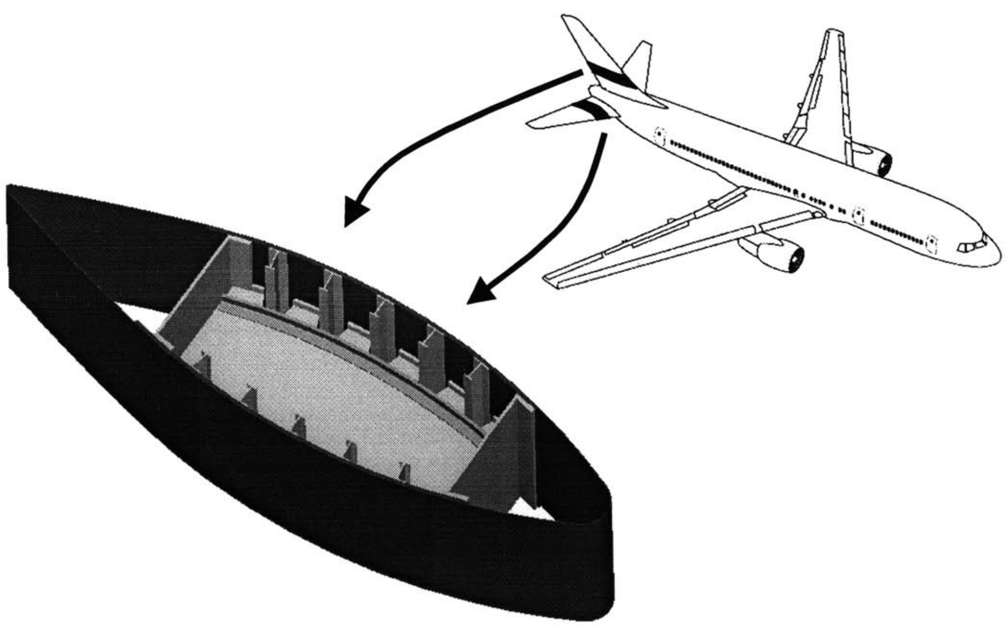


Figure 2-1 777 Vertical fin and horizontal stabilizer structure

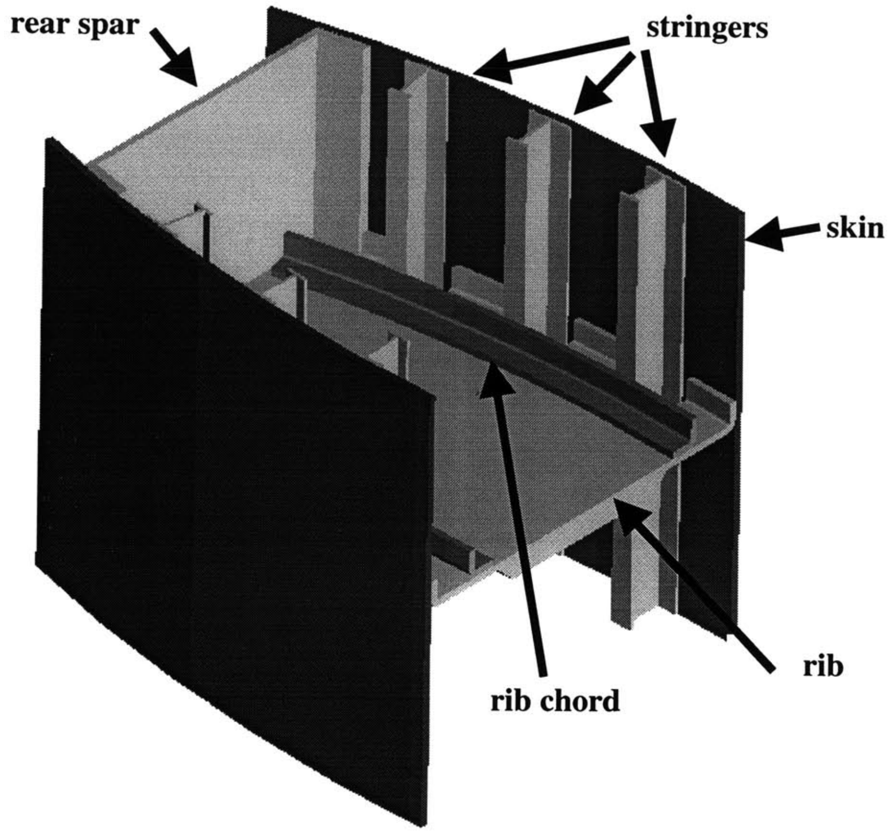


Figure 2-2 Empennage structure

Figure 2-3 777 Rib chords

The parts are made with graphite/epoxy prepreg woven into a fabric. They are layed up on male Invar 36 cure tooling so that the tool side of the parts is on the inside of the parts and not the outside attachment surface. A model of the cure tool with a rib chord is shown below.

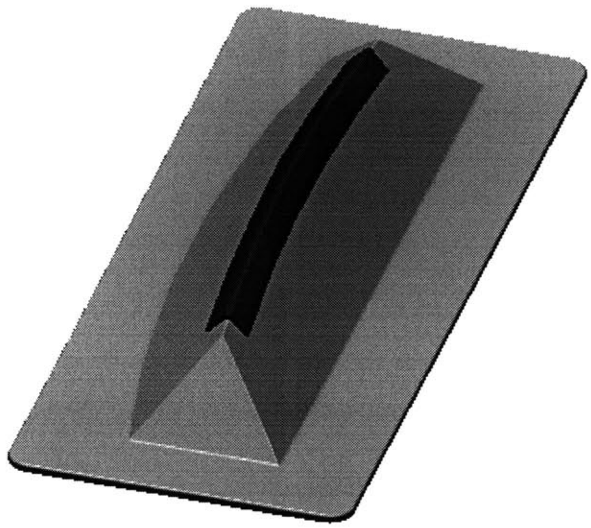


Figure 2-4 Cure tool with rib chord

The parts vary in layup, length and curvature but all are quasi-isotropic (incorporating both lengthwise, "0°" plies and bias, "45°" plies). There are no ply drops or material splices so each ply is the full size of the part. The following table shows the family of rib chords, their locations and the amount of 0° vs 45° plies. All the chords have flanges that are 2-3" wide each. The numbering scheme is the same for the vertical fin and the stabilizer with rib one being at the fuselage. Not all ribs have rib chords. The rib chords for ribs one and two in the stabilizer, and rib one in the fin are titanium. The rib chord for rib three is of a different shape from the rest and is not included in this process. Since the exact dimensions of the parts are proprietary to Boeing, the numbers shown below are intentionally ambiguous but include the actual sizes within the range. The figures that are listed as "percentages of rib 2" demonstrate the amount of variability in the family of chords while keeping the actual sizes ambiguous. The actual number of plies changes with most parts but is generally in the two dozen range.

Rib number	Major radius, percentage of fin rib 2	Length, percentage of fin rib 2	Chord height, inches	% zero degree plies
NOTE: Exact dimensions are proprietary so all dimensions listed are intentionally ambiguous.				
Vertical fin				
2 (fuselage)	500-600 inches	5-6 feet	1.01	64 %
3	92 %	95 %	0.99	67 %
4	81 %	91 %	1.01	63 %
5	77 %	86 %	0.98	63 %
6	69 %	83 %	0.99	63 %
7	66 %	78 %	0.94	63 %
8 (tip)	65 %	75 %	0.88	63 %

Rib number	Major radius, percentage of fin rib 2	Length, inches	Chord height, inches	% zero degree plies
Horizontal stabilizer upper surface				
4 (fuselage)	297 %	94 %	0.30	64 %
5	211 %	89 %	0.38	64 %
6	147 %	84 %	0.49	58 %
7	102 %	81 %	0.65	64 %
8	88 %	77 %	0.68	56 %
9	68 %	73 %	0.81	56 %
10 (tip)	83 %	70 %	0.60	63 %

Rib number	Major radius, inches percentage of fin rib 2	Length, inches	Chord height, inches	% zero degree plies
Horizontal stabilizer lower surface				
4 (fuselage)	103 %	94 %	0.87	64 %
5	103 %	91 %	0.79	56 %
6	96 %	86 %	0.76	63 %
7	73 %	81 %	0.91	63 %
8	70 %	77 %	0.86	63 %
9	63 %	73 %	0.87	56 %
10 (tip)	75 %	70 %	0.69	56 %

Figure 2-5 Rib chord dimensions

Since the parts are used in a few dozen different locations throughout the empennage, each rib location has a different geometry. The parts range in both length and curvature between each location. The curvature varies widely depending on where the part is on the airfoil but the chord heights listed in the table give a rough idea of the amount of curvature in the parts.

The goal for this project was twofold. One aim was to reduce the amount of time needed for making each one of these parts and thereby lowering the cost. The other goal was to provide an alternative to the current hand layup methods that can result in operator injury. Due to the need to shape the plies into the double curvature the operator must use significant hand pressure and motion to prevent the individual plies from wrinkling. This can lead to severe repetitive motion injuries in the operators.

2.1 Forming Rib Chords

The challenge in forming rib chords is that there is significant double curvature involved causing very high compressive forces during forming. Imagining the transformation of the part from the straight and flat state that the plies begin in, to the curved shape of the final part, it is easy to imagine what the wrinkling will look like. The stringer flange does not go through any in-plane bending and so does not wrinkle. The rib flange however, undergoes significant in-plane bending causing significant wrinkling.

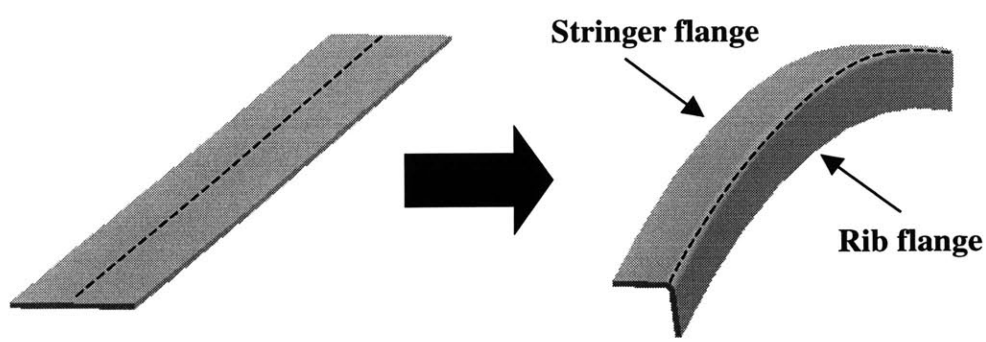


Figure 2-6 Transformation of flat preform into formed rib chord

The result of this in-plane bending is that the edge of the flange toward the center of curvature will undergo significant compression and shortening of its length causing it to wrinkle. Since the preform for this part is rectangular the manufacturing process must put this in-plane curvature into the part.

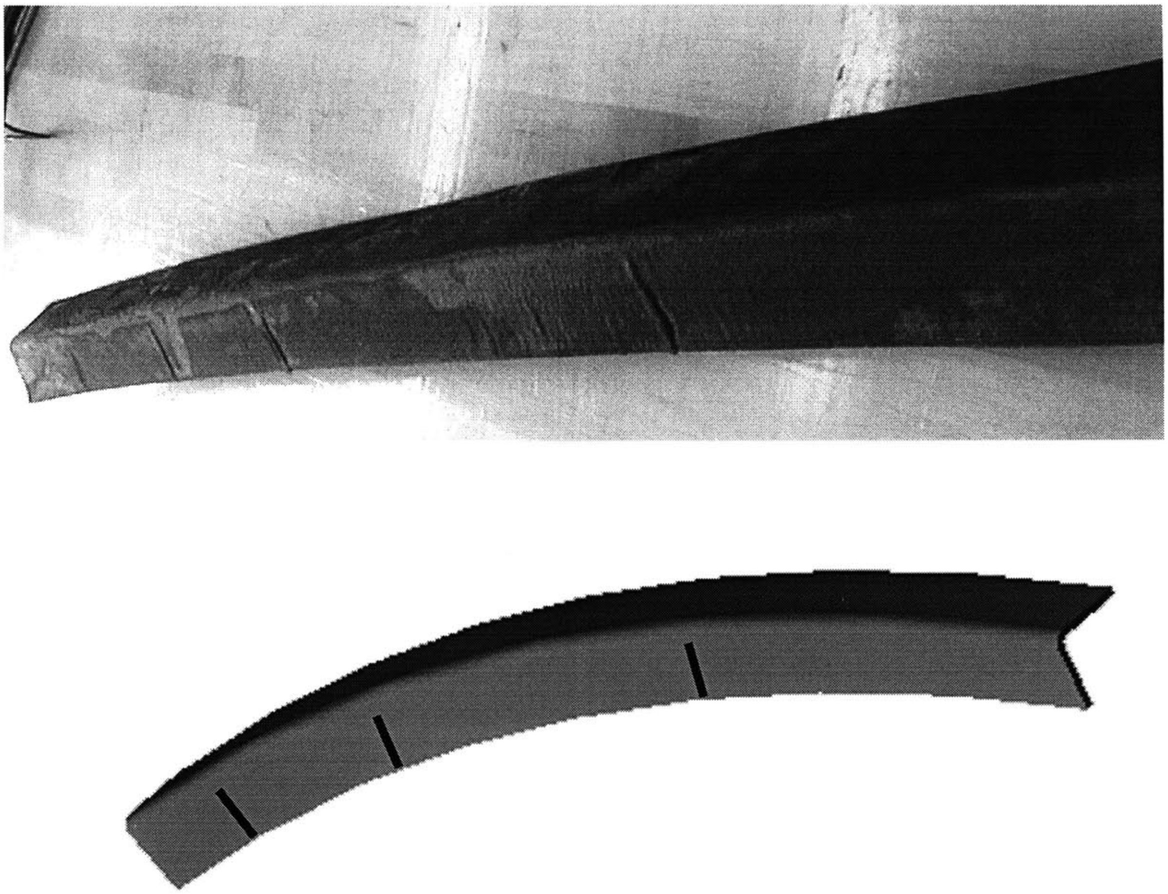


Figure 2-7 Wrinkles due to shape change

To prevent this wrinkling the diaphragms must provide considerable support to the preform. Unfortunately, the geometry of the parts complicates the process of generating this support. The basis of double diaphragm forming is that the compressive forces that cause wrinkling are overcome by means of stretching of the diaphragm. The greater the tendency to wrinkle, the more the diaphragm has to stretch to prevent it. Beyond the simple need for stretching, the extension must be in a direction perpendicular to the wrinkle in order to "smooth it out".

Unfortunately, in the case of the rib chords both these conditions are not met. The flanges of the part are very short so the diaphragm does not stretch much during forming, meaning that there is little tension generated to prevent wrinkling. In addition to this, the extension of the diaphragm is parallel to the wrinkles, not perpendicular to them, meaning that the little stretching available does not contribute any smoothing action to them.

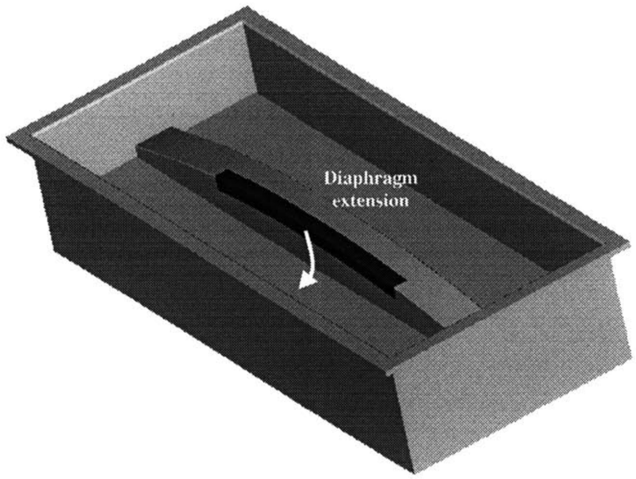


Figure 2-8 Direction of diaphragm extension

2.2 Two Step Forming

Since it is double curvature that wrinkles parts, tests were performed using a process called two step forming aimed at separating the forming into two discrete steps. This process was developed jointly with Boeing and draws upon the fact that a simple bend does not introduce wrinkling. Thus forming a flange that consists of long simple bend provides much of the shape while not promoting wrinkling. This is the first step. The second involves shaping the forming tool from a straight bar into a curved one and creating the final shape.

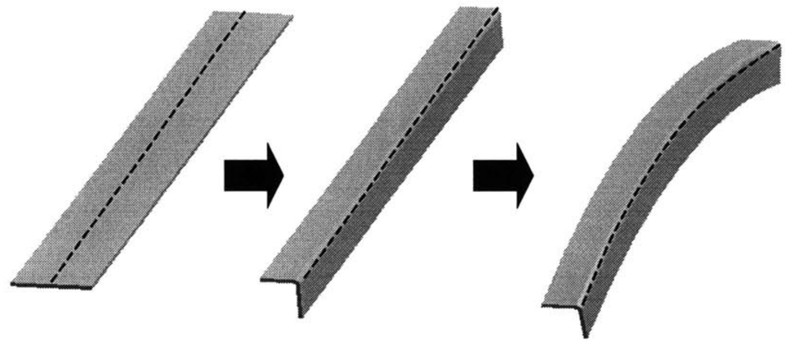


Figure 2-9 Two step forming

To accomplish the second step mechanically requires substantial modification of the forming machine. The new machine would need a flexible tool that was strong enough to withstand the considerable load placed on it by the forming vacuum but still remain straight. Once formed, the tool then had to push into the diaphragm a few inches in order to flex the tool into the shape of the rib chords.

This was accomplished by means of a central steel tube that ran the length of the machine. On top of this bar was a stack of flexible plastic bars each 1/4" thick and 3" wide. These bars are made to be easily flexed into position but hard enough to not deform under the forming loads. The top bar has an rounded edge which provides the radius to the final part.

The bars are shaped by means of a series of steel pins that push up through holes in the steel tube and press up against a steel plate that runs underneath the plastic bars. The steel bar helps to distribute the load of the diaphragm between the pins and prevent the bars from being pushed down in between pins. The steel pins that are used are adjustable so that the shape the tool forms to can be changed to make different rib chords.

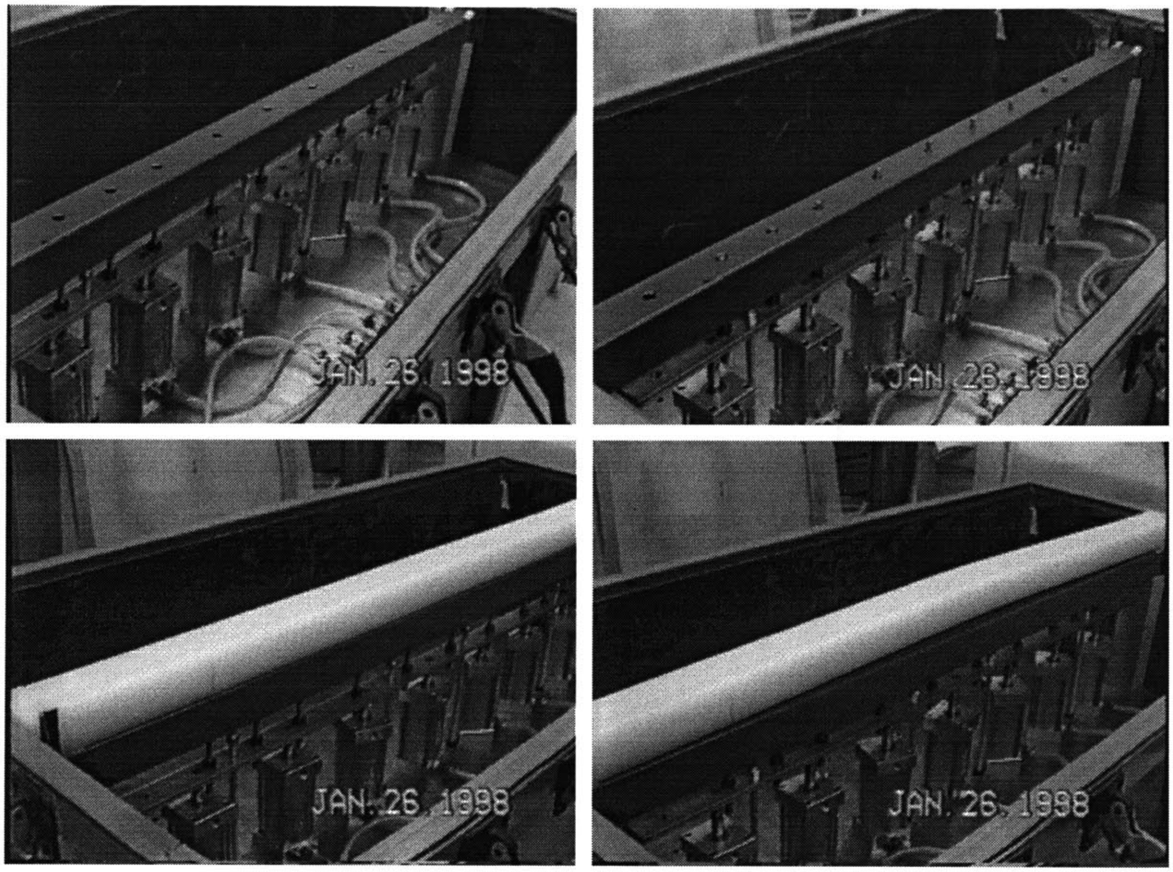


Figure 2-10 Two step forming machine

The pins were mounted to a second bar that ran beneath the steel tube. This second bar was actuated by a series of air cylinders that pushed upwards. In trials the pin arrangement led to some difficulties with the lower bar bending too much and producing inconsistent curves on the top of the stack. To avoid, this the pins were replaced by a half inch thick aluminum plate that was cut to the appropriate curve for the part being made. This plate would stick up between two steel bars on edge rather than as pins going though holes in the steel tube. This plate provided ample stiffness between the cylinders and so it moved as a single part and did not suffer from the deformation between pins.

Mechanically this machine worked well but the forming results were not very good. While it did improve the results somewhat in terms of wrinkle prevention, it did not solve the problem well enough to create successful parts. One reason for this may be that forming the simple bend first puts the part into a position whereby it is internally stiffened. Relative movement between the plies as a means of relieving compressive forces is likely harder to generate if the part is stiffened by the bend.

A second problem was noticed during the testing of this machine. The part was first heated to lower the viscosity of the resin prior to forming to make it easier for the fibers to move and relieve compression. This temperature had to be maintained until after the simple bend was formed since the second forming step is where the heat is needed most. An overhead radiant heater was used to heat the outer diaphragm which in turn conducted the heat through into the part.

Once the part formed down into the simple bend it was held completely against the tool by the pressure difference. Since the tool was not heated along with the part, it acted as a heat sink and cooled the part off dramatically as soon as the part came into contact with it. The part has very little heat capacity compared to the tool and so would cool off quite quickly. To prevent this, the part could be heated to a higher initial temperature so that it could lose some heat to the tool and still be at forming temperature. This could not be done however, since the prepreg's maximum exposure temperature is quite close to the forming temperature.

To combat the effect of the tool cooling the part it was rebuilt with integral heaters and the plastic bars replaced with aluminum to keep them from softening due to the heat. This was to ensure that the part was truly at its proper temperature prior to forming. This did not improve the wrinkling results very much and did cause enormous cycle time delays by requiring that the entire tool cool down before the part would reach a low enough temperature where the top diaphragm could be removed without undue distortion occurring in the part.

2.3 Pretensioned Diaphragms

Given the tendency of the parts to wrinkle on the rib flange perpendicular to the length of the part, the diaphragms had to reduce the compressive forces in the lengthwise direction to counter wrinkles. Since the diaphragm stretched very little in this direction because of the part's narrow flanges, increased stiffness had to be provided. One approach was to pretension the diaphragms so that what little stretching that did occur would be to a much higher level of tension.

This was done by means of a machine where the diaphragms were held onto rollers that were free to slide vertically on four posts at the corners of the machine. The diaphragm rollers would be rotated to pull the diaphragms tight and then locked in position. They would then be lowered into place and clamped before drawing vacuum.

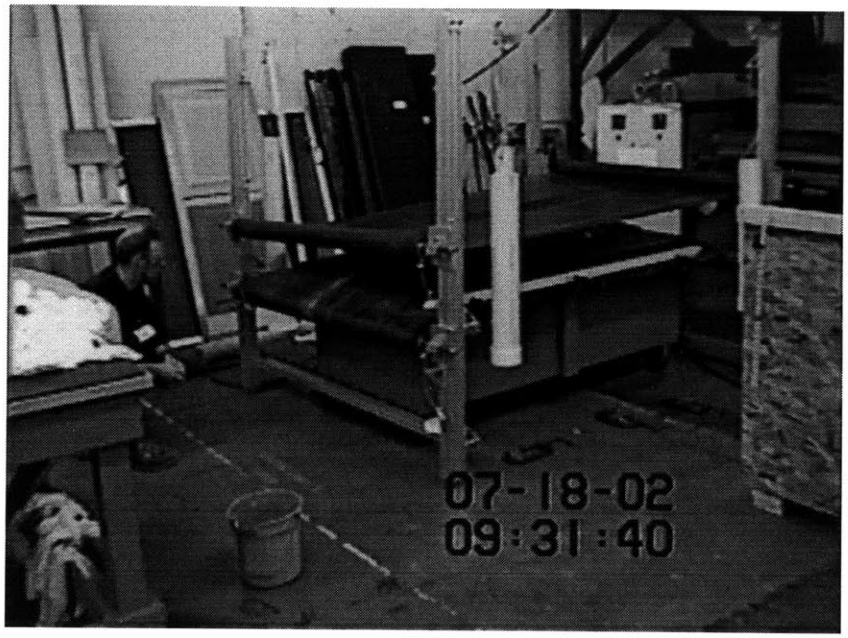


Figure 2-11 Forming machine with tensionable diaphragms at Boeing

This concept had been tried previously in the lab on a smaller scale and resulted in the fabrication of a pre-tensioning apparatus to examine the effects of diaphragm tension.

The results of the tensionable diaphragm approach were only marginally better than those achieved by untensioned diaphragms. One effect that was noticed right away was that the transverse stress in the diaphragms would cause large wrinkles down the length of the diaphragms as the material buckled in the transverse direction to the tensioning. This was considered not directly harmful as the necessary characteristics of the diaphragms were not diminished, that is they still held greater than normal tension. This tension however did not alleviate the wrinkling problem as the tension developed while forming was still the same. The difference in tension between the formed and the unformed states seems to be the critical effect. Since the compressive forces only develop while the part is being formed, the diaphragms must stretch during that time as well. Given that there is a certain amount of compression that must take place, there is a corresponding amount of tension that must be transmitted. The absolute value of the tension in the diaphragm does not seem to matter as much as the amount that is transmitted to the part during forming. For this the diaphragm must stretch while in contact with the part.

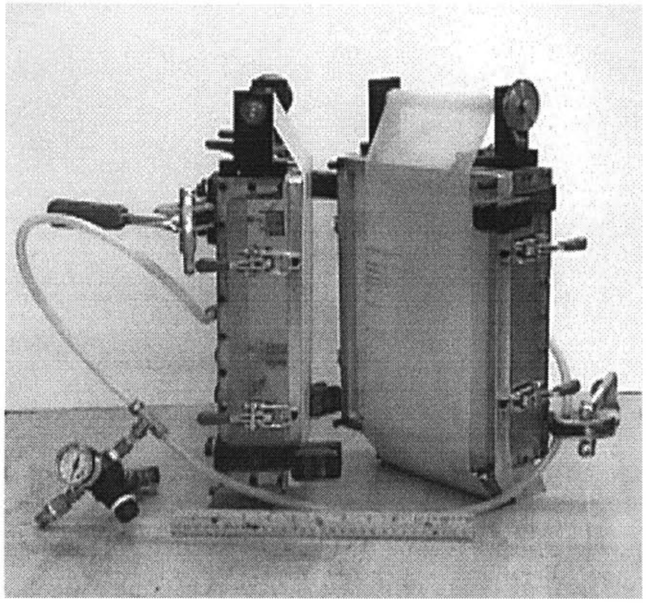


Figure 2-12 Apparatus for investigating diaphragm tension

2.4 Mechanical Clamping

Since the wrinkles with this process were somewhat smaller than normal it was thought that they might be able to be flattened out by mechanical action either before or after the forming process. Two approaches were tried on the pretensioning version of the machine while at Boeing in July 1998. The first was to use two step forming and provide mechanical clamping by way of a rigid aluminum bar clamped on the outside of the tool during the second, curve forming step in the process. This would prevent any out of plane wrinkling from occurring. This approach resulted in reduced wrinkling out of the plane, but the wrinkles were still present, just not as large. Instead of forming a large smooth wrinkle the parts tended to produce much tighter and more closely spaced wrinkles.

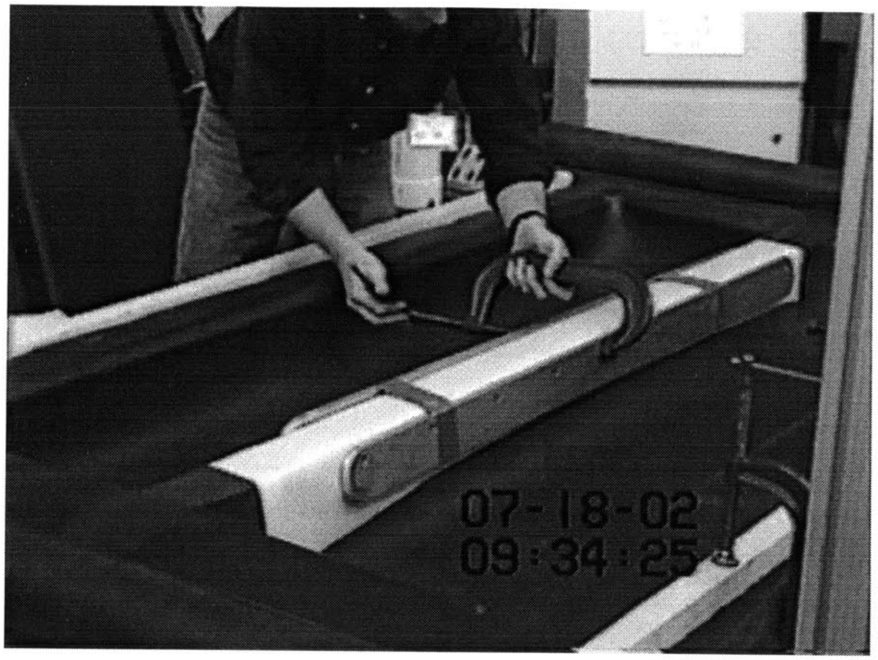


Figure 2-13 Mechanical clamping of part after forming

Since the bar prevented gross deformation out-of-plane but did not provide a very large amount of localized pressure, the wrinkles were able to form by deforming into the diaphragm material itself enough to relieve the compressive forces. There was nothing in the process that relieved the compression so the part still had to wrinkle.

The other method employing mechanical clamping was the use of the clamping bars after the part had been formed and wrinkled but while it was still hot. The approach sought to press the wrinkles flat after they had formed. Since the material was still hot it would still be somewhat flexible and able to move and flatten. The results achieved were encouraging in terms of reducing out of plane wrinkling but had other effects that were undesirable. The clamping produced a lip at the top of the part along the radius resulting from the material bunching up there as a result of the bar clamping.

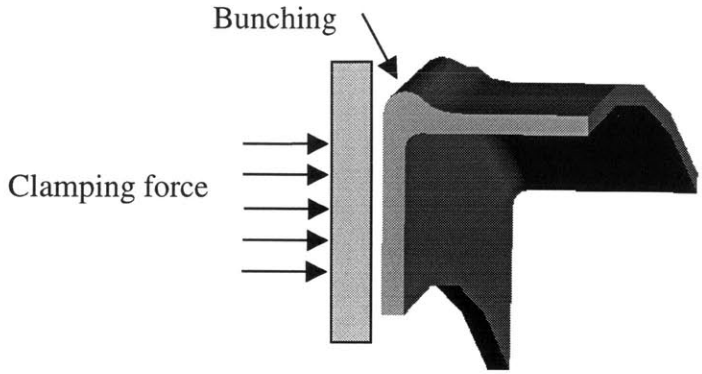
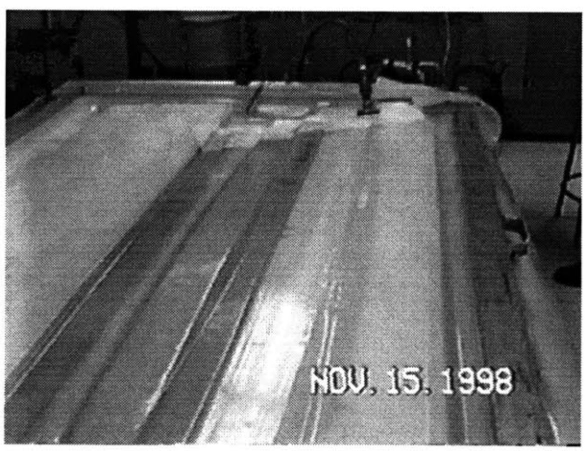


Figure 2-14 Cross sectional view of part with material bunching

Once the machine returned to MIT at the end of the summer of 1998 the diaphragms were switched back to the unpretensioned ones and tests were conducted to establish if there were significant advantages to the pretensioning. These were not found and the machine was left with the fixed diaphragm frames.

2.5 Raised Tool Machine

The results of the summer's testing had been successful enough that the machine was modified to become a test bed for production style machine features. The major modification in this was to change the method of forming from pulling the diaphragms down around a stationary tool into wells on either side, to moving the tool up through the diaphragm.



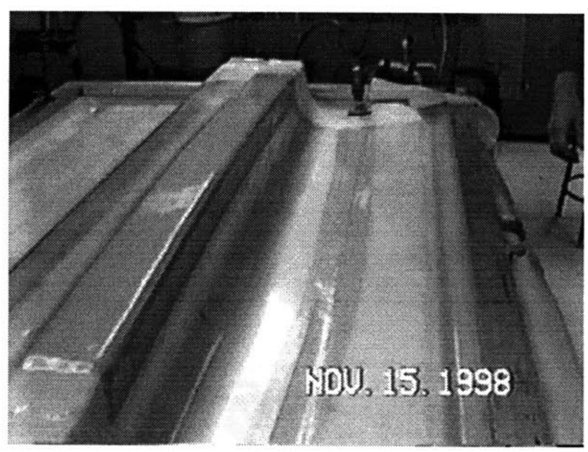


Figure 2-15 Forming machine with movable tool

This was done for two reasons. The first is that it provided a stable surface at the top of the tool to lie the parts down upon. Since the part was placed on the tool with the centerline on the edge of the tool, it had a tendency to slip off resulting in poor alignment between the part and the tool. If the surrounding area of the machine is at the height of the tool, then the part's rib flange is supported from slipping off and more accurate locating of the part and tool can be achieved. This is very important in a production environment.

2.5.1 Diaphragm Extension

The other advantage of this set up is that the extension of the diaphragm is not as great so that it does not get "stretched out" from repeated cycling of the machine. Since the diaphragm is heated and then stretched very tight for long periods of time, with each cycle it develops a significant amount of permanent stretch. The result of this is that it has large wrinkles when lying flat before forming. This in turn complicates the process of achieving accurate alignment between the part and the tool as the residual stretch in the diaphragm must be taken up while the diaphragm is pulling tight over the tool. This creates a window where the part has excessive mobility during the forming process allowing for misalignment. By reducing the need for the diaphragm to stretch the full height of the tool twice during forming the stretching of the diaphragm is reduced.

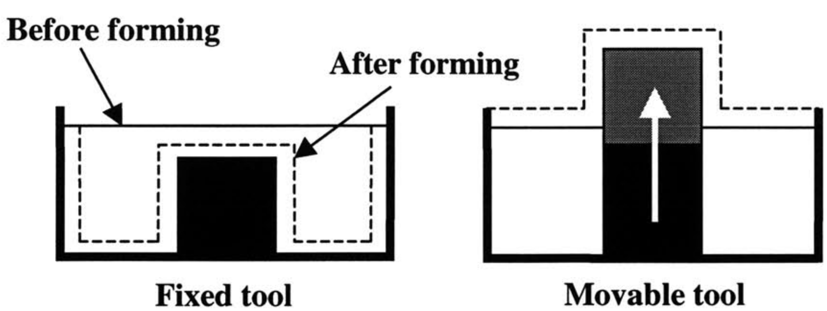


Figure 2-16 Difference in diaphragm extension achieved by raising the tool

This limiting of stretching, of course reduces one of the main features of forming which is the tension generated in the part by extension of the diaphragm. This compromise was made due to the fact that stretching of the diaphragm perpendicular to the part does not provide tension in the part across the wrinkles as they develop parallel to this direction.

2.6 Reinforced Diaphragm Forming

Additional support must be applied to the part by some other method. During testing a breather material was sometimes placed between the diaphragms with the part in order to ensure that the part had full vacuum all along its surface. Initially, it was thought that this might reduce the ability of the diaphragms to transmit tension to the part by introducing a stiff material between the two and thus limiting the stretching of the diaphragms. Comparative testing however, showed no difference between the two set ups.

The addition of this stiff material, when it extended beyond the part, had the effect of stiffening the diaphragm dramatically since it would limit the amount of stretching achievable by the diaphragm. This is the same effect as if the diaphragm itself were made from a very stiff material. What this meant to the process was that the diaphragm could achieve very significant stiffness without significant stretching. This idea was recognized early on as beneficial. There was considerable investigation of it in the early work on diaphragm forming by Professor Gutowski et al. The culmination of this work resulted in U.S. Patent # 5,578,158 by Gutowski et al.

This process was tried with two different materials. The first was fiberglass which, being extremely stiff, produced the greatest amount of tension. The second was a breather material called Airweave® from the Airtech company. Airweave® is a loose felt-like material used as a breather film in vacuum bagging parts. Here it was used to allow for a certain amount of stretching due to the loose fibers pulling straight and then becoming fairly stiff. Once the fibers were straight and aligned with the extension of the diaphragm, it would produce a large amount of tension. The Airweave® was used more successfully than the fiberglass. The process did produce a fair amount of "straightening" of the part whereby the part would slide off the tool in the middle and make the rib flange straight rather than curved.

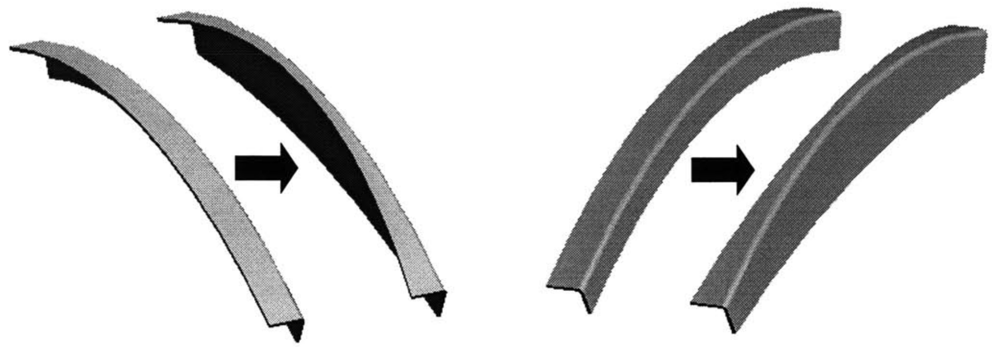


Figure 2-17 Straightening of rib chords

This reduced the wrinkling by reducing the amount of in-plane bending in the part and thus the need for wrinkling. The straightening is due to the transverse tension generated by the stiffened diaphragm pulling across the part first in the middle (highest point) of the tool as the tool was raised out of the table. This effectively provided more pulling in the middle of the part than at the ends. The result of the straightening is that the fibers in the part no longer run parallel to the rib flange as they are supposed to do for maximum mechanical properties in the final part. This meant that the parts would not be acceptable.

This tension also created another issue. Since the stiffness of the added material would limit the maximum extension of the diaphragm, it created an uncertainty of whether the parts would form completely or not. If the diaphragm reached its maximum extension before it had stretched completely down the sides of the tool, the part would not be completely formed. The maximum extension of the diaphragm is reached when the pressure difference across the diaphragms balances the frictional forces of the diaphragm pressing down on the surface of the machine. When the diaphragm meets a corner it will form a radius between the two surfaces. Since this radius will extend a certain amount up each surface before it flattens against it, the part must be out of the radius area or the flange will end up rounded.

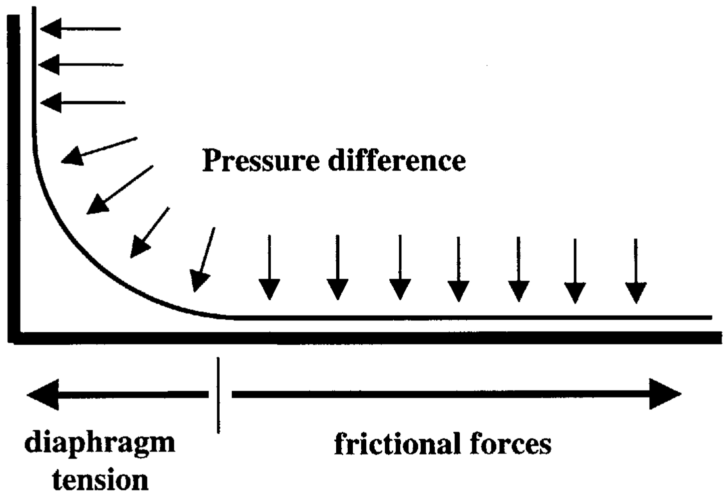


Figure 2-18 Equilibrium force balance during forming

2.7 Moving Surfaces For Complete Forming

The way to ensure that the part has completely formed is to lower the friction between the diaphragm and the machine surfaces. This does allow the part to completely form but it also eliminates the tension created by the reinforcing material since the diaphragm isn't pulling against anything. The added stiffness created by the inclusion of the fiberglass serves no purpose in this situation.

The tension can be maintained however, if the friction were slowly reduced so that the part stayed under tension while forming but there was no equilibrium point at which the forming would stop. This can be achieved by slowly moving the surfaces of the machine which are stopping the diaphragms in toward the tool once the pressure difference has drawn the diaphragms tight. If the surfaces are moved very slowly then they will maintain the tension in the diaphragms during the whole forming process. This movement can be accomplished through very simple means.

Modifications of the forming machine to accomplish this involved attaching a moving sheet of aluminum that spanned the whole "floor" of the machine. This sheet was attached to a series of air cylinders which were mounted horizontally underneath the floor pointing in towards the tool. Once the diaphragm had formed down far enough to draw tight, the cylinders were slowly actuated so that the tension was maintained in the diaphragm while they moved all the way to the tool face.

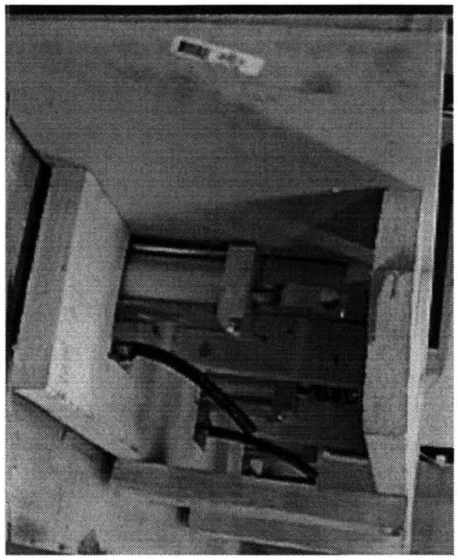


Figure 2-19 Mechanism for moving machine surfaces

Figure 2-20 Forming test before and after surfaces have moved

This technique did maintain a very high degree of tension in the diaphragm during forming. By pressing on the diaphragm throughout the actuation of the cylinders it was easy to feel a dramatic rise in tension in them. Despite this however, the parts formed were only marginally better than those without this process.

2.8 Reinforcing Wires

The problem with this method of introducing a stiffer material in between the diaphragms to raise the tension in them is that the tension is generated parallel to the wrinkles not perpendicular to them. Since there is no stretching in the direction perpendicular to the wrinkles there needs to be some way to transfer the tension that can be developed parallel to the wrinkles to a direction perpendicular to them.

To do this a series of wires were placed along the part, and so perpendicular to the wrinkles, across the full width of the rib flange. The intent was for the fiberglass to draw tight in the diaphragms and thereby hold the wires in place. With stiffness across the wrinkles it was thought that they would not be able to form.

The first approach involved individual wires that were simply placed along the flange. There were 8 stainless steel wires 1/16" in diameter and 36" long placed at .25" intervals across the flange. The results from this were dramatically better than previous tests. The wrinkles formed were much smaller than previously. These first wires did not run the full length of the part though and the ends tended to stick into the part quite a bit causing a fair amount of wrinkling at this point.

To solve this problem the wires were laid out in an offset stack so that every other wire extended to alternating ends of the part. The wires were taped together to make sure that they kept the appropriate spacing and didn't bunch up.

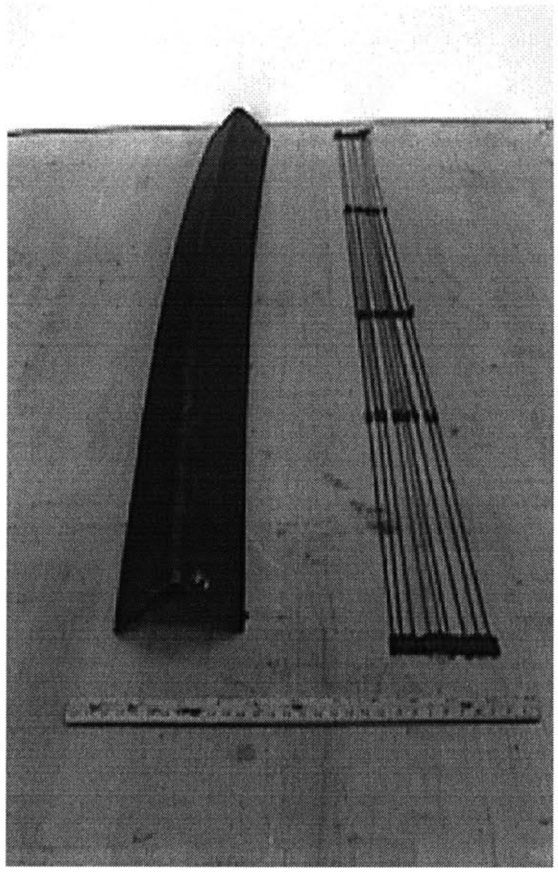


Figure 2-21 Wire reinforcement

The results of this testing follow the previous pattern in that there was much less wrinkling overall and that it was confined to the area around the ends of the wires. To solve this the wires were welded end to end to create wires that could span the full length of the part. This resulted in very little wrinkling and a big improvement over previous tests.

The drawback of the wires however, was that while it suppressed most of the wrinkling it caused significant impressions in the part. These impressions are created since the round wires exert significant pressure on the part. The diaphragm is thick enough that it will not conform tightly to the round wires leaving gaps on either side of the wires. The material is malleable enough when heated that it will flow into these gaps and leave very sharp edge impressions in the formed part. These can be seen even after the part is cured.

2.8.1 Reinforcing Bar

In an effort to reduce these impressions the wires were replaced with an aluminum bar 1/8" thick and 2" wide down the full length of the part. The bar did result in the same dramatic reduction in wrinkling as with the wires and in reduced impressions overall. It did however lead to sharp impressions at the edges of the bar. More importantly though it was unable to form the curve of the part and so led to a similar effect of straightening the part. The middle of the part would form down properly but the ends would not form at all because the bar would not bend in-plane to form the curve. This resulted in bunching of the part at the ends.

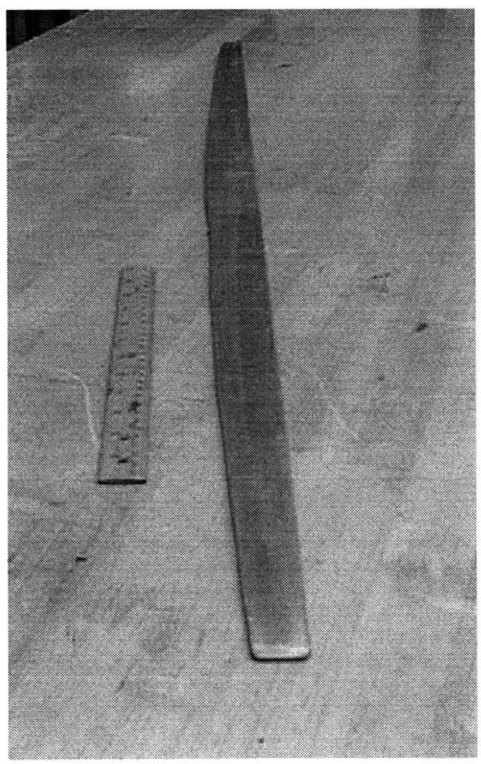


Figure 2-22 Reinforcing bar

Since the bar would not bend in-plane but did help the wrinkle suppression, some way of allowing the part to move independent of the bar would allow it to fully form. To accomplish this fiberglass was placed between the part and the bar in an attempt to lower the friction between the two enough to let the part slide.

This approach did not work very well as the friction between the fiberglass and the bar was still quite high. The edges of the bars also caused problems by digging in to the part is the same way as the individual wires. This prevented the part from sliding perpendicular to the bar. The main problem with this approach however is in the fact that in the areas where there is fiberglass there is no stretching of the diaphragm. This means that there is nothing to pull the part into shape. The fiberglass anchors the diaphragm and the bar anchors the fiberglass so nothing moves unless the bar does.

2.8.2 Wire-Embedded Sheet Reinforcements

Given this relationship between the reinforcement, the part and the diaphragm it is clear that the reinforcement must be made to bend in-plane with the part. Using a series of wires was the answer to this problem. They can be stiff enough to prevent wrinkling but flexible enough to form the overall curvature of the part. When laid next to each other they are able to reinforce the whole flange. The problem of the impressions generated by their use remains however.

To prevent these impressions from forming, the wires were bonded onto a flat sheet of rubber which was laid on the part as reinforcement. The sheet material was usually 1/16" thick silicone rubber bonded on with flexible silicone rubber adhesive. The wires used were all steel in either 1/16" or 1/8" diameter. The wires would stiffen the diaphragm while the smooth surface of the rubber sheet would reduce the impressions of the wires into the part.

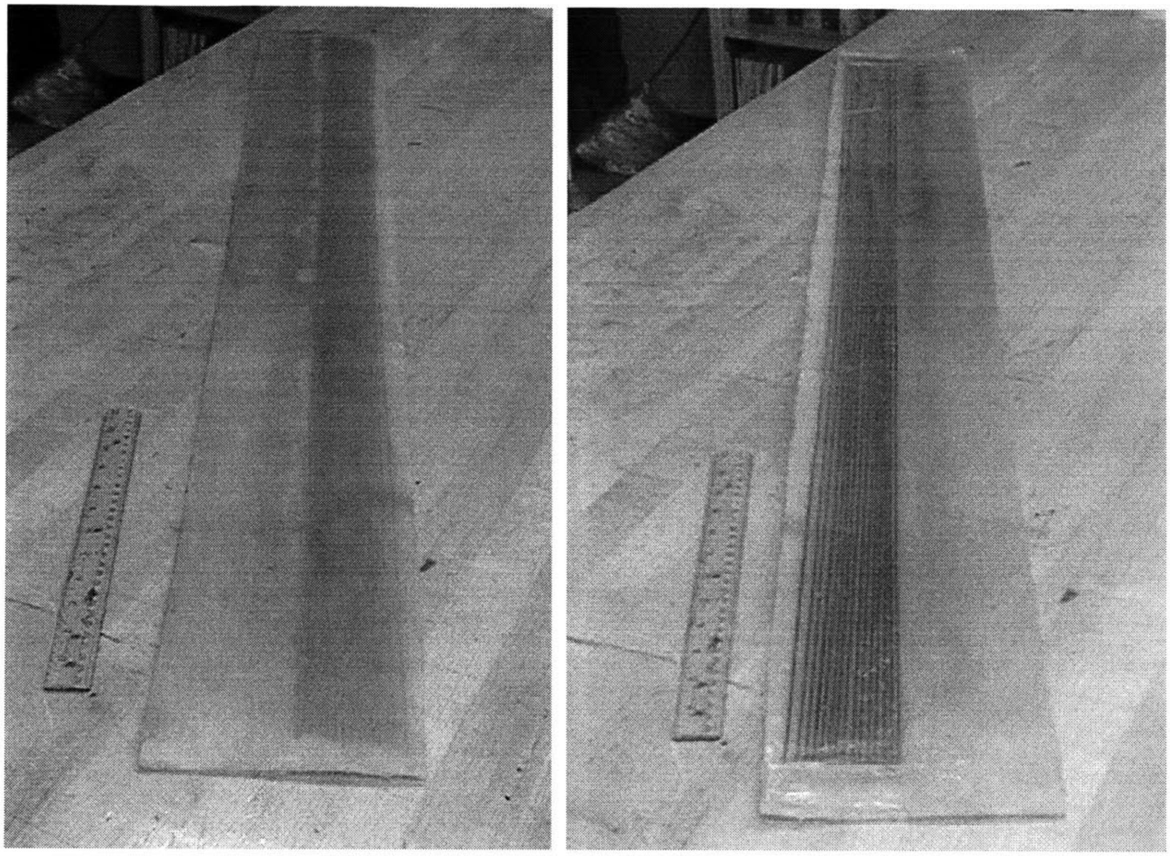


Figure 2-23 Wire-embedded sheet reinforcements

This scheme resulted in full formation of the curve and no impressions in the part but the wrinkles reappeared though less than before. Since the reinforcement could be seen during forming and since no wrinkles appeared in it, they must have then been forming away from the outside reinforcement and into the unsupported bottom diaphragm.

This could have easily been the case as the area of an individual wrinkle is quite small resulting in a small amount of force from the vacuum between the diaphragms. Since the compressive forces are quite large, it is relatively easy for the wrinkles to push the non-reinforced lower diaphragm away from the reinforcements creating enough room to wrinkle.

2.8.3 Double Reinforcements

The solution to this problem is to reinforce the bottom (inside) diaphragm as well. Therefore the part will be completely constrained in-plane and physically unable to buckle. This approach, while clearly one that would solve this problem, is not desirable from the point of view that any additional material between the part and the tool will result in a large step in the part when it forms onto the flat surface of the tool.

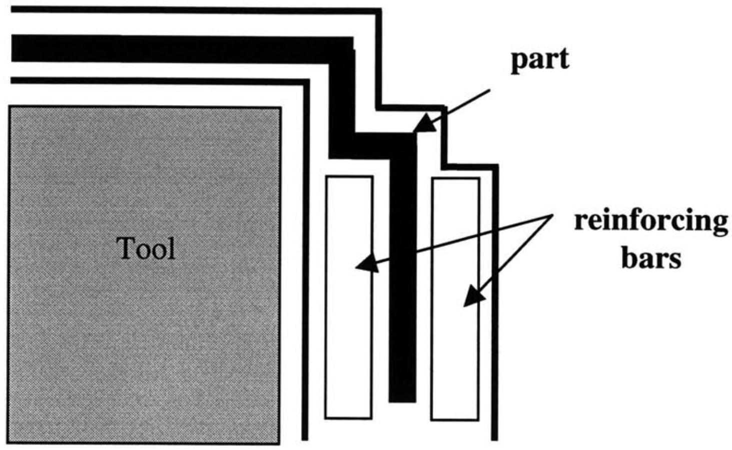


Figure 2-24 Cross section of step created by double reinforcements

The inside reinforcement must be thin enough to prevent large impressions from being formed into the part but stiff enough to prevent the part from wrinkling. Initial testing was done with a straight bar on both the inside and the outside of the part. This lead to the creation of a large step and exacerbated the problems of bunching the parts at the ends as was found with the original single reinforcing bar.

Wires embedded in rubber sheets were then used on both the inside and the outside of the part. This method provided by far the best results in terms of low wrinkling but did not eliminate the problem. The wrinkles that did occur were clearly a much different sort. The "classic" wrinkle from early testing is large and smooth like a wave on the ocean. The wrinkles that now formed looked very much tighter and smaller. Instead of waving far out of plane they tended to look like they had just been jammed together. Clearly the reinforcements fought the tendency of the part to wrinkle out-of-plane but the wrinkles managed to jam together.

This behavior seems only possible if there were a substantial compressive force acting to jam the material together in a tight area. This would tend to occur if there were no mechanism for relieving the compressive forces on the part. The wrinkles therefore were restricted from extending far out of the plane but were not prevented from forming in a much more compact manner. In fact, this type of wrinkle is far worse for the part mechanically as there is no way of smoothing it out where as a larger, more gentle wrinkle would be able to flatten out with subsequent hand work or vacuum bagging.

The results of this testing brought into focus one of the primary features of forming rib chords. The transformation of the part from the flat state into the formed state involves significant deformation of the part in the area of the rib flange. The figure below shows what would result if a straight angle part were bent in one plane only to form the shape of the rib chords. The ends would stay radial with the center of curvature of the bend and there would need be significant shortening of the inside edge of the rib flange. This shortening results in wrinkling in a part the shape of a rib chord: the thin wall buckles under the load.

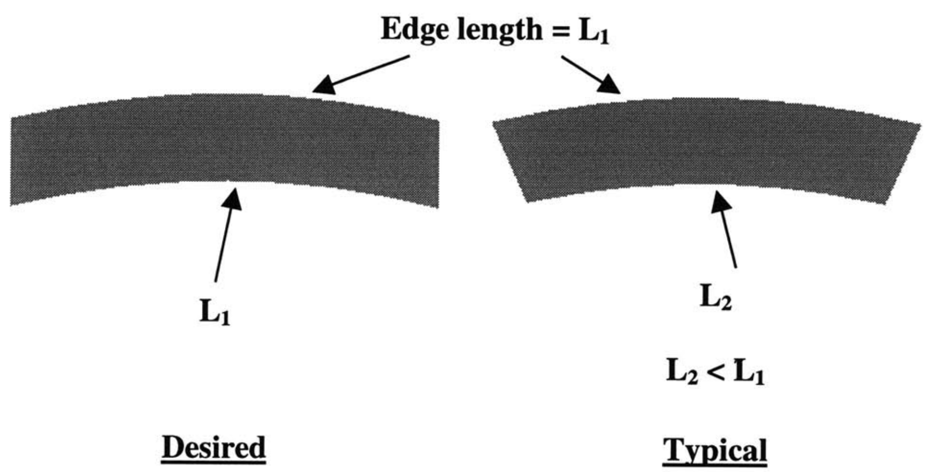


Figure 2-25 Desired and typical forming shape transformation

For a material to go through the shape change necessary in forming rib chords it must be able to bend in plane. Unlike most materials, composites can deform easily in-plane, especially when woven into a fabric. This desired shape change is shown on the left and involves the inside edge of the rib flange not shrinking but rather maintaining its original length. This occurs when the rib flange material spreads out along the length of the part as shown in the figure. If the inside edge of the rib flange does not shorten then there is no need for the material to wrinkle. If the forming process allows the compressive forces to relax then the part will not need to wrinkle. A means of developing this mechanism must be incorporated into the process to get the part to spread out into this state.

Examining the system it appears that friction between the part and the reinforcement or diaphragm will decrease the ability of the part to spread out in this fashion. Since the diaphragm is not stretching the part along its length, the resistance to the spreading must be lowered by reducing the friction between the part and the reinforcements.

2.9 Friction Reduction and Part Mobility

To reduce this friction and allow some movement of the part, a layer of peel ply was added between the part and the reinforcement on either side. Peel ply is a finely woven release cloth that is coated to prevent parts from sticking to the breather or other materials used during vacuum bagging. It can have a low friction surface. This succeeded in reducing wrinkling by allowing for some relaxation of the compressive forces. It also reduced the complete formation of the curve. In these test parts the ends of the parts did not form down as much resulting in some straightening of the part.

This effect is due to a lack of friction between the part and the diaphragms pulling the part into shape. The reinforcements are pulled into the curve easily since they are made of rubber and so are gripped well by the diaphragms. If the part has the ability to move relative to the reinforcements then it will tend to resist forming the rib chord shape. The compressive forces generated on the rib flange will tend to push the ends up over the tool resulting in the straightening effect seen when the middle was pulled down by transverse tension generated by stiffened diaphragms.

To maintain the grip of the diaphragms for pulling the part into shape, tests were conducted with both the outside edge and ends free of peel ply. This in effect created "grip areas" where the diaphragm could pull on the part. There was some improvement in results but not a dramatic reduction in wrinkles.

The peel ply material, despite having a fairly slippery surface, is still a fabric which has two implications. The first is that the part would get very soft at forming temperatures and the weave of the peel ply would imprint into the part dramatically increasing the friction between the two. The second implication is that the material would not stretch at all because it was a woven fabric with fibers running the length of the part. Therefore a non-extensible grip between the part and the reinforcements occurred once again and wrinkling resulted because there was no way to relieve the compressive forces. Even aligning the weave of the peel ply at 45° to the length of the part which makes it compliant in the direction of the reinforcement had no effect on the wrinkling.

Other materials were tested as low friction buffers between the part and the reinforcements but ran into similar problems. No material seemed to allow the part to slip and relieve the compression. The Teflon® sheet that was used as a barrier on the part to prevent contaminating the diaphragms should have been an ideal material. Once heated though the film became soft and lost its low friction characteristics. This is probably due to the weave of the material printing through and pushing into the rubber face of the reinforcements causing it to grip the rubber.

2.10 Bare Metal Reinforcements

Some material had to be found that would allow the part to spread down its length. Since the rubber face of the wires seemed to be causing all the problems the reinforcements were redesigned to incorporate the smooth metal wires and a non-marking surface. This was achieved by using 1/4" square aluminum rods taped side by side. These rods would easily bend with the part and also allow for low friction while minimizing the impressions left in the part.

The results on the wrinkling were dramatic. There was very little wrinkling left at all. The little that did occur was due to the edges of the tape where the rods had been wrapped together. When the rods were taped just on the back side, so not against the part, the results were excellent: no wrinkles formed down the length. These results were duplicated many tests over which proved the mechanisms involved in the process. The double reinforcements prevented out of plane buckling while the bare metal surfaces allowed the compressive forces to be reduced by the part spreading down the length.

The surface left on the part was still left with some impressions along the length. The parts also had a large step impressed into them by virtue of the thick rods between the part and the tool on the inside of the diaphragms.

What created the impressions on the outer surface was that the square rods have a certain radius on the corners. When these radii match up between two adjacent parts there is quite a sharp feature created into which the part can, and does, flow.

The impressions created on the inside of the part result from the same phenomenon and the simple fact that they are between the part and the tool and so create a step in the part by simply being there. To reduce the step on the inside, the inner rods were changed to 1/8" which obviously reduced the step significantly. To lower the impressions formed on the outside of the part the square rods were bonded onto the back of a series of flat wires 1/8" by .020". This was to avoid the large gaps between the rods since the flat wire had much smaller corner radii and would leave fewer impressions in the part.

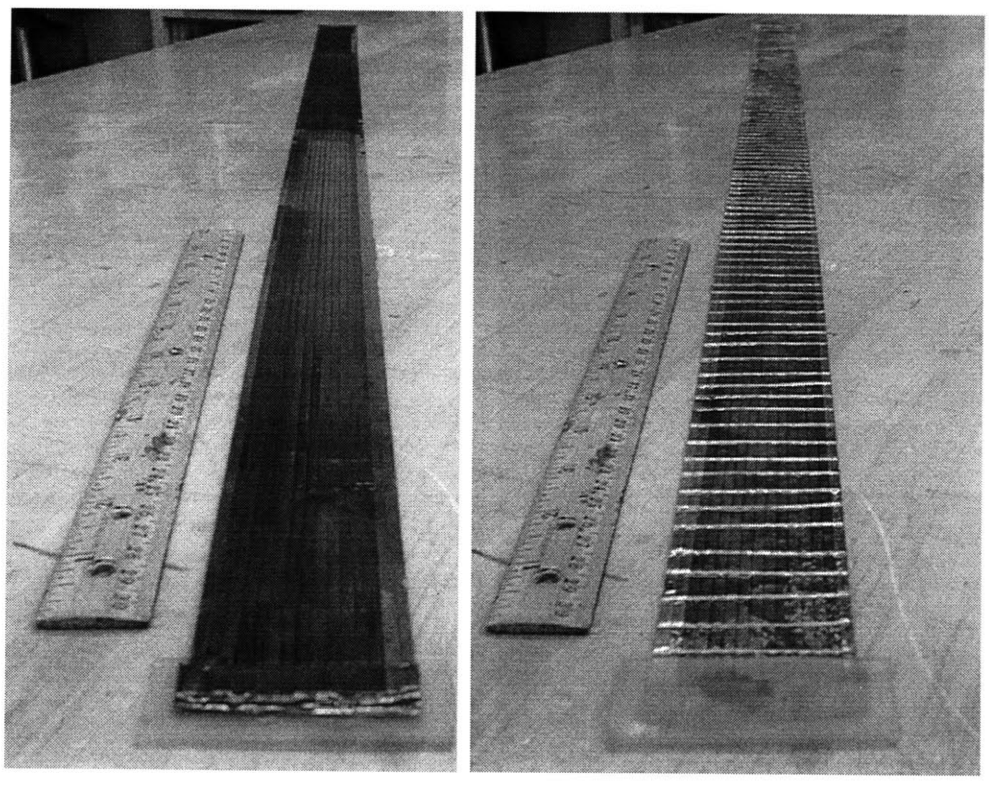


Figure 2-26 Flat wire reinforcements

The wires themselves were very flexible in-plane as they were only an 1/8" wide. However when the 1/4" aluminum square rods were bonded onto the backs of them there was a significant drop in the flexibility of the combination. This was caused by the fact that the rods could not slip relative to each other to produce the in-plane flexibility needed. They started to act more like a solid block of material because there was no stretching possible in the very thin space between rods. So while the performance of the reinforcement was very good at lowering impressions, the flexibility was too low to form the part adequately. This problem could be mitigated though through careful construction of the reinforcements. If enough space is left between the adjacent bars then they are able to slip enough to form the gross curvature of the part.

2.11 Sheet Metal Reinforcements

The inside reinforcements still cause a problem in that they create too much of a step in the part. To prevent the formation of the step and also the impressioning of the part, the inside bars were replaced with a series of waterjet cut stainless steel sheet metal pieces .030" thick. The pieces were slanted diamond shapes such that they would not have any edges that ran parallel to the wrinkles to avoid initiating them. The whole series of pieces would be able to slide next to each other to provide the effect of bending in-plane so that the curve could be completely formed without having to bend the metal itself.

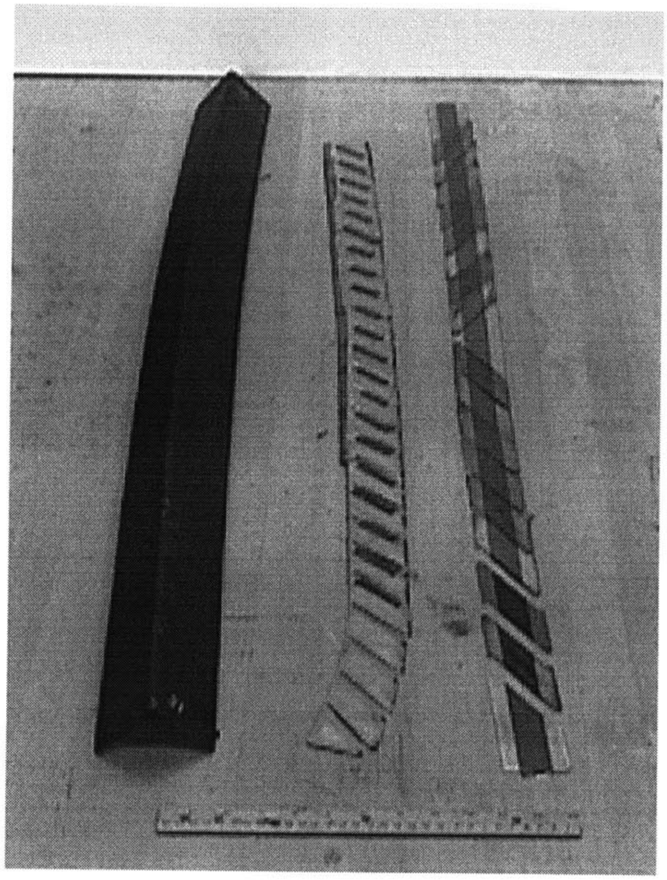


Figure 2-27 Two versions of the sheet metal reinforcements

While the sheet metal was thick enough to prevent out-of-plane wrinkling and thin enough to prevent impressions from forming, the edges of the sheet metal tended to create areas of in-plane wrinkling as the rib flange bent in-plane and twisted the material.

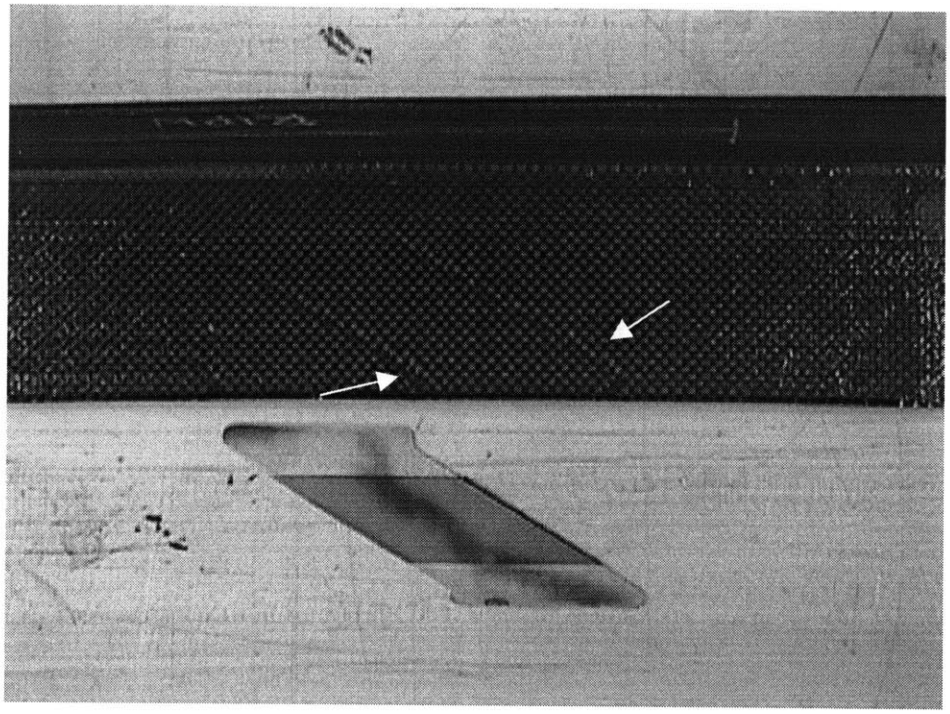


Figure 2-28 In-plane wrinkling caused by edge of sheet metal reinforcement

The sheet metal edges were covered in very thin .003" shim stock to prevent them from twisting the material. This worked very well except that relative bending between two adjacent pieces was not uniform causing areas where there was considerable bending between two pieces resulting in a high level of distortion in the part at that point.

To fight this effect the sheet metal on the inside was replaced by flat wires taped side to side. These had all the necessary flexibility in-plane and stiffness out of plane to provide wrinkle free parts and produced excellent results. They were also thin enough to prevent any significant step from forming on the inside of the part.

Since the parts were being heated to forming temperatures prior to the forming cycle, the outer reinforcement (which sits on top of the rib flange of the part) causes a large resistance to heat transfer. The part heating time is controlled mainly by the heat conduction through the outer reinforcement. Since the material cannot be exposed to temperatures over 200 F and the forming temperature can be very near that, (160-180 F) the heating system is required to be closely controlled. On the one hand a high gradient is needed to conduct quickly through the 1/4" rods of the reinforcement, and on the other there is a need for close control of the maximum temperature. Tests were conducted to see if thin, flat wires on both sides of the part might be able to reinforce the part without unduly slowing down the heat cycle.

About mid way through forming the part buckled over its length into very large wrinkles, about 6" in "wavelength". These were caused by gross buckling of the part under the compressive forces of forming. A compromise has to be made between stabilizing the part against the compression and enabling a fast heat cycle.

2.12 Part Transfer

A major issue in the application of double diaphragm forming to a production environment is the curing step. The part cannot be cured while in the forming machine and so must be removed and placed on a separate curing tool. This is because the diaphragm between the part and the tool will in general have a non-uniform thickness. It will stretch non-uniformly, and therefore thin in different spots. This results in low fidelity to the tool geometry in the final cured part. Even if a tool were made to try and account for the diaphragms thinning, it is not always consistent so the tool may match at some times and not at others.

Another complication is that to achieve high resin-to-fiber ratios and prevent porosity in the parts the cure step is performed at pressures significantly higher than atmospheric. This means that the tool must be in an autoclave for the cure. This is a pressurized oven that can apply heat and high ambient pressure to the part. Putting a forming machine into the autoclave would complicate the machine design immensely. It would also mean very inefficient utilization of the autoclave. For this reason the parts must be removed from the forming machine and placed on a cure tool for curing.

Getting the parts out of the machine involves inflating the space between the diaphragms while keeping the vacuum on in the tool chamber. This must be done to prevent the bottom diaphragm from relaxing and distorting the part. Once the top diaphragm is off, the part is exposed and can be removed. There are two main complications to this process. First, there can be a significant "grip" between the part and the diaphragm causing the part to stick to the diaphragm. This can be overcome through the use of a non-porous material that does not allow the epoxy from the part to stick to the diaphragm. Tests were performed using FEP Teflon® sheet both .001" and .002" thick as a release material.

The .001" material tended to tear at the edges during extension of the diaphragm. The .002" thick material was stronger and avoided this problem and is the preferable material. Both materials were able to dramatically reduce the tendency of the parts to stick to the diaphragms so that they could be lifted off easily.

2.12.1 Spring Back

The second and much more important issue involved in transferring the parts successfully is that of spring back. Since the epoxy is somewhat elastic in nature some part of its distortion, which is necessary for the fibers to move and form new shapes, will also be elastic. Therefore the parts exhibit a tendency to spring back from the fully formed shape after the top diaphragm is released and the parts are no longer fully constrained. A little bit of spring back can be tolerated as the part will conform to the shape of the cure tool once the part is pulled onto the cure tool by the vacuum bag.

The vacuum bag is a thin nylon sheet that is placed over the part and its edges sealed to the tool. Vacuum is drawn inside the bag which applies the ambient pressure to the part to compress the plies together. When this is done a small amount of shape difference between the part and the tool can be overcome as the bag forms the part to the tool, if there is too much of a mismatch between the part and the tool then the part will deform.

There are two ways the spring back can occur and so two ways deformation will occur when the mismatch between part and tool is too great. The first mode is when the angle of the cross section of the part is too large. If vacuum bagged in this condition this results in the two flanges pinching together along the top radius without touching the tool.

The other mode is spring back of the main curvature of the part. This results in the part being straighter than desired. If this occurs too much then during vacuum bagging the part will be bent over its length and the part will wrinkle.

2.12.2 Matched-Tool Vacuum Transfer

The first method developed for part transfer to the cure tool utilized a vacuum system. A rigid transporter was made to the same shape as the formed part and a vacuum seal was placed around the periphery. The vacuum would hold the part up against the rigid tool which would hold the part in the correct shape.

This system had significant problems. The first was difficulty in getting a consistent seal to the part. For the vacuum to hold well the seal had to be very good. If one part of the seal leaked the vacuum would be lost and the part would drop. This is exacerbated by the low flow vacuum system used on the shop floor. If the system is low flow then even a small leak will let in enough air to overcome the rate at which it can be removed by the vacuum system raising the pressure inside. Only a very high flow system would be able to make up for small leaks and gaps in the seal.

Secondly, the use of a rigid transporter requires the use of a dedicated tool for each part. This doubles the number of tools used by the process which complicates the system.

2.12.3 Magnetic Transfer

The transporter was then changed to use a magnetic system. This again incorporated a rigid tool but now had strong magnets placed around the edges. The part was formed with metal washers placed around its edges that the magnets on the transfer tool would attract. This system worked well enough but again required a dedicated shape to support the part. Also, while the magnets would hold at the edge there was nothing to prevent the part from "opening up" or opening the interior angle by the parts sliding along the face of the tool.

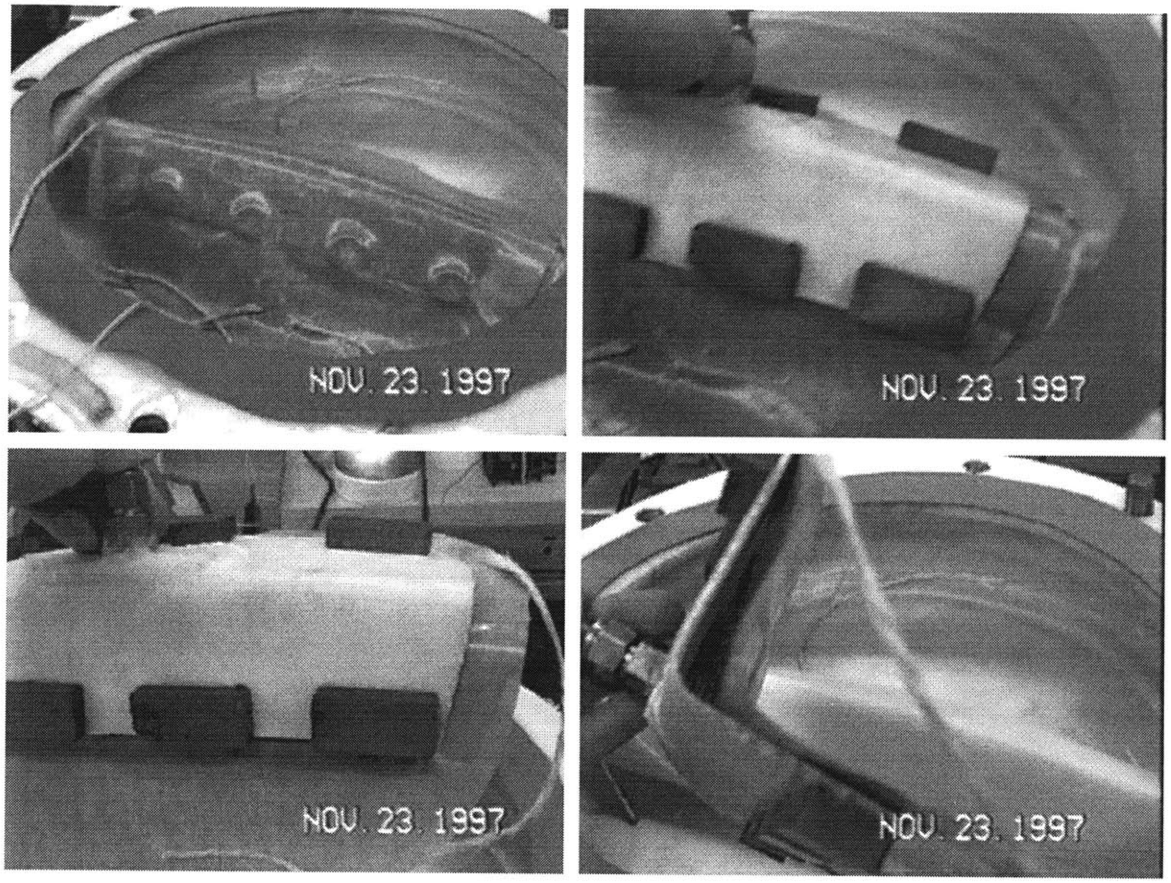


Figure 2-29 Rigid magnetic transporter and part formed with metal washers

The main disadvantage of the process was the need to closely match the shape of the transfer tool to that of the part as the magnets had a limited air gap across which they could exert a useful force.

Further refinement of the process limited this air gap by using a second set of magnets on the part that had been bonded onto half of a square of sheet metal. The magnets would then not be under the part but would be butted up against the outside edge and the free half of the sheet metal would slip under the part as "fingers" to lift the part. This enabled the magnets to touch each other on the periphery and maintain good contact for maximum strength.

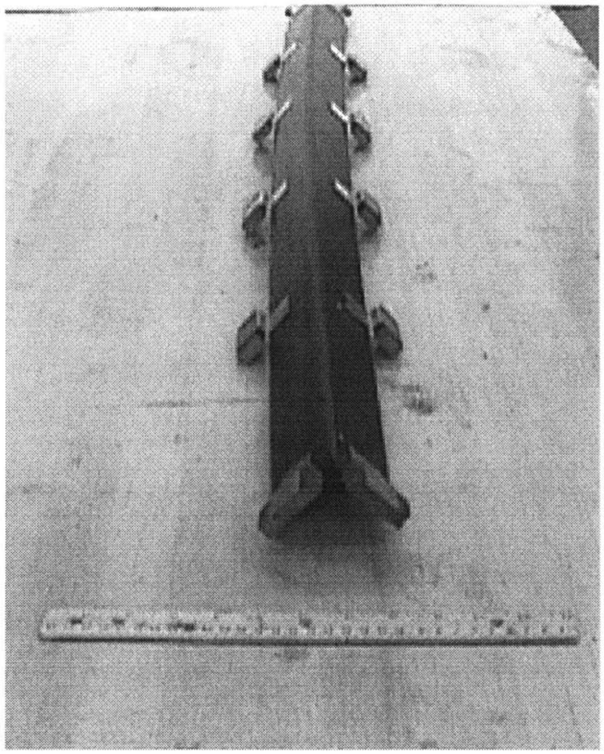


Figure 2-30 Full size magnetic transporter and magnetic "fingers"

This system however has problems during the forming process. Since the magnets were beyond the edge of the part they touched both the inside and outside diaphragms. Differences in extension of the two diaphragms caused the magnets to "tumble". Since the top diaphragm extended further, the top of the magnet was moved relative to the bottom. This caused the magnet to rotate and the sheet metal finger to push into the part causing significant unwanted distortion.

The process was changed into adding the fingers after the part had been formed. This successfully transferred parts but added unwanted steps and complications to the process. It also did not counter the problem of maintaining the shape of the part well enough as the part was able to move due to slippage of the magnets across their faces.

2.12.4 Vacuum Cup Transfer

The magnetic approach was abandoned and a new version of the vacuum system was used. This system utilized individual vacuum cups rather than a whole vacuum surface. This eliminated the problems of sealing the large surface. Also since the individual cups were very pliable they could conform easily to a rough surface. This system also reduced the ability of the part to spring open as well by supporting it at definite places in space. Since the cups could not slip along the surface of the part and the transfer tool restricted the ability of the cups to move relative to each other, the part could be held successfully in shape during transfer.

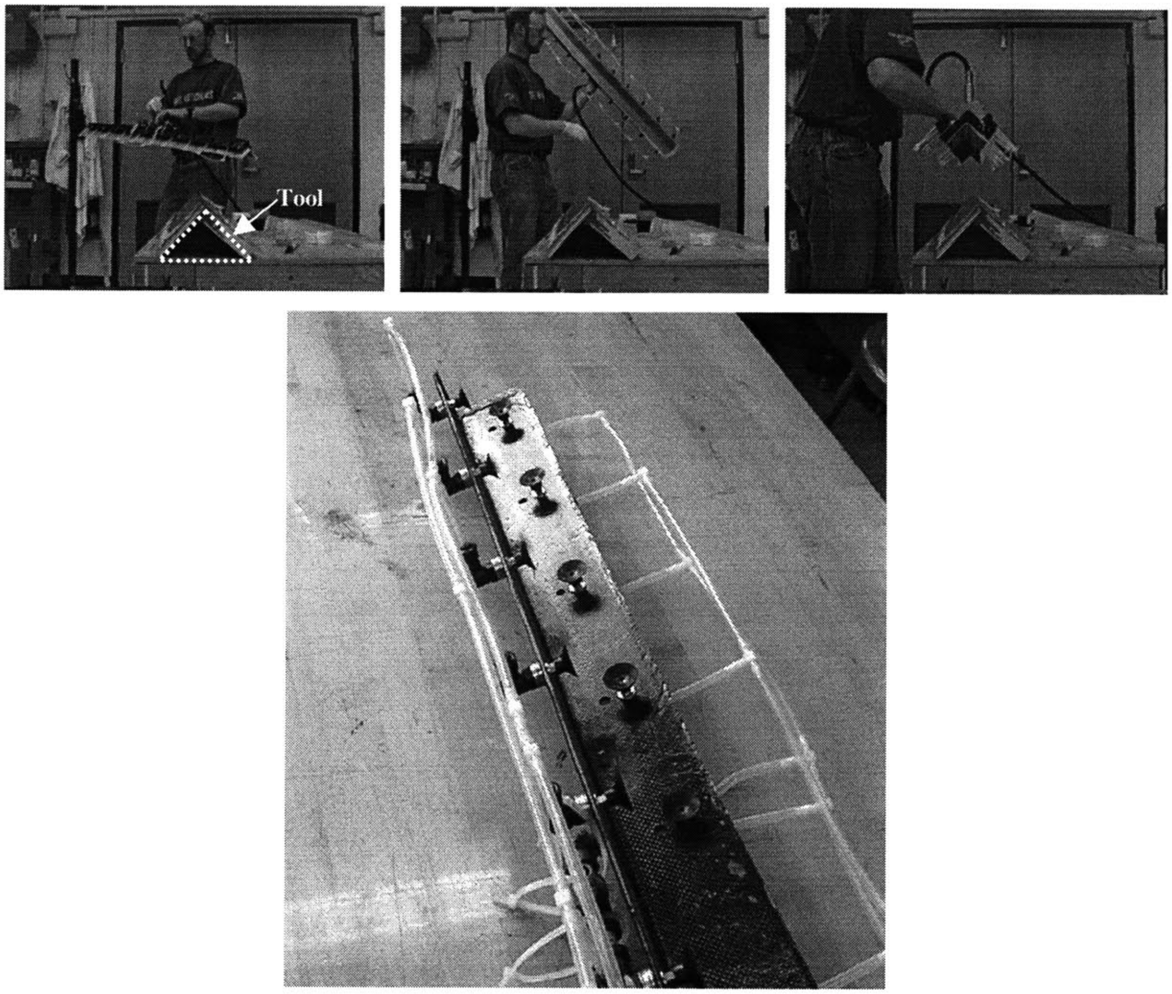


Figure 2-31 Full size transporter with vacuum cups

The only limitation of the process is that its effectiveness was reduced by porosity in the part. The strength of the vacuum cups was tested by pulling on parts of varying thickness'. These tests showed that the greater the number of plies, the better the cups would hold. This is due to the overall porosity of the fabric material since it included many weave holes. Composite tape material would likely fair much better due to the lack of weave holes. This problem in fabric can be overcome by using a nonporous material on the outside of the part and not allowing air to pull through the layup.

Since the part was formed with non-porous FEP film on both sides already, overcoming the porosity in the part was not an issue. Also, the pull tests were performed on unformed and unconsolidated parts which would have the highest level of porosity. A part that had been formed would likely be less porous due to the heating and compaction of the diaphragms.

The use of small individual cups meant that the transporter no longer had to be a complete rigid part: the cups themselves could be relocated to suit each part's curvature. Since the cups worked very well in holding the part all that was needed was to create an adaptable transporter to match all the shapes and overcome the need to have so many dedicated tools.

Adaptability was achieved by using the fact that the rib flange of all the parts is planar. Therefore all that is needed is for the cups on the stringer flange to be varied in height and tangent angle of the curve at each point. A system of this type could be set on the cure tool, which would be nearby anyway, and locked in position by a series of joints.

2.12.4.1 Segmented Adaptable Transporter

The first design for an adaptable transporter used individual segments to make up the full length of the part. These segments were joined using an air-locking rotary piston. This piston had two ends, one that held an arm with the vacuum cups out at the correct angle, and the other which connected to the next segment setting the overall curve. When unlocked the segments were infinitely adaptable but when the air was on the pistons would all lock. The locking was achieved through the use of either high friction material on the inside of the piston or by face gears that would intermesh.

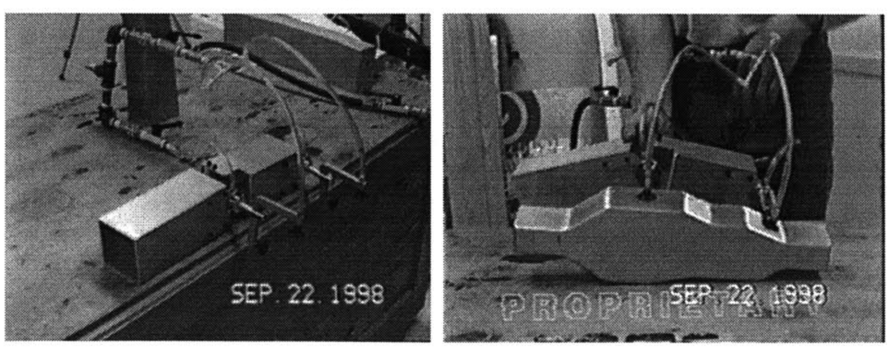


Figure 2-32 Air-locking rotary piston with two segments

This segmented approach created problems with weight and stability. Since each joint had to be mounted to the next, the system was heavy due to all the connections. It was also quite clumsy to use. This could be mitigated by restricting the range of movement of the segments to just enough to match all the parts necessary.

2.12.4.2 Single Piece Adaptable Transporter

A better system used a single thin-walled composite beam that had a series of actuated arms mounted to it. Since the height and angle of each arm relative to the others was all that was needed, the actuators could be simplified. This was done by mounting the arms to a gear that slid in a track. The gear could slide up and down enough to set the height and rotate just enough to match the part angle at each location. The gear would be held in place by means of two arms with gear racks on them. They could be closed by pulling on a linkage that brought the tops together locking the gear in both height and angle. A series of these actuators could be brought together by combining the linkages to operate together using only one air cylinder.

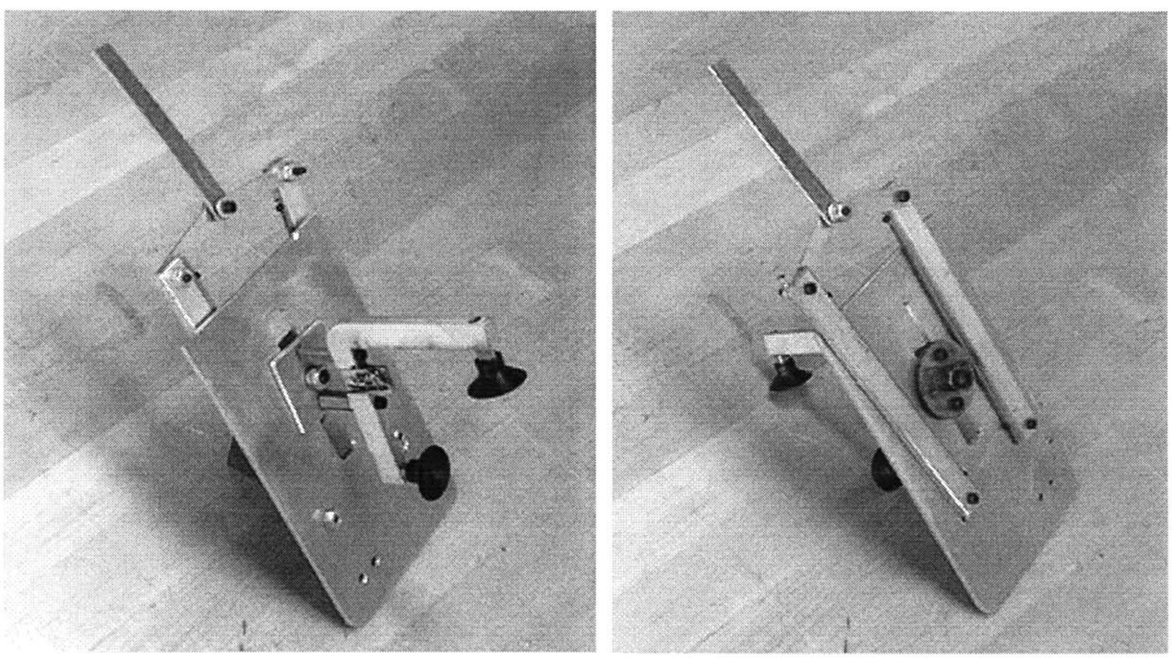


Figure 2-33 Gear and track actuator locked and unlocked

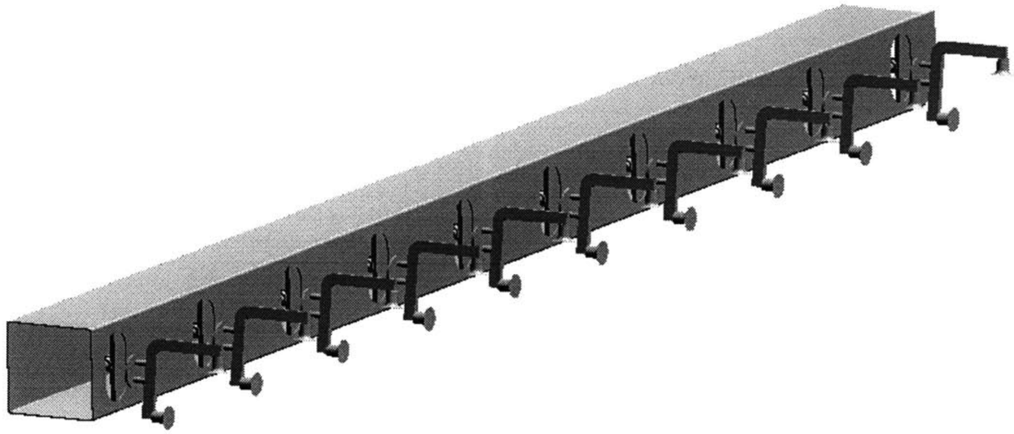


Figure 2-34 Complete transporter with gear and track actuators

2.12.5 Active Cooling Transfer

By far the most useful system did not use a reinforcing structure at all. Instead it relied on the part to support itself. This method was based on the fact that the viscosity of the epoxy in most industrial prepregs varies inversely with temperature. Thus dropping the temperature increases the viscosity and vice versa. This is why most parts are formed at elevated temperatures: to allow for the epoxy to flow and allow for fibers and plies to move relative to each other. Therefore if no movement is wanted, as in the case of transfer, the temperature should be reduced. Active cooling to or below room temperature will make the part much stiffer and so less likely to deform.

The tendency of a part to spring back is greatly affected by cooling but it must be done while the part is in the fully formed state. To accomplish this, cooling channels were created within the tool itself so that once the part has been fully formed onto the tool, it begins to cool down. Once the part has been cooled sufficiently, usually to about 60-70 F, it can be handled without deforming the shape significantly. If the part was not cooled and the diaphragm was opened at an elevated temperature it would be too malleable to maintain its shape during transfer. With cooling the part is stiff enough that it can be picked up and moved by hand. This is ideal as it eliminates the need for any additional parts of equipment on the production floor. For parts larger than the rib chords though, a transporter system will be necessary as a person will not be able to move them alone. Also the larger and heavier the part, the more it will need to have a reinforced transporter that can move it without deformation due to its own weight.

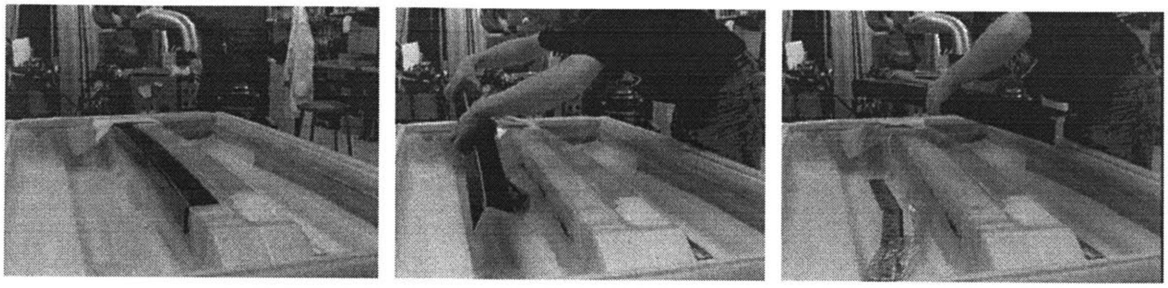


Figure 2-35 Hand transfer of formed rib chord

2.13 Effects of Heating On Spring Back

A further influence on the amount of spring back exhibited by the part is the degree of heating prior to forming. Since the heating of the epoxy reduces the viscosity it enables movement in the laminate to take place. This takes place in the form of fibers moving within the fabric of one ply or in one ply moving relative to the others. Since the part starts out flat and is bent into an angle, there needs to be relative movement between the plies. This is to make up for the longer path around the outside of the bend than on the inside. This means that the ends of the outer plies do not extend as far along the flange as the rest of the plies.

If the epoxy does not flow and allow the plies to slip relative to one another the part cannot form the bend completely. Likewise, if the relative movement of the epoxy is elastic in nature the part will only be fully formed when it is being held in place by the diaphragms. As soon as the part is no longer held in place, it will spring back elastically to the relaxed position. This behavior is similar to bending metal in that the deformation has both elastic and plastic components.

2.13.1 Resin Characteristics

Epoxies for different applications have different viscosities and flow characteristics. In particular, resins for structures that incorporate honeycomb cores are made with a more elastic, and hence less flowable, resin to avoid the problem of the resin filling in the core cells. Resins used in laminated structures tend to be higher flow, lower viscosity kinds to avoid the problems of porosity in the final parts.

The resin in the fabric used for the rib chords is designed for core structures. The reason it is used in this application is that the fabric weave of the fibers is more easily shaped by hand to the double curvature of the rib chords.

With this framework in mind, the way to achieve actual relative movement between plies is to get the viscosity as low as possible through the application of heat. This reduces the amount of elastic residual stress in the part and hence the potential for spring back. Once the part is formed however, the resin should exhibit high viscosity to avoid spring back and deformation during transfer. The part is therefore cooled to increase the viscosity and reduce the ability of the part to spring back.

Test results have followed this behavior. The early tests were conducted with preheat temperatures in the 170-180 F range and with no active cooling of the parts. When the parts were removed at a temperature of 80-90 F they sprung back by about 20°.

When the parts were heated to the same temperature and then actively cooled to the 60-70 F region the parts exhibited spring back of only 5° or so. The parts also exhibited sufficient rigidity at this temperature so that they could be handled without undue deformation.

When the preheat temperature was decreased to 130 F the parts continued to form without wrinkles but two other effects were observed. One is that the spring back increased significantly so that parts were displaying up to 45° of spring back when cooling to 70 F. Even lower temperature tests were conducted at 100 F and the results were even more dramatic. The parts were formed without wrinkles but the spring back was so severe as to require significant hand work to reform it to the tool.

Spring back then seems to be a combination of preheating the resin to allow for net resin flow during forming and then cooling to prevent residual elastic spring back from deforming the part during transfer.

2.13.2 Mid-Flange Wrinkles and Overforming

While these spring back effects on the gross shape of the part can be largely overcome by the vacuum bag pulling the part back into the shape of the tool, the results were inconsistent in terms of wrinkling. The formed parts would come out of the machine without any wrinkling but after cure there were occasional wrinkles that appeared on the rib flange. The wrinkles tended to be about 1/3 of the width of the flange and only appear in the middle of the flange instead of starting at one edge. They were of a very different sort than the normal wrinkling. It is thought that they occur when the unsupported reforming of the part by the vacuum bag "bunched" the material up on the flange.

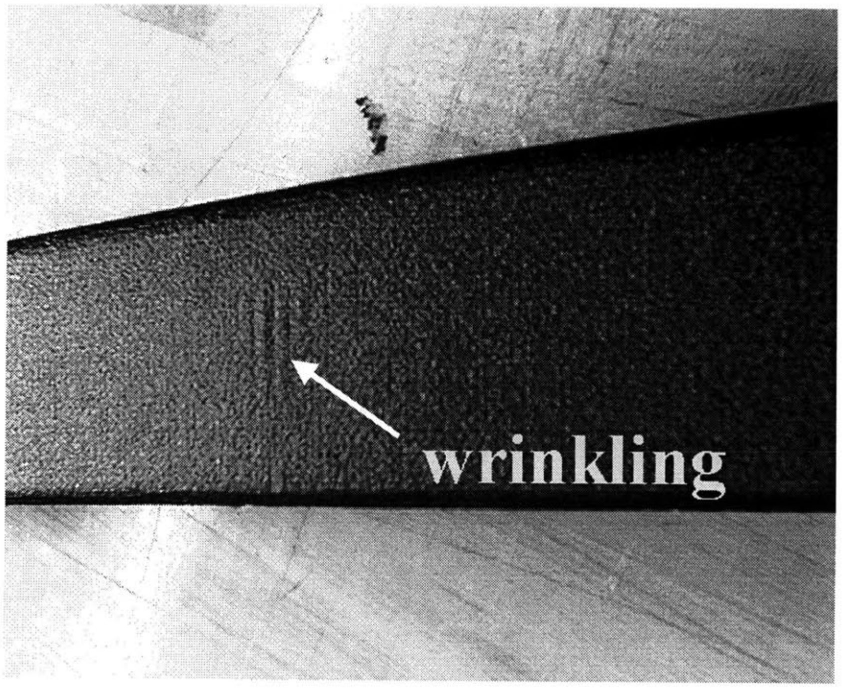


Figure 2-36 Mid-flange wrinkling

These wrinkles can be overcome through the use of a technique called overforming. This technique was developed to allow for the elastic spring back of parts so that the relaxed part matched the shape of the tool more closely. The parts would be formed to an included angle of 85° rather than 90° . This meant that the part would fit the tool very closely and the vacuum bag would not have to reform the part at all. Since the adoption of overforming there have been no recurrences of mid-flange wrinkles.

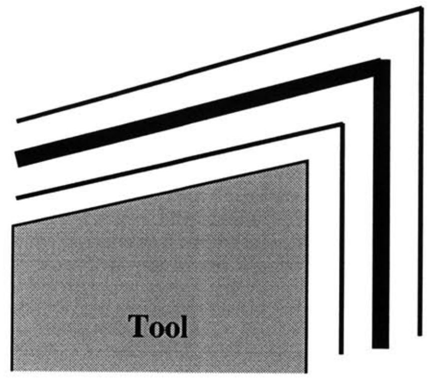


Figure 2-37 Overforming of a rib chord

2.13.3 Tool Side Surface Finish

The other heating effect observed is that there was significant resin starvation on the tool side surface of the part when it was not heated in that area prior to forming. Qualitative comparison of the formed but uncured parts at the two different forming temperatures showed that the parts that had been heated to an elevated temperature showed a glassy inside surface. Parts that had been raised only to the lower 130 F temperature had a surface similar to the unformed prepreg where the weave of the fabric was the predominant surface feature.

This trend also appeared during trials of a heating system that relied purely on heaters underneath the part. The heating system used only flexible heaters attached to the supporting bar that would hold the rib flange up during loading and heating of the part. Since there was no overhead heater and the other half of the part (the stringer flange) would be supported by the tool it would not get heated. Further, any heat that did conduct along the part would be lost to the tool as it is cooled continuously. This resulted in the rib flange being heated while the stringer flange stayed cold. The final cured parts from these test exhibited significantly more surface resin starvation on the stringer flange than the rib flange. Suggesting that the preheating of the flanges had the effect of reducing surface resin starvation.

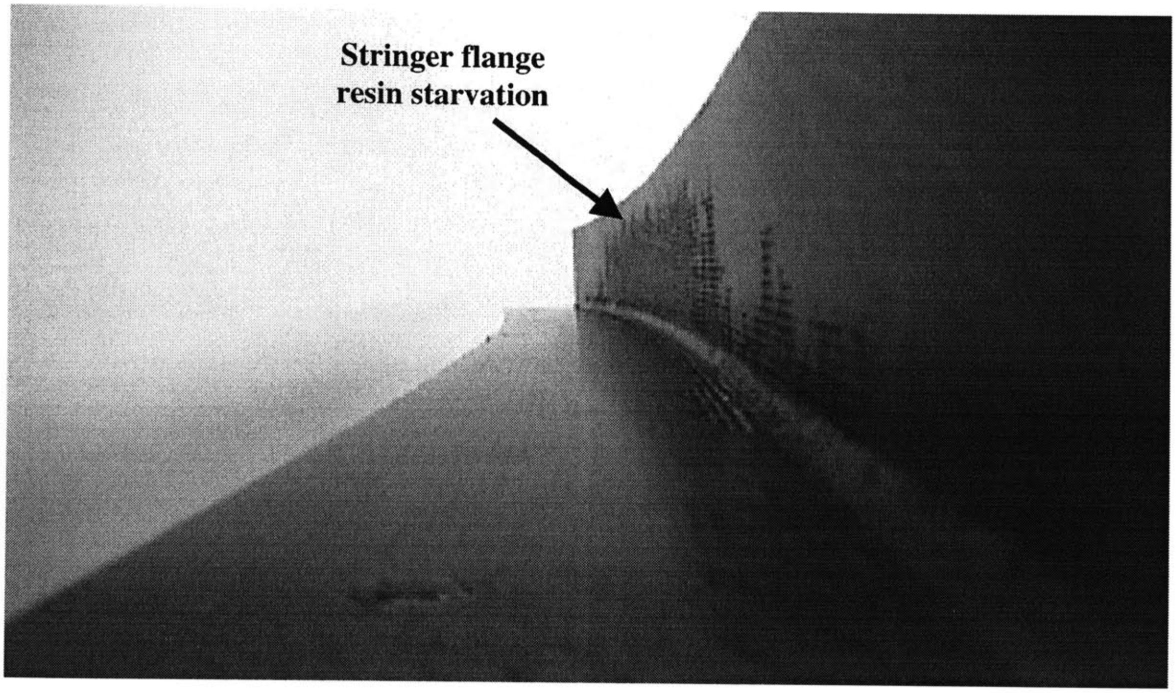


Figure 2-38 Unheated stringer flange exhibiting resin starvation

This phenomenon fits the viscosity behavior model of the resin well. It seems that the preheating has the effect of allowing the excess resin to flow into the gaps created by the weave. This would explain the glassy surface exhibited by the preheated but uncured parts. Similarly, the parts that were not preheated may have maintained their rough surfaces because no resin was able to flow from the prepreg to fill in the surface.

Chapter 3

3 Production Machine Design

There are many techniques for forming composite parts and each is generally suited to the geometry of a certain part. Where many parts can be grouped in families there will be certain characteristics that drive the design of the forming machine for those parts. The goal of developing a design for a production style machine then involves a blending of the needs of the forming process and part with the needs of the worker and production system.

In developing a design scheme for the 777 rib chord forming machine there were two sets of considerations. The first is process related, including part geometry, production system requirements and facility compatibility. The other is operator related, including ease of use, ergonomic design and mistake proofing. Since adoption of the forming process creates both time savings and avoids the repetitive motion injuries associated with hand layup, creating an ergonomically correct machine was a top priority.

3.1 Tool Locations

The first step in developing a design scheme was to decide on the number of tool locations. In the traditional method of forming, the tool is located in the middle of the machine with the excess diaphragm material for forming being between the tool and the machine sides. This scheme is the natural one to start with but introduces a potential for misalignment between the preform and the tool. This arises from the fact that the lower diaphragm is between the preform and the tool so that there is no direct connection between the two making alignment difficult. Further, if the diaphragm material is not transparent, as is the case for most of the high strength materials, there is no way to see the tool. Lastly, since the diaphragm is heated and stretched with every forming cycle it develops a large amount of permanent extension. This results in there being a "sag" in the diaphragm when it is not under vacuum. This sag can allow the diaphragm to pull to one side at the beginning of forming which will pull the preform out of alignment with the tool.

To avoid these problems tests were run with the tool stations on the sides of the machine to create a fixed reference for alignment. Since the distance from the side of the machine to the tool is fixed then being able to reference the preform to the side of the machine allows for indirect but reliable alignment of the preform to the tool.

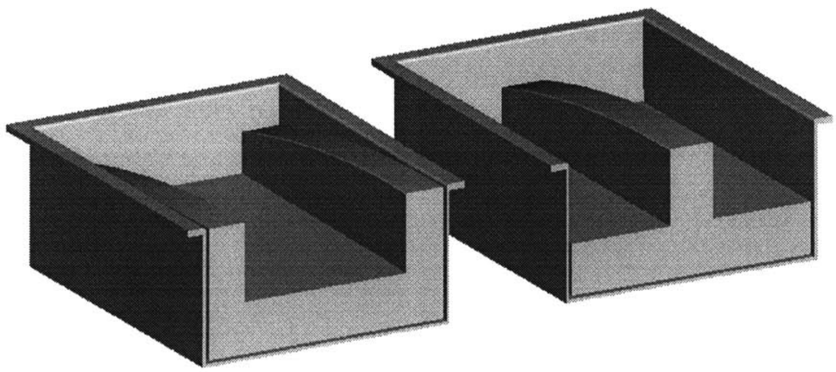


Figure 3-1 Cross sections of side and center tool arrangements

From the side placement arrangement it's easy to see the potential of combining both systems and adding an additional tool in the center and creating a four-station machine.

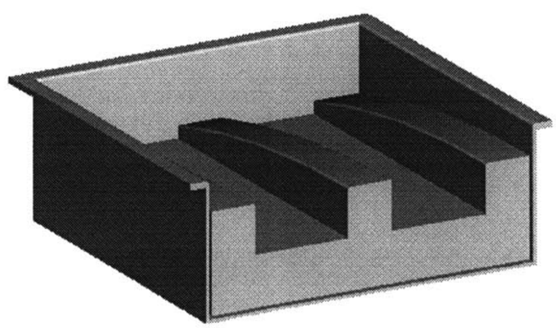


Figure 3-2 Four-station tool placement scheme

A four-station machine has obvious attractions from a production rate standpoint. Here the machine cycle time could be spread over four parts instead of just two lowering the production time per part. However, the spacing between the tool stations must be such that the diaphragm can extend deep enough to fully form the part. For a given material there is only a certain amount that it will strain given a certain pressure difference. This results in a certain radius of curvature at the intersection of the floor and the tool.

Therefore for a given height of the tool, and a given pressure difference, there needs to be a certain amount of stretching to make sure the diaphragm forms beyond the part. Some amount of the diaphragm must extend beyond the part in order to insure that the part has been fully formed. If the radius of the diaphragm extends into the region of the part, the preform will end up with a curled edge which causes problems later on for transfer.

The only region of the diaphragm that is free to extend is between the tool stations where it is not sandwiching a stiffer material like the preform. Thus the spacing in between the tool stations must be such that the amount of diaphragm not in contact with the preforms allows for enough extension to lower the final radius of the part beyond the preform.

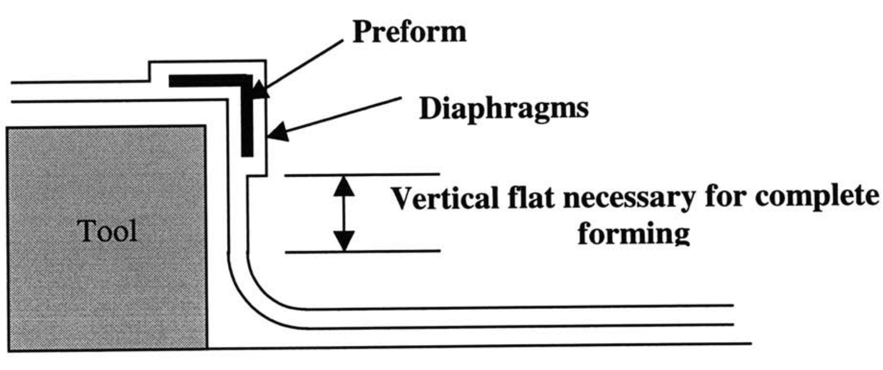


Figure 3-3 Effect of diaphragm radius on tool height

The impact of this interaction on the overall machine design is readily apparent. Given a certain diaphragm material there will be a given width that the machine must be in order to provide sufficient inter-tool spacing. The ergonomic impact of this is that the central tool base will be in the middle of the machine and require that the operator lean far out to place and remove parts. This is very undesirable since shorter operators will have to lean far into the machine to access the parts putting strain on their lower back.

For these ergonomic reasons the final design was limited to two stations one along each side of the machine. This decision also eliminates the problems of maintaining accurate alignment between the preform and the tool. Further it allows for easily accommodating production volume. The table below is a comparison of year 2000 production support levels and the time needed based on this machine. Following is an estimate of the machine cycle time based on a breakdown of the time to make one part with the machine. Since the production flow and process specifications have not yet been written up the numbers used were developed by myself and based on considerable lab experience.

3.1.1 Machine Cycle Time and Production Rate

NOTE: Times estimated based on lab tests Machine steps	Duration (minutes)
Load tooling	5
Lay up two parts	30
Raise table and position lower diaphragm frame	3
Load parts	6
Lower upper diaphragm frame	2
Lock frames	2
Run cycle	30
Open upper frame	2
Unload parts	10
Total time	90
Time per part	45

Figure 3-4 Machine cycle time

Given this machine cycle time the production rates necessary give the shifts needed for meeting production volume. The times for part production include 30 minutes for vacuum bagging with the current reusable vacuum bags.

Production rate analysis for one worker	
planes per month	5
parts per plane	44
hours per part	1.25
production hours required per month	275
production days available per month	20
production hours required per day	13.75
shifts per day	1.72

Figure 3-5 Shifts needed to meet production volume

This figure of 1.72 shifts per day needed to meet production demand is based on only one worker operating one machine. It can be seen that this improvement alone can easily meet production goals even when operating on a two shift day.

3.1.2 Diaphragm Material

The pressure difference across the diaphragms is limited to a great extent by the fact that vacuum will only apply up to one atmosphere of pressure on the diaphragms. In practice plant vacuum is about 28" Hg. To provide additional pressure for forming thicker diaphragm materials there must be an effective raising of the ambient atmosphere by applying positive pressure from outside the diaphragm. This has been done in lab experiments with the goal of forming diaphragm materials much stiffer than the standard 50 durometer commercial silicone used in most testing. The implications of this positive pressure on the machine design are dramatic. Since the over-pressure must be contained over the whole of the top of the machine the top the force becomes quite substantial. The top unfortunately also must be removed to gain access to the parts so a large flat panel built strong enough to withstand pressure on the order of an atmosphere must be moved easily. This creates quite a significant design issue. Therefore, for a practical machine the pressure difference is limited to about one atmosphere.

This problem is alleviated somewhat by the use of a low modulus rubber. By way of making the diaphragms more tear resistant a high strength, low modulus silicone rubber was used on the production machine. This was also done because the material had already been certified for use with composite materials production. It is the same material as is used in reusable vacuum bag systems. The material used was EP78 calendered silicone, .085" thick. The material exhibited significant tear resistance, well above the commercial grade translucent silicone used in the initial lab testing. A tear started in the commercial rubber would tend to propagate easily resulting in dramatic failures under load. A tear initiated in the high strength material however, would continue for a very short distance and then form a hook shape and stop. At this point it was very difficult to continue the tear. The different tear patterns are shown below.

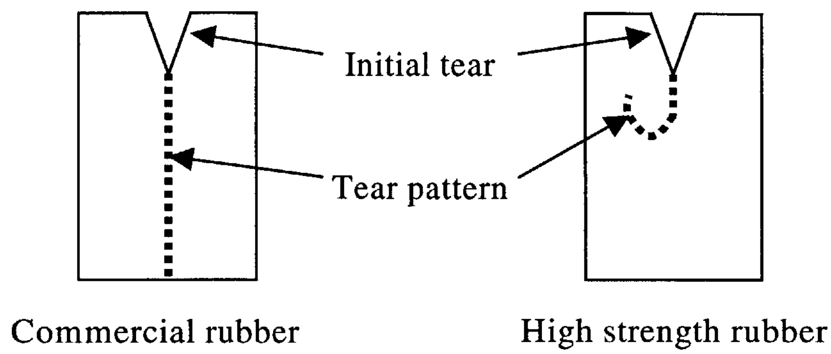


Figure 3-6 Tear resistance of high strength rubber

The high strength rubber is used primarily for extra durability in a production environment for even in a clean room grit and foreign objects can accumulate on the diaphragm surface. There is a second benefit though which is that the low modulus of the material acts to lower the over all forming pressure difference needed. This translates into a number of savings. First, it take less time to evacuate the chamber to the forming pressure which decreases the machine cycle time. This is no small benefit since the machine's internal volume is quite large: 96" x 35" x 21". More importantly though it reduces the level of vacuum needed for forming dramatically which means that the machine structure can be much lighter.

3.2 Forming Loads

The impact on the structure is that it can be built lighter since it need not withstand high forces. Given that the top of each wall of the machine is open it is not a very efficient structure at resisting pressure given the very large surface area along the side of the machine. However, the pressure difference will cause the diaphragm to pull down against the tool base before it is very large. Once this diaphragm is flat against the wall it is balanced with the pressure on the outside of the wall and it's contribution to bending the plate is zero in this region. The remaining net forces will be on the lower portions of the wall. Use of a low modulus rubber increases this effect in that it extends significantly with relatively small pressures so the diaphragm has flattened against the top portion of the wall before the pressure difference rises significantly.

3.3 Diaphragm Frame System

Once the tool station scheme has been determined, the next most important design decision for the machine is the diaphragm frame system. This is driven by the location of the tools as their location determines where the operator must interact with the machine to load and unload parts. In the lab environment ergonomics were not as important as on the production floor and the frames were simply hinged along the long side giving easy access to only one of the tool stations. For a production machine, however, ergonomic, safety and efficiency concerns dominate the design decisions.

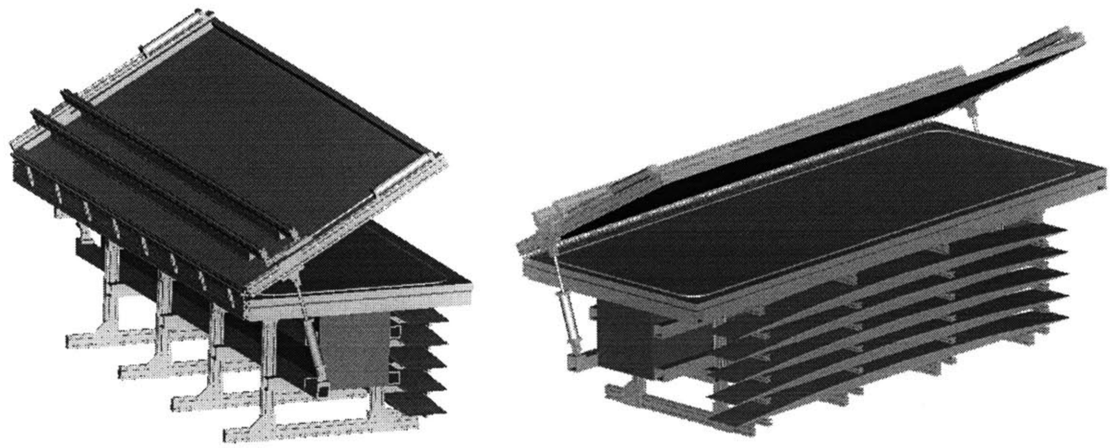


Figure 3-7 Forming machine concept with single hinge from side

Since the tools were to lie along the sides of the machine and the operator needed to easily reach both tool stations there needed to be access from both sides of the machine along most of the length. This left only a few options. The first option, seemingly the simplest and most efficient in terms of foot print (an important factor on the production floor) was to raise the frames vertically in all four corners with either fixed posts or telescoping actuators. Mechanically this was a bit of a challenge. The obvious options for the actuators would be long throw air cylinders (hydraulic were looked on unfavorably given the oil contamination issue in the clean room). These would not be able to raise the frames very much as they would have to fit within the height of the machine or else extend above the height of the frames and pull them up. A telescoping system could accomplish this however one problem remained with every configuration namely keeping the frames going up squarely during actuation. This is due to the fact that coordinating the cylinders motion is difficult to due to different air supply and friction for each of the cylinders. A mechanical compensation issue was seen as unnecessarily complex.

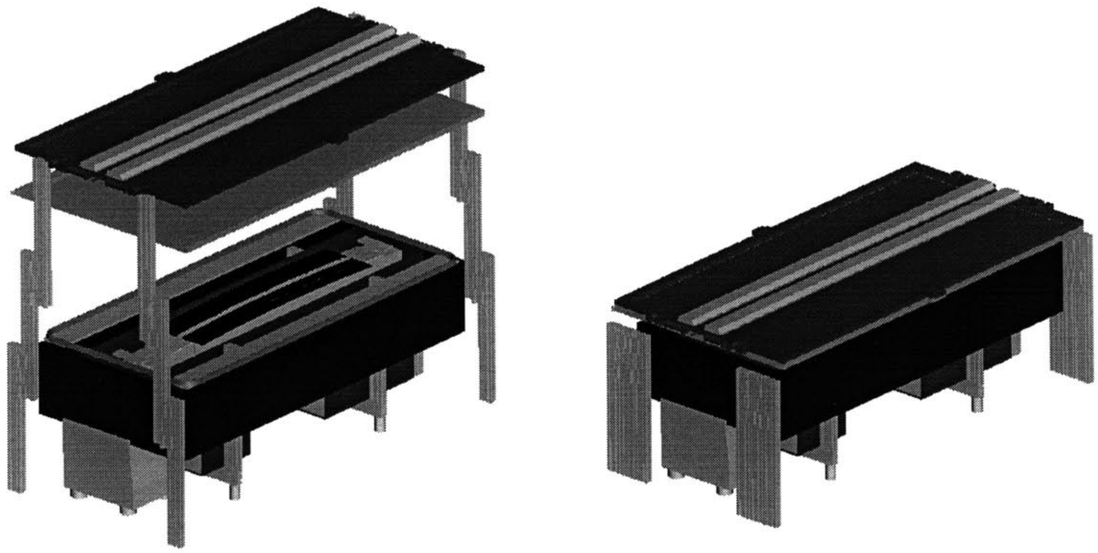


Figure 3-8 Diaphragm system on telescoping posts

One modification of the theme was to have the telescoping frame legs be actuated with a gear and pulley system. This would eliminate the problem of coordination between the legs and keep the frames going up together but it meant substantial infrastructure in terms of pulley mountings and chain channels to protect against safety issues related to the pinch hazards in the gears.

The frame system was finally abandoned due to the overriding safety concern of the overhanging system endangering the operators. Since the operators spend much of their time over the machine setting parts in place and aligning them, it was deemed unsafe to have a heavy diaphragm frame hanging above them. Additionally, in order to avoid having the operators stoop to work under the frames, the frames would have to be raised quite far up. This would cause a stability issue as the telescoping columns would end up being very slender.

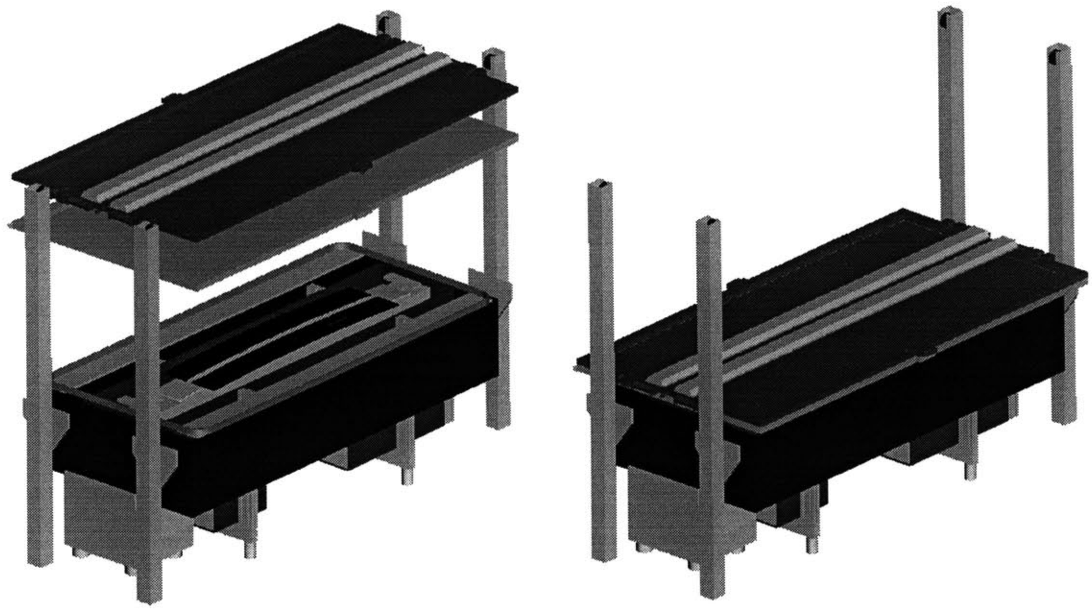
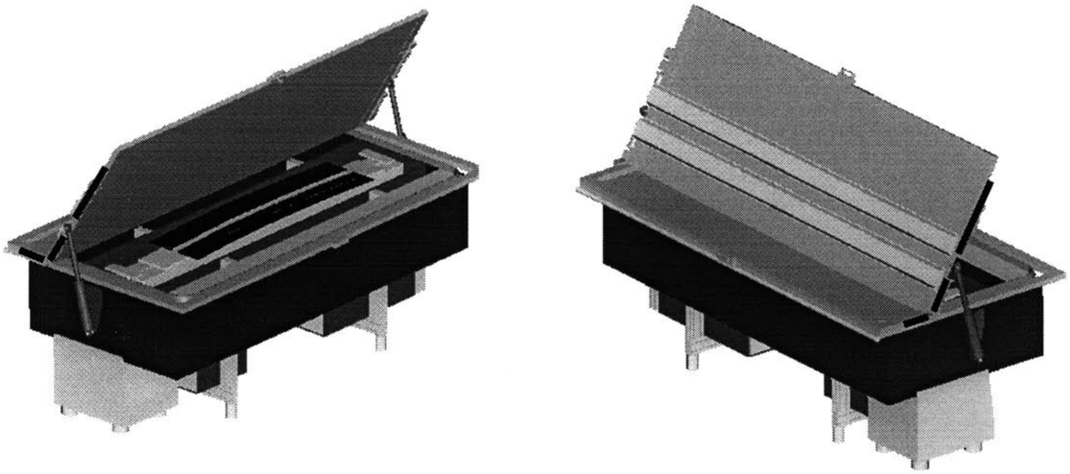


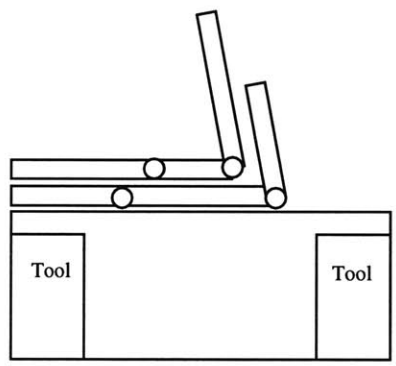
Figure 3-9 Diaphragm system with posts

3.3.1 Hinged Diaphragm Frames

The other obvious option for the frames was a system by which the frames could be hinged in a way to give easy access to both of the tool stations. Hinging both upper and lower frames down the long axis of the machine would allow full access to the tool stations and be easy to operate. Since the frames would be fairly narrow from the hinge to the outside edge they could be actuated with a simple air cylinder arrangement or gas springs. There is no coordination issue given that each side would go up independently. There is also sufficient width to allow the frames to lean back on each other in the center of the machine so there would be no overhanging issue.



Centerline tool placement



Side tool placement

Figure 3-10 Frames hinged in the middle

As can be seen from the hinge placement, the hinging of both frames with one below the other requires that the hinge points be staggered to allow clearance for the bottom frame to hinge up and miss the top one. To open the frame to one side and not the other there are pneumatic locking pins that span the hinge joint for both sides of the machine. To open one side, the locking pins on the other side would be set meaning that its hinge would not rotate when the actuator pushed up on the frames. The other side of the frame would be locked to the machine base thereby holding the frame edge down while the actuator opened the far side.

The hinge clearance issue of this design would be somewhat problematic in that the hinge joint were directly on the vacuum seal. If the seal were positioned on the frame itself then it would have to extend around the hinge as the frame was opened. Similarly, when the frame closed then it would have to contract and still maintain a sufficient vacuum seal. The seal would also not be able to be bonded to the frame because the hinge area would be opening up as the frame was opened. These issues could be eliminated by having the seal be on the machine surface and have the frame come down and meet up with it. This is undesirable as the seal would then be in an area where the operators would be working and the possibility of damage would be great. On a seal so large even a small amount of contamination over the surface could lead to sealing problems. Additionally, the problems facing the upper hinge are doubly tricky. Not only does it face the same extension problem if the seal is mounted onto it but if the seal were to be placed on the bottom frame then it would be crushed at the hinge as the bottom frame was opened. The hinging scenario would also present considerable problems for maintenance of the internal equipment such as the support table. To get access to the middle of the machine the frames would have to be entirely removed, not an agreeable task especially if maintenance requirements called for frequent access. For these reasons the middle split hinge concept was abandoned as being impractical.

The concept that was eventually decided on was one that involved a significant structural issue but also solved many of the problems that occurred on earlier design ideas. Cantilevering both frames from one end of the machine is a concept that looks rather drastic, the opened height of the machine would be over 12 feet tall, but solves most of the problems with other concepts. The system allows for both tool stations to be fully accessible while keeping all moving parts at one end where the safety issue can be mitigated by grouping all the systems together.

By hinging off the end of the machine the frames could be entirely opened to provide complete access to the inside of the machine for maintenance purposes. The obvious issue with this design is that of the frames towering over the operators and the significant pinch hazard created when the frames began to close.

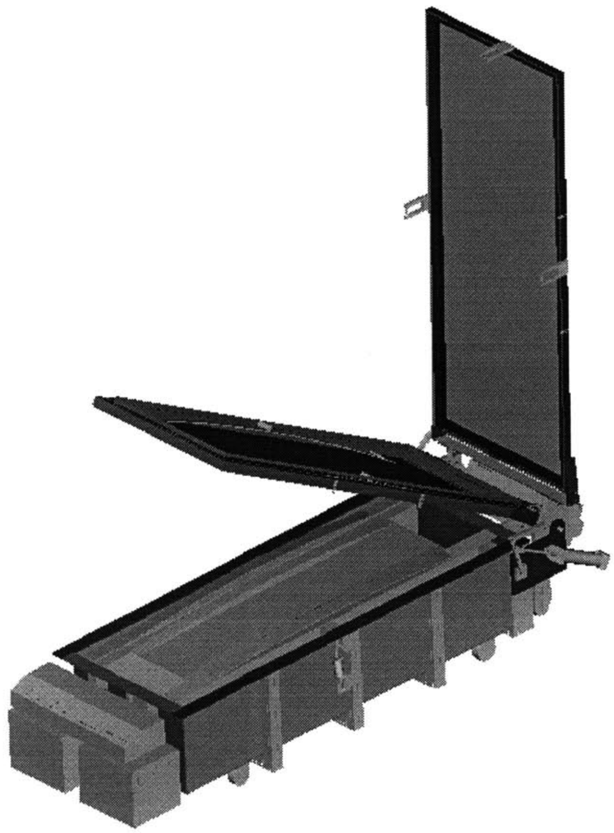


Figure 3-11 Diaphragm system hinged from end

The overhang issue was initially addressed by use of a pneumatically actuated linkage that would lock in the open position thereby preventing inadvertent closing. This would effectively lock the frames in the up position unless the air cylinders were operated to lower the frames. The frames were also allowed to lean back beyond the vertical by a few degrees (depending on the counterweight location). This eliminates the overhang of the frames and contributes considerably to the comfort of the operators nearby.

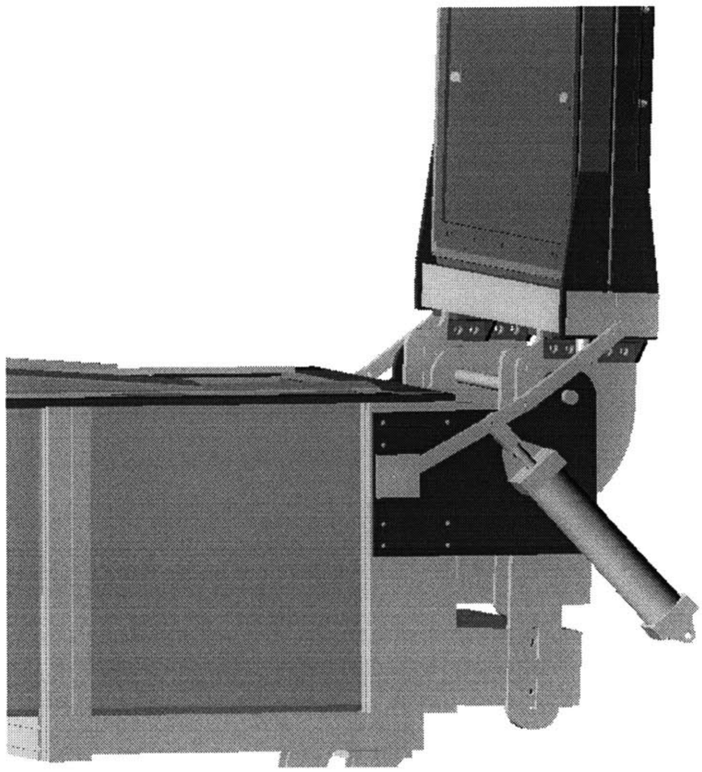


Figure 3-12 Machine with frames open and linkage locked open

Mechanically the system relies on the frames being counterweighted to the point that the load on the actuators is only that of overcoming the friction in the bearings and the rotational inertia of the frames.

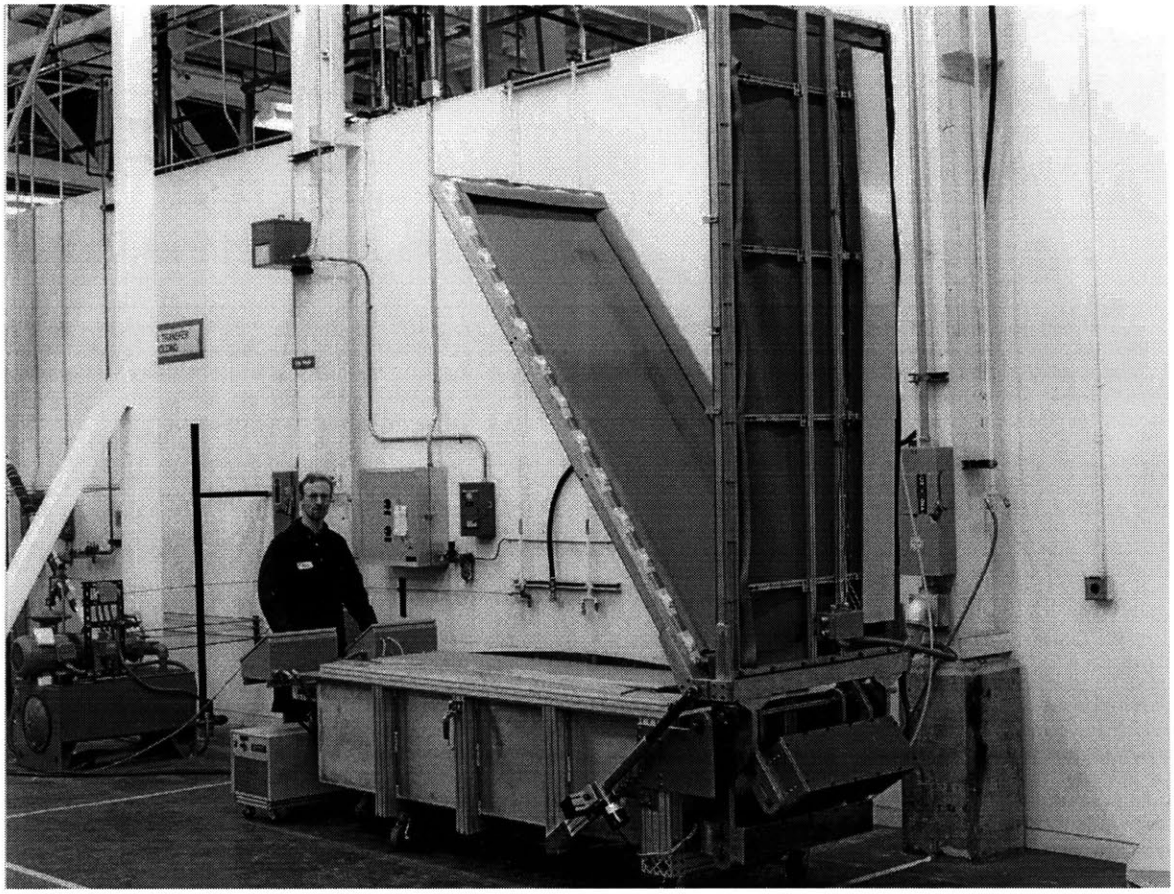


Figure 3-13 Machine with counterweight system at Boeing

In the figure above it can be seen that the frames, when in the fully up position are quite substantial but also leaned back far enough to avoid any overhang of the operators. In this picture it's also evident that the air cylinder linkage has been replaced by an electro-mechanical lead screw actuator. This simplifies the control system quite dramatically in that there is no need for any air regulation system and it eliminates the sometimes erratic response of the cylinder. Since the actuators cannot back drive (i.e. be pushed open or closed without power), the frames only move in response to a control input where as loss of air pressure midway through actuating would result in the frames being free to move.

The overall safety of the system is maintained by having the counterweight system extend off one end and have the frames lean back over the area. This way all the hazards can be confined to this area and placing the machine up against a wall in the production room allows for the machine to be used safely. The pinch hazard of the frame closing can be solved through the use of safety mats. These are floor mats that act as electric switches to shut off the motors should anyone stand on them. They effectively provide assurance that no one is in the hazard area when the frames are actuating. Additionally, having the frames hinged off of one end means that the controls can be mounted on the far end ensuring that the operator can see the whole machine while running the controls.

3.3.2 Counterweight Mounting

Given that the diaphragm frames are cantilevered out over the 8 foot length of the machine, the loads at the base are quite high. Exacerbating this effect is that the spacing between the frames is quite low and so the attachment point is only 3" high and must resolve the moment of the 8 foot frame cantilevered out. Taking the frame as a cantilevered beam under uniform loading we can determine the moment that must be developed at the connection as an approximated point load 4 feet out.

Balancing moments:

100 lbs. x 48 inches = 4,800 inch·lbs.

The attachment was made as a pinned joint for ease of disassembly for transport from MIT to Boeing. Also, the arms that held the counterweights out were made from 1" thick aluminum plates to take the load of the counterweight baskets. A pinned joint then was needed to avoid the problem of welding the solid 1" plate onto the thin walled tube and brackets of the frames. This welding difficulty arises when the thin parts heat up much faster than the thick plate and consequently will either melt all together before the thick plate can melt locally to weld. If the thin parts are heated to their welding temperature then the thick plates will not be hot enough for a good weld. This weakness would end up being right in the area of the highest stress and would lead to structural weaknesses. The pinned joint does not rely on the weld and so can be much more easily made and accurately analyzed.

Since the frame thickness is only two inches for the lower frame and 1.25" for the upper frame, the joint for the attachment needed to be thickened in order to have some distance between pins. Therefore both frames had 3", .25" wall square tube welded on to allow for this spacing. In order that they not interfere with each other, they were both welded on flush with the middle between the two frames.

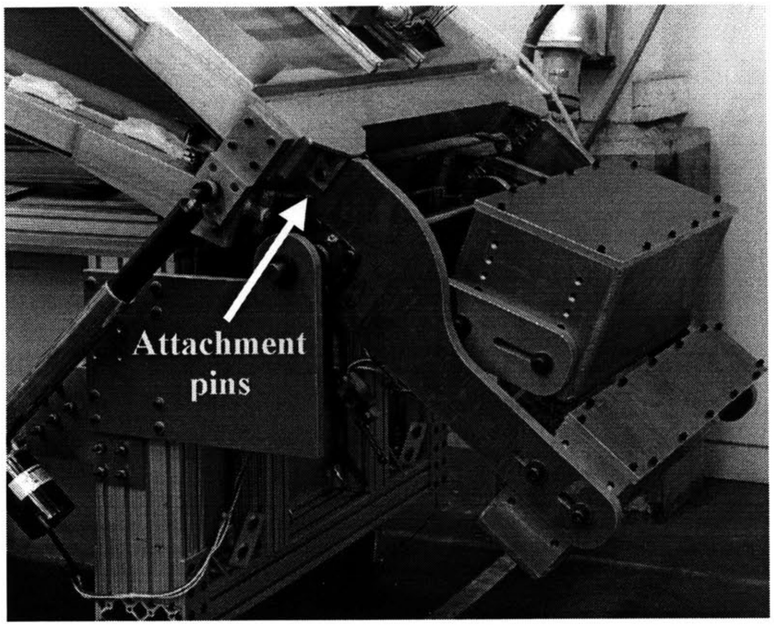


Figure 3-14 Attachment of frames to counterweight system

The frames themselves were made of stock chamfered and welded in the corners. In order to reduce the stress in the welded joint a gusset plate was welded on each corner to transfer the moment of the attachment from the square tube into the long sides of the frames without stressing the welded corners.

With a pin spacing of 2 inches the loads on the pins are:

4,800 in·lbs. = 2(pin load x 1 inch)

pin load = 1,200 lbs.

This is based on using four pins to attach the frame, two on each side.

From this pin loading we can determine the stress in the aluminum brackets. The important stresses will be the tensile ones in the aluminum above the top pin. The bottom pin stresses will be compressive and supplemented by the bearing of the hinge arm on the welded tube at the end of the frame. To reduce the stress in the material above the top pin a bracket was welded onto the top of the brackets to provide another load path for resolving the moment.

The counterweights had to be very adjustable given that the loads of the frames could change quite significantly. Extra weight for heaters, heater guards and metallic shielding had to be allowed for. Since the area of the frames is quite large and the contribution of any weight covering the frames would be focused over 4 feet from the hinge while the counterweight is located only 1 foot from the hinge. Therefore any extra weight required 4 times the counterweight be added. Any weight added to the frame could change the loading of the counterweight significantly.

3.4 Tool Design

The forming tool design was driven by the need to lower the investment and inventory in new tooling for the project. Since the project needed to meet a certain return-on-investment for use in production keeping the tooling needs as low as possible was important. The project already benefited from not requiring new cure tools and so it was important to not introduce the need to inventory and transport all the tooling.

The method for reducing the number of tools needed was to create tool families whereby the rib chords would be grouped into families of parts which could all be made on the same tool. There is a significant degree of commonality in the parts which allows this grouping to occur. Since all but a few chords fit into the structure in the same way they share a common angle of 92°. This is the angle between the ribs and the stringers. This common angle enables the tools to be configured such that the top is curved to match the curve of the part and the side is flat.

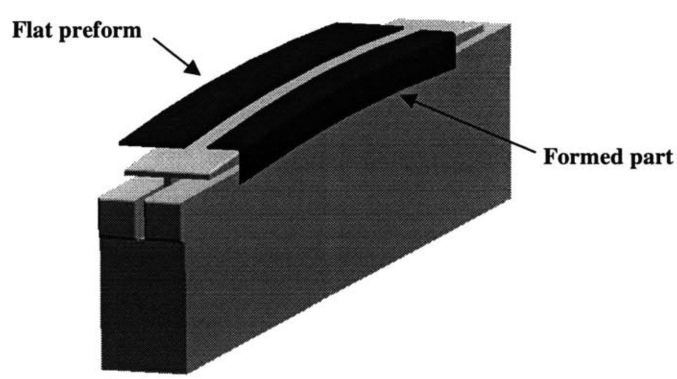


Figure 3-15 Tool station with top curve to match stringer flange

The grouping of chords then becomes a matter of matching the curved sides of each part into families. Thus changing the top curve of the tool changes the part being made. Building on this fact the tool bases could be kept common while just the top could be changed to change tooling. This allows the tools to be made very small which in turn means they can be made light enough to be carried by an operator eliminating the need for another person to transport and inventory the tooling.

3.4.1 Gross Curvature

The curves can be grouped by gross curvature based on their position in the plane. The following figures illustrate the changes in gross curvature of the parts Both images are looking down the length of the fin and stabilizer towards the fuselage

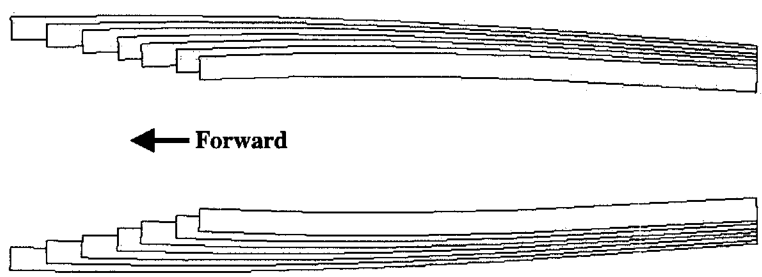


Figure 3-16 Vertical fin rib chord shapes

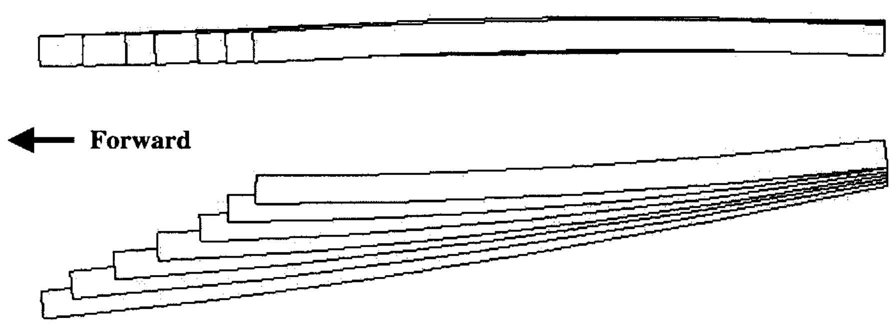


Figure 3-17 Horizontal stabilizer rib chord shapes

The general trend can be seen in the curvature. In the vertical fin since it does not need to provide any lift normally, both sides are of equal curvature. To generate lift the rudder is moved to one side. In the stabilizer however, the curvature is different between the upper and lower surfaces. This is because the whole surface is continuously balancing the weight of the plane. The plane is balanced so that it is front heavy which explains why the more steeply curved (low pressure) side of the surface is down: so that it continuously holds the tail down and the nose level.

3.4.2 Tool Families

The figures make visible that the rib chords are flatter (larger major radius) towards the root and more curved towards the tip. This is not so much due to decreasing curvature towards the root as it is to the fact that the chord length contains less of the total airfoil curve at that point. Further, the lower skin of the stabilizer has a greater curvature than the upper skin. The groupings of parts will then follow this tendency as the parts are grouped by major radius. This means that parts from the stabilizer could match up with parts from the vertical fin provided the major radii are similar.

3.4.3 Curve Shape and Features

The parts are not necessarily the same shape though in that the curves are not always symmetrical down the length. This is because the length of the rib chords will cover less of the airfoil in different locations.

This asymmetry will mean that the parts must be grouped with others of similar major radius and similar shape. This is the case with the vertical fin parts. The skins of the fin thicken as they near the rudder to take the increased load from the rudder forces. The stringers, which are attached to the inside of the skins will follow the curve change as it nears the rudder. The rib chords will also need to change their curve due to the locations of the stringer caps.

This means that vertical fin parts will have a consistent aft end and varying forward ends. Unfortunately, this means that the vertical fin tools will not be able to form the stabilizer parts.

This scheme has been proven in testing by using a common tool for part ribs 2 through 8 in the fin. The tool was machined to match the rudder joggles at the aft end and then made to follow the steepest curvature of the chords (rib 8) and then extended to the length of the longest one (rib 2). The tool was made to over form every part to the steep curve and then rely on full length part relaxation to match the flat curve of rib 2.

This consistency in the curve shapes means that all the parts can be referenced from the same point along the length of the tool. This means that there is no need to locate the parts relative to the tool beyond the end point and the edge. This makes fixturing the parts in the machine very easy.

In testing this scheme worked very well producing good results for every chord. The one issue that arose from this testing was on rib 2 where there is a deep joggle in the rudder thickened area. The joggled region of the tool was made to match rib 4 based on the fact that rib 4 has the most sharply defined joggle but not the deepest. The cure mold for rib 2 then had deeper joggles than the forming tool resulting in under formed joggle regions for this part. The result on the part is that there would be some slight resin starvation in the region of the joggle as seen in the figure below. This occurs because the rib flange is very stiff in-plane which prevents the part from forming down into the joggle. Out on the stringer flange there is no flange stiffening the region and it will form down into the joggle easily. This is why the resin starvation occurs only in at the radius.

Figure 3-18 Joggle

Exacerbating the problem of forming the rib flange down into the joggle is the fact that the reinforcement, if not carefully designed will add stiffness to the flange and prevent the rib flange from bending in-plane sufficiently to match the joggle. The reinforcement must be made such that it has very little in-plane stiffness but considerable out-of-plane bending stiffness to prevent wrinkles.

Based on this experience the horizontal stabilizer was set up based on features and major radii. For the stabilizer there are features that determine the shape of each part. Looking at the overall shape of the parts they can be divided into different families characterized by features. Features include joggles and kinks. A joggles occurs when the chord must step up to a different level forming a z-shape. A kink occurs when the part has an abrupt change in direction not as a smooth curve but as a sharp angle. The parts in the table are now grouped by feature and major radius.

For the stabilizer the parts are put together with features grouped. The parts on rib 4 both upper and lower have joggles while rib 7 upper and lower plus rib 8 upper have kinks. The other parts follow the trend of flattening towards the root and exhibit a general major radius. Thus the parts with features will be grouped together and the ones without features will be grouped by major radius.

3.4.4 Double-Sided Tooling

The rib chords are not symmetrical along the length and so have left and right parts in the airplane. For each rib in the vertical fin there is a left and a right part. Likewise for each rib in the stabilizer there is not only a left and right part but an upper and lower part as well. In order to provide for all of these parts the tooling was made with two forming edges, therefore each tool could be simply turned around to make the matching part from the other side of the plane.

One further detail to the tool set up is that the 5° over forming angle must be accommodated. This is accomplished by chamfering each side of the tool in at 5°. The tool base is also angled at 5° such that when the tool is placed on top, the side is flush with the vertical side of the tool base.

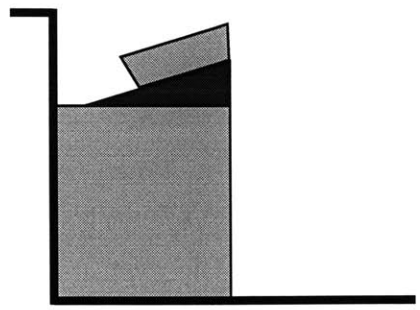


Figure 3-19 Tool position on base

In order to maintain the flush edge with the tool base which would otherwise imprint on the part, there are two rows of holes for locating pins. These are each a set distance from their respective sides and so always hold that reference while the holes in the other side "float". The middle hole is round while the other four holes on each side are slotted to avoid over-constraining the tool and having it pinch the pins and be difficult to remove. The thermal expansion of the tool is another issue. It is loaded at room temperature and will be cooled down to 40° during the cool down portion of the cycle. Since it may have to be removed while cool the thermal contraction of the tool could well overcome the clearance with the pin holes. Since the edge must be kept flush the clearance sideways is the lengthwise clearance.

alpha for 6061 aluminum = 13.1 E -6/F°

tool length = 72"

delta T = 35° F

thermal contraction: 13.1 E -6 * 35 * 72" = .033"

This is clearly enough to cause problems with round holes if the clearance is kept tight to maintain flush edges. The slots therefore allow the ends of the tool to contract without jamming the tool on the pins.

The tool design has been further refined to the point that each tool is designed to be split into two pieces. This accomplishes two objectives. Firstly, it makes the individual half tools under ten pounds, light to be carried by all operators, even those who are on restricted work duty due to medical problems. The second impact of this is that the tool families can be reduced to use common ends. There are many parts that have similar curves for at least half the length of the part. Utilizing one common end tool with two other ends saves one tool from the inventory.

In order to split the tools and to make them light enough to carry they must be hollowed out on the back side of the part. A hollowed half tool is shown in the figure below. The forming loads on the tooling are quite moderate due to the use of the low modulus rubber for the diaphragms. The pressure on the tooling at full forming vacuum is only 7" Hg (3.7 psi). This is low enough that the wall thickness of the tools can be quite small without allowing much deflection. In the area of the locating pins there is more material allowing for steel bushings to be inserted to prevent wearing of the pin holes and slots.

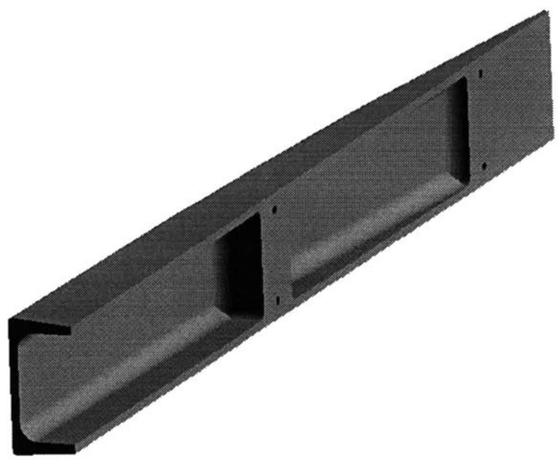


Figure 3-20 Back of tool hollowed out for light weight

Analyzing the two major forces on the tool we can set the wall thickness based on acceptable deflection. First there is the uniform load of the forming pressure along the top surface of the tool. The tool surface is 4"wide and can be approximated to be a simply supported beam as the vertical legs of the tools are not attached or welded to anything and so are free to rotate and only provide vertical forces and no moments.

max deflection = $5wL^4/384EI$ (Beer and Johnston)

.005" = $5*3.7*4^4/384*10e6*(1*\text{thickness}^3/12)$

thickness = .144"

The other loading of the tooling is a lateral force from the forming pressure. This force comes about from the fact that only one side of the tool is exposed to the forming pressure because the other side is up against the machine side and so does not provide a balancing force to the lateral forming pressure. Based on a maximum tool height of 1.5" the lateral force in the region of maximum height can be approximated by a uniform load on a beam with one fixed and one free end. The bottom end of the tool "leg" is fixed since it is prevented from lateral movement by the alignment pins.

max deflection = $wL^4/8EI$ (Beer and Johnston)

.005" = $3.7*1.5^4/8*10e6*(1*\text{thickness}^3/12)$

thickness = .084"

The loading across the top can be seen to be the more important of the two loads. We can take that thickness as the thickness of the tool and not worry about excessive deflection of the sides.

At the time of design it had not yet been decided what level of operator would be using the machine so there was much discussion about to what extent the tooling system ought to be made mistake proof. Since forming to the wrong contour could result in a part that would not fit the cure mold for which it was intended, using the wrong tool would result in a scrapped part. There were a number of different approaches to determining which tools were loaded and whether they were set to produce right of left parts.

The most mistake proof method would utilize a barcode on the work order that comes with the kit for the parts. A kit consists of pre-cut material for making one specific part. The machine would scan this barcode and check it against the tool loaded in the machine. Tool sensing could be accomplished through a few ways. Proximity sensors are the preferred type of sensor for the factory equipment. These could be mounted into the tool base where they would "read" a series of holes machined into each half tool. By the presence or absence of the holes the tools could not only be identified easily as the correct one but could also be determined positively as being correctly loaded correctly. If the tool were not loaded correctly onto the positioning pins then the sensors would not read any holes at all and issue a fault.

Since the tool base was made up of a hollow tube through which the cooling water flowed, mounting the sensors inside it would make for difficult maintenance. The other option for sensor location is on top of the tool base looking horizontally at the end of the tool. The holes in this case would be replaced by slots cut in the end of the tool. In this configuration the sensors would be much more easily accessed for maintenance and would still be able to recognize an incorrectly loaded tool.

Given the extra complication of the control system for such a scenario the decision was made to leave tool sensing as an option if needed in the future. Any tools machined could be retrofitted later with tool slots and then sensors could be easily attached to the surface of the tool base. Instead, the tools are designed to incorporate specific joints between the halves that ensure that only compatible tools can be used together. As for using the correct tool, a color coded scheme could be used whereby each tool is anodized a specific color and the work order comes with a visual diagram of how the tooling ought to be set up.

3.5 Support Table

The preforms are loaded into the machine such that their centerlines are along the edge of the tool. Given that the lower diaphragm is not stretched tight across the middle of the machine and in fact sags quite a bit, the preforms will tend to slip off of the tool edge and misalign or even slip off entirely. In order to prevent this there must be some support from below that prevents this from happening. This is accomplished through the use of a moving support table that can be raised to the height of the tooling and support the part all the way along the contour and then drop away for forming.

3.5.1 Support Table Requirements

Since the tools all have different contours, the table must be able to match the contour of the tooling with some form of adaptable surface. This surface and the rest of the table must also be able to withstand the enormous force developed when the forming pressure is exerted over the entire face of the table. This force will be:

3.7 psi over 21" by 80" = 6,216 lbs.

The table must also be able to extend up to the height of the tooling and then collapse down far enough to be able to fit inside the tank. None of the actuators can penetrate the tank as it needs to remain vacuum tight. The actuation system used must be able to raise the table smoothly and squarely since it will be raised between the vertical sides of the tool bases. Finally the whole system must sit below the table surface and it cannot have tracks or any sharp protruding parts into the space above since the diaphragm will be drawn down tight against every surface above the table during forming.

3.5.2 Pneumatic Actuation

The simplest method for actuating the table is to use air cylinders standing on end and bolted to the table structure. Hydraulic actuation was not a possibility due to the problems of oil contamination in the clean room environment. There were two problems with using a system of air cylinders. The first is mainly one of packaging: the easiest way to mount the cylinders would be to have them stand on end and simply actuate straight up. However most standard air cylinders have an overall length that is far greater than their stroke (extension) length. In the table application the height to the top of the table surface had to be 15" while the stroke length had to be 8". Most cylinders in the size range needed (2" bore) require about 5-6" of room beyond the stroke length for end plates, bases, piston etc. This means that an 8" stroke cylinder would need 13-14" of length for itself. This length plus mounting attachments and the table structure above it would make for a very compact set up indeed.

However the problem that prevented this method from being adopted was the need to coordinate the cylinder's motion as was also the case for the vertical diaphragm frame system. The potential for jamming the table inside the machine during actuation was made all the more difficult by the fact that the table fit into the well formed between the two tool bases with only .25" all around. This tight fit was necessary to prevent the diaphragm material from becoming caught between the table edge and the tool bases.

The table would have to be a fairly substantial structure to withstand the forming load which meant that it would be relatively deep. This would present all the more need for having the table actuate up flat and square. This issue prevented end mounted cylinders from being adopted.

A pneumatic system still had appeal given the ease of set up and maintenance and the cleanliness of operation. The use of a scissors lift design solved both of these problems. Firstly, it could be very compact when in the down position and with a simple arrangement of an air cylinder across along the base could raise the table top very high. Secondly and more importantly, the design allowed for one air cylinder to be responsible for coordination of all the table's movement. The scissors arrangement would take care of the problem of raising the table flat and square.

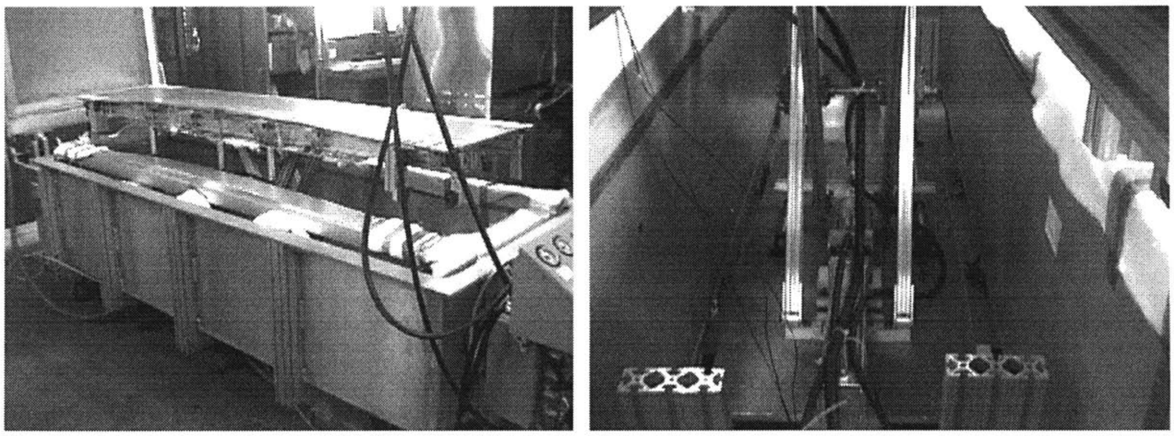


Figure 3-21 Scissors support table design and prototype

The scissors system did have it's own problems though. While it worked very well to keep the table flat and square, it was very wobbly when it was fully raised. This came from the fact that the well it sat in was very narrow which in turn meant that the legs of the table had to be very close together. Any play in the bearings would be magnified and make the whole table wobble. To amplify this effect the lengthwise footprint of the table would also decrease resulting in a square footprint from the legs on a very long heavy table. While this did not strictly affect the performance of the table it was deemed unacceptable.

The second and more important problem though was that the air cylinder would be actuating on the bottom of the scissors along the length of the bearings. This meant that the resultant force upwards on the table would be highly non-linear and dependent on the position of the table. When flat, the angle in the scissors would be very small resulting in very little upward force. Once the scissors began to actuate, the angle of them would begin to increase meaning a much greater force upwards on the table. The system would in effect "run away" as the increased angle led to greater upward component on the table. The air pressure running the cylinder would have to be reduced in order that the table not accelerate while actuating. One way this problem is typically solved is that an adjustable valve is included in the system to limit the flow to the cylinder and thereby limit the actuation speed. This would not work in this application however since the pressure needed to maintain a given upward force on the table would drop as the leverage of the scissors angle increased. Therefore even if flow were stopped the continuing expansion of the air already in the cylinder would continue accelerating the table.

3.5.3 Jack Screw Actuation

The second design of the table used a series of small jack screws in the corners to solve the problems encountered with the scissors lift. The four jack screws were mounted to a frame that sat inside the well of the machine. There is a plate that runs between the two screws at each end of the frame. This plate would support the table itself which had two full length rails supporting a frame underneath the top plate. The two lengthwise rails extended over the plates between the screws and would therefore be picked up by the plate as it extended up. When the table was lowered it would be dropped off by the screw plates onto a series of rests built into the frame. The screw plates would then lower another half an inch ensuring that the forming loads would be carried by the frame rests and not the screw structure.

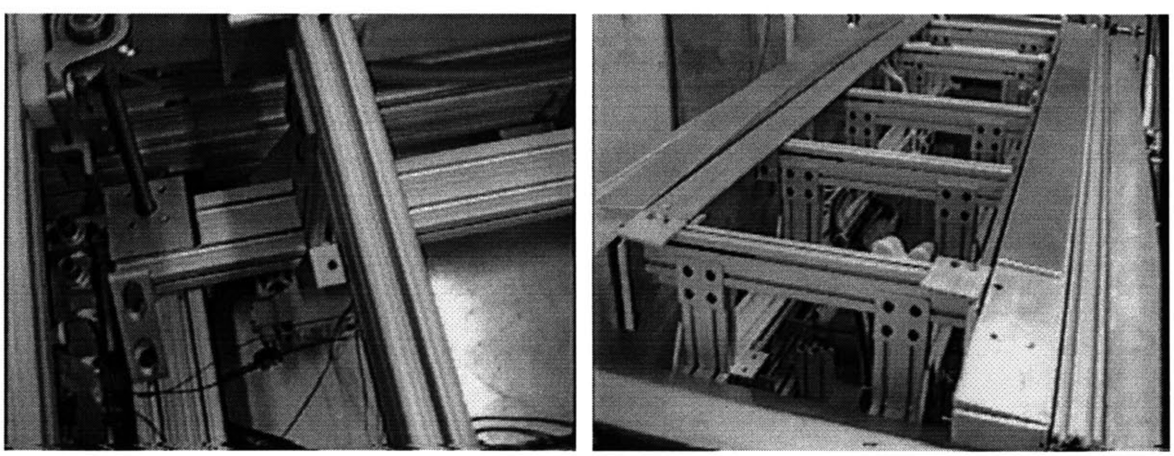


Figure 3-22 Lift table with jack screws

3.5.4 Part Support Plates

The main purpose of the table is to support the parts while they are loaded into the machine. In order to accomplish this however, they need to match the shape of each of the parts. Since the parts have curvatures that vary from flat to highly curved the table must somehow adapt to these in order to support each part properly. Something on the table must then change shape in order to accommodate the shape of the part. Since the two parts being made could be of significantly different shape the whole table top couldn't serve as the shaping mechanism and individual adaptable supports were necessary.

These supports took the form of narrow aluminum plates 3" wide and .25" thick running the full length of the table top. Since they were needed only when the table was in the up position and supporting the part, they were made to actuate up when the table was raised and then to retract when the table lowered.

The plates were attached by a hinge on one end while the other was only held down but allowed to slide along a bar. This was necessary to enable the part to form a curve and also lie flat on the table. The plates were actuated from below at a series of points down the length. For most of the curves the plate could be bent into the approximate shape with just one or two points of support. The first actuator investigated was a small ball screw that would be able to move to different positions depending on the part being made. The actuator would need to include a rotary encoder and controller to position it for the different curves. This would require a considerable amount of equipment under the support rails on both sides of the machine. In order to avoid this the design was modified to use individual air cylinders mounted to a rail running the full length of the table to push up on the plates in various locations. With a series of these rails, the whole range of parts could be made by using whichever cylinders were needed. The control system then simplified to a series of air control valves acting as a multiplexer. For each part that needed to be made there was a different air cylinder which would deliver compressed air to the appropriate combination of cylinders. Since the actuation time of the cylinders doesn't matter, the flow coefficient of the valves could be small allowing the whole valve to be small as well.

With all these systems mounted inside the machine there needed to be some way to access them for maintenance. Since taking out the whole table was needlessly difficult the top of the table was made from a series of small sections that could easily be removed by hand.

3.6 Heating System

The heating system was made up of two parts, a radiant system from above the parts and a flexible system that would mount to the bottom of the part support plates. Since the outside reinforcements needed to be thick in order to avoid buckling there was a significant time delay before the actual parts started to heat. This was due to the need for the heat to conduct down through the reinforcement. Therefore the heaters mounted to the part support plates would heat the plates and the parts resting on them would warm up while the top heaters heated the reinforcement. This reduced the amount of time for part heating and lowered the cycle time significantly. In practice, the most time was spent heating up and cooling down the parts.

The top heaters were necessary to augment the heating from below. The top reinforcements constitute a large thermal mass that, if left unheated, would be a heat sink which would pull heat out of the part. Additionally, the stringer flange would not be heated causing surface resin starvation on the final part.

The top heaters would be operating as radiant heaters since they were located so far from the part. Since the parts are curved some areas would be closer to the heater than others and the result would be that they were heated much faster than the rest of the part. To avoid overheating in areas the heater was made up of three pairs of tubular heaters each with its own thermocouple and controller. The idea was to break up the part into three zones each controlled individually therefore no zone would be over heated even if it was much closer to the heaters.

In testing, however, this system did not work very effectively and the zones would heat unevenly. Therefore, a second scheme was employed where the heaters would operate together off of one thermocouple and the system would "bake" the part. Small skirts would drape off the heater reflector and prevent heat from being lost. This would mean that the air temperature would be kept at a certain even temperature that would yield the highest gradient and prevent the part from locally overheating despite different curvatures.

3.7 Cooling System

The cooling system serves to cool the parts down after they have been heated and formed. This is necessary for two reasons. Firstly, they have to be cool enough for the operator to touch. Secondly, they must be cooled to the point that they can be hand transferred without deforming. The cooling system consists of two liquid chillers that can be separated from the machine depending on the installation site. The cooling control scheme is to continuously cool the tools rather than cool only when needed. This is because the tools themselves constitute a large heat sink and would therefore slow the cooling of the part considerably if they had to be cooled first. Secondly, in order to cool the parts as quickly as possible the highest possible gradient had to be maintained between the part and the tool.

The chillers were sized to provide enough cooling capacity to meet the heat load of the two parts being cooled down from forming temperature at the maximum machine production rate. To ensure that the water was as cold as possible the cooling system also had a 5 gallon reservoir included. This would provide an offset to the heat absorbed by the tools and maintain the high gradient instead of overwhelming the chillers.

3.8 Reinforcement Design

The inside reinforcement consists of flat wires placed side by side to keep the part from wrinkling out of plane. The wires are .060" wide and .020" thick and made from stainless steel rolled to have the sharp corners which reduces the imprint of the wires into the part. The width was reduced from the .125" width used during testing to .060" to allow for more flexibility in-plane and thus better performance in joggle regions. The wires must be kept together to keep this smooth surface but also have to be free to bend in plane. Since the part-side of the wires must be kept smooth to allow the part to spread out and relieve the compression, the connection between them must be all on one side. Initially, they were connected by means of tape that would hold them tightly together but would allow them to bend in-plane in between the strips of tape. The problem was that as the diaphragm stretched it would pull the wires apart necessitating that they be retaped after every test otherwise the gaps between them would produce significant impressions in the part.

The tape was replaced with fiberglass bonded onto the wires with a flexible silicone adhesive. This caused the wires to become very stiff in plane. Even when the fiberglass was slit perpendicular to the wires to avoid making it stiff in plane, it still would not flex enough. For all the wires to bend in-plane they must be able to slide relative to each other or they will behave like a beam and not flex. To keep this flexibility the backing must be flexible enough to allow the wires to slide relative to each other but stiff perpendicular to the length to keep them from separating. This is accomplished using a series of individual strands of fiberglass laid across the wires at half-inch spacings bonded to the wires by silicone adhesive. The fiberglass keeps the wires from separating but the space in between them is fully flexible and allows relative slip.

The only problem with this arrangement is that the wires on the outside wires are only bonded by the ends of the fiberglass and can be easily pulled apart. For the production machine the series of wires is then bonded to an outer sheet of .015" silicone rubber as a backing sheet to keep the wires from being pulled off.

The outer reinforcement has many more issues affecting its design. It has the same main requirement as the inner reinforcement in that it must be stiff and smooth to prevent wrinkling and flexible in plane. However, due to the need to prevent buckling of the reinforcement due to compression it must be fairly thick.

The use of a Teflon® bar produced excellent results in terms of forming unwrinkled parts with smooth surfaces but it developed a residual bend after forming that made repeated use difficult as it would no longer be straight. Since the bar needed to be 2.5" wide in order to cover the whole rib flange there were significant stresses in the bar while bent for forming. Since the bar was also at a high temperature (between 150 and 200 F) these stresses relaxed some in the formed position. Further exacerbating this, the bar was then cooled in the curved state preventing it from bending back to straight.

There are other ways a bar of plastic could be utilized that did not result in a residual bend after forming. All that is needed is for the stresses to be lowered when it is bent. Since the width is fixed, and therefore so are the stresses, one approach could employ a number of smaller bars next to each other. Since the individual bar's width would be much smaller, each bar would have much less stress in it and thus would not develop a residual bend. In order to keep the bars smooth on the part side surface there would have to be some feature, such as a groove, running the full length of the bar to keep them aligned similar to tongue-and-groove lumber.

3.8.1 Thermal Design

Thermal considerations are the more important factor in the design of the outer reinforcements. Since the bulk of the machine's cycle time is involved in thermal processes, heating up and cooling down, the thermal properties of the system become the limiting factor in the cycle time. The outer reinforcement is the greatest thermal load of all the components. In order to heat the part, the outer reinforcement must also be heated otherwise it will behave as a heat sink. Likewise, in order to cool the part, the outer reinforcement must also be cooled otherwise it will be a heat source to the part. Since the part is between the top heater and the part, it needs to have a high conductivity in order to conduct the heat through it quickly enough. During cooling however, the heat capacity and the conductivity become important since the more heat that is stored in the reinforcement, the longer the cooling cycle.

Looking at the outer reinforcement in the light of thermal considerations plastic becomes much less useful as a material. Despite the great surface finish that is achieved through using plastic, the thermal problems become problematic. Below is a listing of various materials and their relevant thermal properties (Green et al, Carvill).

Material	K (Btu/hr•ft •F)	Specific heat (Btu/Lb•F)
Teflon® PTFE	.11	.25
Steel A536	20	.16
Aluminum 6061	104	.23
Copper C145	205	.09

Figure 3-23 Thermal comparison of various materials

From the table it is easy to see that Teflon® is not the best choice for a material. Since the thermal cycle is driven by the Fourier law of conduction (Thomas):

$$q_x = -k \cdot A_x \cdot dT/dx$$

This relation describes the rate of heat transfer in one direction based on the temperature difference, area and thermal conductivity. This is a good approximation of the part-reinforcement system. There is very little conduction in the plane of the bar so the heat loss will be acting primarily through the thickness of the reinforcement and the part. The reinforcement therefore needs to have a high k to conduct quickly while having a low specific heat to reduce the amount of heat that needs to be transferred.

3.8.2 Part Feature Consideration

The mechanical design of the reinforcements must be such that it can meet the three main requirements for the reinforcement: in-plane flexibility, out of plane stiffness and a smooth, low friction surface on the part side. Beyond these requirements the reinforcement must be able to form all the parts reliably, this will include forming the joggles adequately. During trials joggles proved to be difficult to form reliably. This was due to the reinforcement's in-plane stiffness "bridging" the joggle. If the reinforcement has too much in-plane stiffness then it will form into the major bends of the part but not follow the contour in areas where the curvature changes quickly such as joggles. The consequence of this bridging is that the part will not be able to form into the joggles as well. The reinforcements press into the material to a large degree, particularly the edge of the bottom reinforcement. This creates a lip that the part will not be able to slide past so if the reinforcement bridges the joggle then the part will not form down into it. The result is resin starvation on the final cured part.

In order to develop this in-plane flexibility the reinforcement cannot be made from a single piece of material. Even for a soft material like Teflon® the large width of the part will prevent it from bending easily. The moment of inertia of a beam and the resulting deflection under a uniform load are (Beer and Johnston):

$$I = \text{Base} \cdot \text{Height}^3/12$$

$$\text{Delta} = 5\, w\, L^4 / 384\, E\, I$$

$$w = \text{load} / \text{unit length}$$

E = Young's modulus

The moment of inertia is a function of the geometry where the dominant feature is the height where as the deflection is governed by both the moment of inertia and the stiffness of the material. Moduli of several reinforcing materials are listed below (Beer and Johnston, Athalye).

Material	Young's Modulus 10^6 psi
Teflon®	.45
Steel	29
Aluminum	10

Figure 3-24 Young's modulus of reinforcing materials

When the reinforcement designs are viewed from the standpoint of in-plane flexibility the Teflon® bar again does not provide good results. The quantity 1 / E I is a measure of the deflection for a given load for various combinations of materials. It is easy to see that a series of thin wires side by side are much more flexible than a solid bar of material.

Reinforcement	1 / E I
2.5" x .5" Teflon® bar	3.41E-06
10 1/4" square aluminum bars	3.07E-03
20 1/8" x .020" steel wires	2.12E-01
40 1/16" x .020" steel wires	3.39E 00

Figure 3-25 Deflection under a given load of reinforcements

The use of thin wires provides the best way to get this flexibility. By limiting the width of the wires, their "height" in bending, the reinforcement becomes increasingly flexible. There is a minimum width needed for the wires however so this trend cannot be followed without limit. This minimum width is to allow for enough bonding surface on each wire to make the assembly durable. Also, if the wires get to be too small, .020" square for instance, they will be difficult to keep straight making the fabrication of them troublesome.

The numbers in the table for the steel wires will be reduced somewhat by the way they are connected and also the need to add more material to increase the thickness to prevent buckling but the numbers listed give an idea of the magnitude of reduction that can be accomplished. The bar however, since it is the entire reinforcement is accurate.

The connection between the wires can be accomplished without diminishing flexibility in the same way that the inner reinforcements were connected with silicone rubber adhesive. The difficulties arise when the thickness is built up to prevent buckling. The easiest way to accomplish this is to bond on a series of square rods on the back side of the wires as was done in testing. The rods, though, will add significant stiffness by virtue of their width. Since the thickness is needed to provide out of plane stiffness, it must be maintained. Reducing the width then makes them more flexible but also leads to stability problems. Thin wires on edge would be rolled onto their sides during forming. One solution to this is to bunch the wires together so that they can support each other. This results in the same effect that occurred during testing. Namely, when the bars are brought close together their ability to move relative to each other is greatly reduced because there is no material between them to stretch resulting in a stiff reinforcement even though each piece is flexible. The wires are the ideal stiffener however if they can be attached correctly. They can be made very thin and so very flexible in-plane but can also be made as tall as needed

The solution to this problem is in not attaching the wires directly to the reinforcement but rather allowing them to run in tubes mounted to the back of the reinforcement which will prevent them from being flattened by forming. The reinforcing wires are connected by means of flexible silicone which is then covered with a rubber sheet to make it durable. Copper tubes are then bonded onto the back side of this sheet. Flat hard temper copper wires are then placed inside these tubes on edge to provide stiffness. To allow the tubes to slip relative to be mounted next to one another but also slip relative to each other they are cut into 1 inch lengths. This way the reinforcement bends in-plane not by stretching the gap between the tubes widthwise but rather stretching the gaps between each group of tubes lengthwise. Copper is used for both the wires and the tubes because of its low specific heat and high thermal conductivity.

3.9 Fixturing of Reinforcements

Once the reinforcements have been made flexible and optimized for thermal performance they must be fixtured such that they can align the parts reliably in the machine. To accomplish this they are mounted on rubber straps that are mounted to the side of the machine. Since the diaphragm does not extend in the region between the side of the machine and the tool, the fixtures can be placed there to effectively line up the parts. The fixtures have to provide positioning in two dimensions only. The offset from the side of the machine to the edge of the tool is consistent which means that the fixtures do not have to adjust in this direction. In the direction down the length of the tool there needs to be some way to line up all the parts. This is accomplished in the tool design. By using a common end point for all the parts the fixture does not have to be adjusted for each part, both lengthwise and widthwise positions are fixed.

One complication to this set up is that the parts have different widths and lengths. Below is a table of the actual flat patterns that the plies are cut to. It is easy to see that they are of quite different widths. Again, dimensions listed are intentionally ambiguous due to the proprietary nature of the exact dimensions.

Part number	Flat pattern width Percentage of rib 2
Vertical fin rib 2	4-5 inches
Rib 3	107 %
Rib 4	107 %
Rib 5	113 %
Rib 6	113 %
Rib 7	105 %
Rib 8	105 %
Stabilizer rib 4	127 %
Rib 5	115 %
Rib 6	125 %
Rib 7	125 %
Rib 8	117 %
Rib 9	125 %
Rib 10	122 %

Figure 3-26 Flat pattern part widths

Despite the differing widths the part all have a common centerline. This means that if they are located by centerline rather than edge, the fixture does not have to be adjustable. The only part of the fixturing that needs to be adjustable is the length. Since all the parts have one end located in the same place the other end, by virtue of the parts being different lengths, needs to adapt to the different positions. This can easily be accomplished by using a simple sliding mechanism.

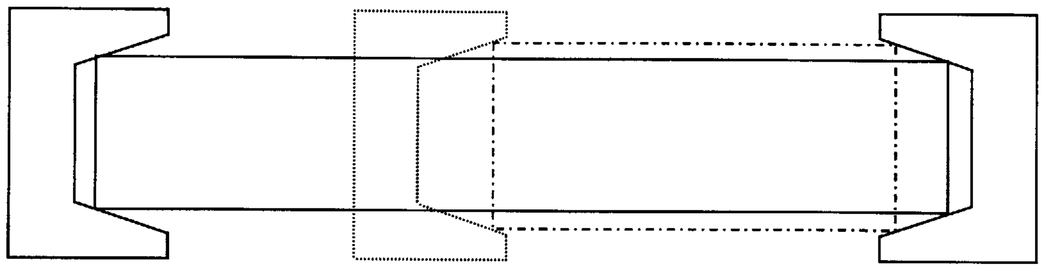


Figure 3-27 Part fixtures

In order to make the fixture line up the parts by their centerlines the end of the fixtures include a notch with angled sides that locates the parts in the middle of them. For a given angle on the notch there will be some difference in lengthwise positioning but this is minor and can be made up when the part is placed on the cure tool.

When the part is loaded, the reinforcements need to be both above and below the part. To allow for the fixtures to be easily removed and replaced reliably they are mounted with stiff rubber strips at each end. This allows for them to be flipped out of the way when the part is loaded and then simply flipped back in before forming. Since the rubber mounting strips are stiff they won't bunch up. This means that they will always lie flat in the machine and locate the reinforcements accurately. Also, when the reinforcements are flipped out of the machine, they will be entirely out and obviously not in place. They will also prevent the frames from sealing and the cycle from starting.

3.10 Impact of Process on Rib Chord Production

Use of double diaphragm forming for rib chord production will have a wide-ranging impact on the production environment. The improvements will be realized in a dramatic reduction in part flow time, increased safety for workers and increased utilization of the production floor and equipment all for very little investment.

Flow time for these parts will be reduced by 70% (Boeing's figure) creating dramatic cost savings. This reduction is possible through a number of improvements over the current method of manufacturing rib chords. First, the parts can be layed up flat which minimizes the time required to create the flat preforms. This can also be done by machine since there is no shaping needed and machine methods have proved reliable on flat lay ups. Secondly, all the shaping for both parts in a machine cycle is combined into one machine step during which the operator can be performing other duties, including making charges for the next cycle. Since the machine is doing all the shaping there is no need for the worker to perform any repetitive stress activities such as shaping the plies by hand and their safety is increased.

The impact on the production floor and equipment utilization is readily seen. Since the one forming machine can easily make production quantities in less than two shifts, all the layup stations that were previously dedicated to rib chord production can be freed up for laying up other parts. This results in large factory floor space savings as well as in increased equipment utilization.

The process will require very little investment in new tooling since it uses the current cure tooling without modification. The forming tooling will be limited in number due to the very few forming tools required and also because these forming tools can be made from inexpensive materials like aluminum rather than Invar 36 or expensive alloys.

The machine itself requires very little in the way of investment. All the components are inexpensive and the structure is very easy to fabricate or adapt. Therefore, all the savings that are produced by the process are not reduced by up front investment in the machine or tooling. The significant savings in terms of the 70% reduction in part flow time is increased when worker safety and facilities savings are added to it. When these savings are viewed relative to the very low investment required to achieve them the great benefits of this process are evident.

Chapter 4

4 Conclusion

The use of composite materials in all industries is expanding. Newly expanding fields include aerospace, infrastructure, construction, automotive, marine and the sporting goods industries. Through advances in material development the materials are becoming less expensive and more adaptable to different applications. Efforts in the manufacturing of the parts themselves though will lead to the real breakthroughs in their usefulness. The need to create simple and efficient methods by which to layup and cure the material is the driver behind a considerable amount of work on composites. As material cost and manufacturing time are reduced composites will be used in more and more applications. Right now they are an ideal material for a huge number of different applications but costs are prohibitive in a many of these.

Carbon fiber is by far the highest performance fiber for most applications. It has remarkable mechanical properties and does not suffer from some of the long term degrading factors that affect other fibers. The processing of carbon fiber, though, is inherently expensive requiring long processing time in large furnaces. The process takes a number of hours to complete and cannot be speeded up to any great extent. Therefore there are unlikely to be any great reductions in price since the cost of running the furnaces at the necessary high temperature is considerable. Also, the amount of time that the material stays in the furnace directly affects the quality of the material and so cannot be reduced substantially.

While the material cost is unlikely to go down significantly, there is nothing intrinsic to the material that prevents it from being manufactured more efficiently. As has been demonstrated in this thesis a huge improvement in processing time can be achieved through a relatively simple manufacturing method. Processes such as diaphragm forming hold great potential for creating significant reductions in the cost of manufacturing composite parts. With each new process composites come closer to the goal of automated production whereby each part can be made without the detailed hand work that is now necessary for some parts. Automation has been the key to some of the large structures that are now being made. Large panels like aircraft skins and large structures like beams and frames can be made by automatic means because they lack highly contoured and detailed areas. In parts that have a high degree of complexity hand layup has remained the typical method of manufacturing.

Reinforced double diaphragm forming is one of the processes that can lead to making these parts more inexpensively. This process and the transfer techniques developed here hold great promise for making composites manufacturing more effective through automation. Since shaping of plies always takes more time than laying them up flat, processes that can transform flat preforms into parts in one step will provide the largest benefits. Clearly, there are structures that cannot be made in this way. Closed structures, for example, like an aircraft fuselage or engine inlet duct have to be made by different methods. Those parts, however, that can start with a flat preform automation is quite applicable.

Current machine methods can layup flat preforms very quickly. These preforms can be transported into place by a variety of methods. The most adaptable methods have been demonstrated in this thesis. A vacuum system that can pick up and transport preforms without distorting them allows the preform to be loaded into a machine automatically no matter what their size. Once the parts have been formed a similar vacuum transporter can then pick up the part and move it to the cure tool without distorting its shape.

The basic framework of forming the part and then transferring it to the cure tool generates a whole range of different options. Since the part can be reliably transported without a dedicated tool structure they can be made while the cure tool is being used in the autoclave. Once the cure is over the new part can be placed on the cure tool and have it sent right back into the autoclave. Hand layup requires that the tool be in the layup area while the part is being made. After layup the tool and part are cured after which the tool can go back to layup for the next part. This method of production cannot continue therefore until the parts are back from the autoclave. The only way to increase this production rate then is to invest in more than one cure tool for a given part. This gets very expensive as most composite tooling is made from very expensive materials.

With a forming process matched with part transfer techniques the parts can be formed without the tool. This enables part to be loaded onto the cure tools immediately after they are out of the autoclave so they can go right back in. Parts could also be stored in the formed condition and placed on tools when they became available. Depending on how high the production rates are, this can be a significant advantage.

For these reasons the forming process is one that enables automation of a whole range of parts. Its flexibility to different sizes and shapes of parts allows the machines to be quite simple. The machine itself is also very simple. All the systems that went into the production machine were very low in cost and easily controlled. So while the machine costs very little, the savings of its use are quite large.

In addition to the machine being simple there is very little additional tooling that is needed for using the forming process. Tooling for hand layup or manufacturing processes that shape material directly onto the tool require that the shape of the tool match the final shape exactly. For double diaphragm forming this is not the case since the part can be formed to an approximate shape and then placed on the cure tool. This means that there will be substantially fewer tools than parts in cases such as the rib chords where the parts follow a general shape. In the case of the rib chords all 42 parts can be made with as few as 7 forming tools.

Reinforced double diaphragm forming has the potential to contribute greatly to the future of composites manufacturing. Due to its easy adaptability to many shapes and materials, the low cost and simplicity of the forming equipment and the substantial increases in production rate, it is widely applicable to different industries and parts. It is through the use of such processes that the manufacturing of composite materials will become cost effective enough to broaden the range of effective applications.

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