Compilation of a Materials Cost Database for a WEB-Based Composites Cost Estimator

by

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Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

June 2001

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ABSTRACT

The production of composite materials continues to be an expensive process. The WEB-Based Cost Estimation Model enables one to approximate the cost of manufacturing composites, so as to assist the user in making sound economic decisions. An extensive, up-to-date materials database is an essential part of such a cost estimator. This paper presents a list of materials to be added to the existing database and also derives a materials selection chart for six manufacturing processes.

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Introduction

The manufacture of composite materials has increased significantly in the past few years. High-strength, light-weight components are no longer coveted by the aerospace industry alone. Rather, as the cost of raw materials such as fibers has steadily decreased, the prevalence of composites in consumer products has been on the rise. Two such examples are the automobile and sports products industries.

The valuable properties of composites have been recognized for years, yet the cost of raw materials has kept composites from widespread application. Although costs are still high compared to their metal counterparts, they are on the decline due to better raw material production methods and a greater volume of production.

The first section of this paper describes the background of the thesis and the motivation for this research. The second section gives a broad explanation of composites. Composite materials, including their properties and physical forms, are discussed in detail in the following section. The actual materials included in the new database are presented in the fourth section. The final section of this paper describes six manufacturing processes for composites, and includes a materials selection chart for these processes.

1. Background and Approach

The goal of this research is the update and expansion of an existing materials cost database for a WEB-Based Composites Cost Estimation Model. This composites cost estimator has been under development for several years now by the Advanced Composites Group of the MIT Laboratory for Manufacturing and Productivity (LMP). The cost estimator is essentially an on-line program which can be used to estimate the manufacturing cost of a composite structure, given a set of inputs. These inputs include the type of raw material, the size and shape of the final product, and the manufacturing process. In order for the estimator to produce a reasonably accurate price figure, the cost database for the raw materials themselves must be as up-to-date as possible. Although materials costs have declined over the past two decades, they are still one of the primary cost drivers in composites manufacturing, as shown in Figure 1.

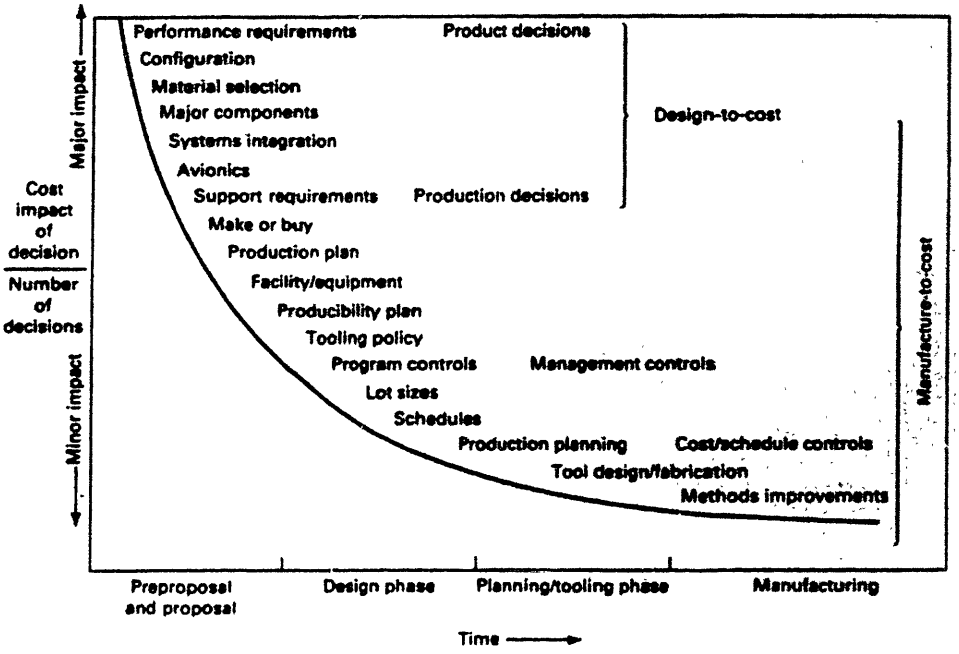


Figure 1: Impact of Decisions on Composites Cost [6]

While the existing database lists materials by generic names, this thesis presents a database consisting of recognizable manufacturer trade names. This move will result in a more user-friendly system for those industry-oriented individuals who are expected to use the cost estimator. This database of trademarked materials with year 2001 prices will be a valuable addition to the WEB-Based Cost Estimator.

2. Composites Overview

A composite is composed of at least two types of materials, a reinforcement and a matrix. The reinforcements, or fibers, provide the strength to the composite. The matrix, or resin, holds the fibers together and works to distribute loads throughout the composite. Carbon fiber, glass fiber, and aramid fiber are the predominant reinforcements found in composites today.

Carbon fibers are renowned for providing the strongest of all composites, yet they are also notorious for their exceedingly high price compared to other reinforcements. Carbon fiber can be produced from a variety of precursors. The most common precursors are rayon, polyacrylonitrile (PAN), and pitch. PAN has the best conversion yield and results in fibers with the highest tensile strength. PAN carbon fibers are the most widely used despite their high cost relative to rayon and pitch carbon fibers [6].

Glass fibers provide the reinforcement in 90 percent of all composites. This is primarily due to their very low cost compared to carbon and aramid fibers. The two most common types of glass fiber are E-glass (electrical grade) and S-glass (high strength) [6].

Aramid fibers are the most abundant organic reinforcements. The term "aramid" describes the substance from which the fibers are formed, aromatic polyamides. Aramid fibers are widely known commercially by the DuPont™ trademark name Kevlar® [6]. They fall between carbon and glass fibers in terms of cost.

Resins are classified as either thermosets or thermoplastics. Thermosets are polymers which cannot be reformed upon heating once they have hardened. Their properties result from the amount of cross-linking at the molecular level [18]. The three most common thermosets include epoxy, polyester, and vinyl ester. Epoxies cost more than polyesters and vinyl esters, and have higher strength. Polyesters are the least expensive of these three thermosets [6].

Thermoplastics are polymers which can be softened (or melted) and reformed upon heating. They are linearly polymerized and do not exhibit cross-linking [18]. Examples of thermoplastics include polyamide-imide (PAI), polyetheretherketone (PEEK), and polyethylene (PE). PEEK has the highest cost of these three, followed relatively closely by polyamide-imide. Comparatively speaking, polyethylene is a very inexpensive polymer.

3. Material Descriptions

3.1 Material Forms

3.1.1 Continuous Roving

The most common dry fiber form used in composites is continuous strand, or roving. Roving is essentially continuous fiber wound on a spool, resembling thread on a bobbin. Continuous carbon fiber is normally referred to as continuous tow rather than roving, but both terms describe the same fiber form. A fiber tow consists of a certain number of filaments, typically in the thousands. Continuous tow carbon fiber with 1,000 filaments is referred to as 1K fiber, while that with 3,000 filaments is known as 3K fiber, and so on. The most widely-used fiber sizes are 3K, 6K and 12K. Others sizes include 1K, 48K, 160K and 320K, which are less common. In general, as the number of filaments per tow increases, so does the weight of the fiber and its tensile strength. The fewer the filaments per tow, the higher the cost [6].

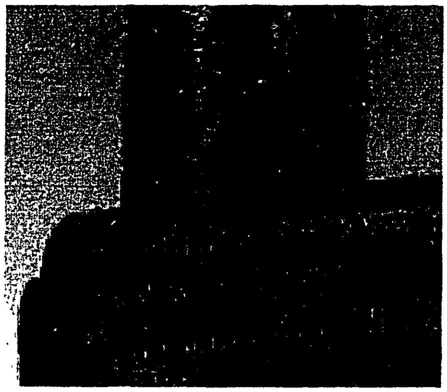


Figure 2: Continuous-Tow Carbon Fiber [9]

Glass and aramid fiber are also produced in continuous filament, or roving form. Various rovings can differ in tow size, denier, and filament diameter. The denier is a weight-per-unit-length measure for fiber in filament form (1 denier = $1.111*10^{-7}$ kg/m) [1]. Each denier size corresponds to a different number of filaments, and therefore a different strength. As carbon fiber is typically referred to by its tow size, aramid fiber is referred to by its denier, and glass fiber is differentiated by its TEX (weight-per-unit-length in grams per kilometer). Typical glass fiber TEX sizes can range from 250 to 8860, while aramid fiber deniers range from about 55 to 15,000.

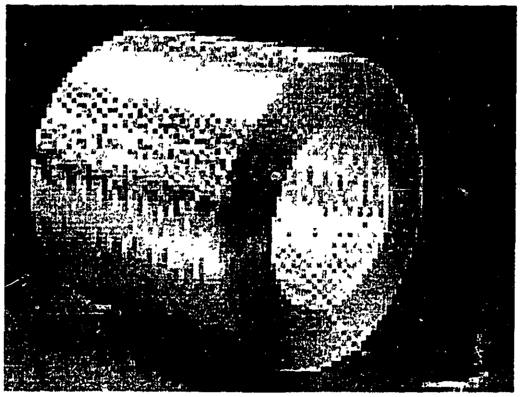
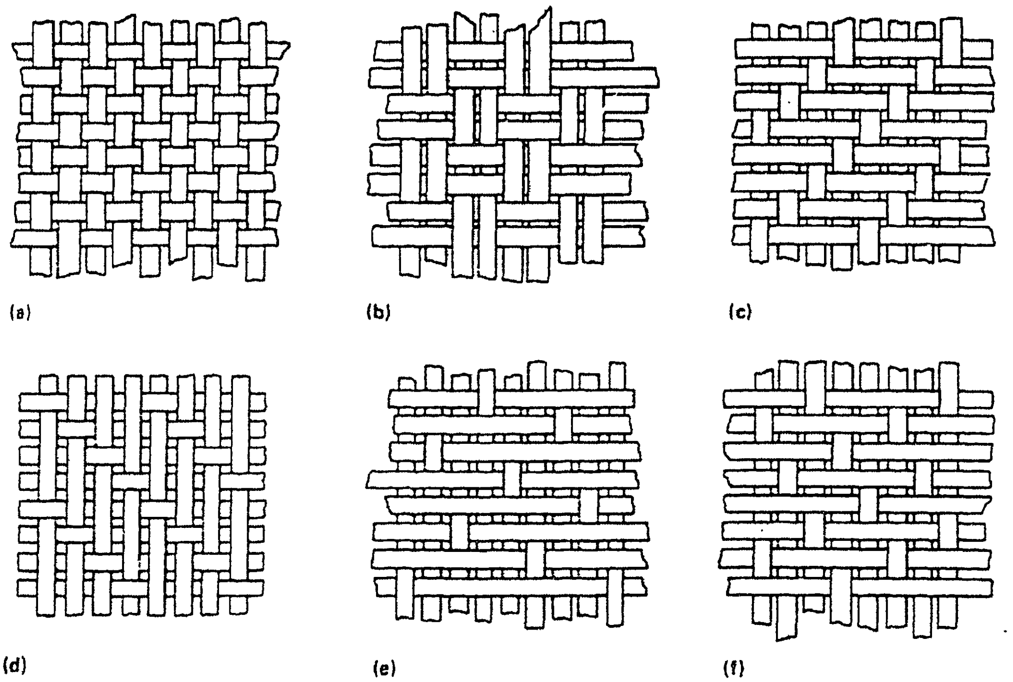


Figure 3: Glass Fiber Roving [15]

3.1.2 Fabric

Carbon, glass, and aramid continuous fiber are also produced in dry fabric form, or woven roving. Glass fiber is also available as continuous strand mat. Continuous fiber can be woven into fabric in a number of styles, each with its own inherent structural properties. Woven fabric is typically sold in rolls which are 38 to 50 inches wide (0.965 to 1.27 meters). The most common two-directional weave styles are the plain weave and satin weave. The plain weave exhibits the most interlacing, resists in-plain shear, and has high tensile strength. The satin weave is less resistant to shear, has high tear strength, and can be draped over curved molds. This workability has made satin weave fabric popular in aerospace composites. Unidirectional fabric exhibits high strength in one direction and is reserved for special applications where such axial strength is required [6].



Fabric construction forms. (a) Plain weave. (b) Basket weave. (c) Twill. (d) Crowfoot satin. (e) 8-end satin. (f) 5-end satin

Figure 4: Fabric Weave Styles [6]

3.1.3 Tape

Another common fiber form is unidirectional (UD) tape. UD tape consists of collimated fiber tows which run in the length-wise direction of the tape [13]. It is most commonly used as a prepreg material and is usually produced in a width of 12 inches (305 mm). For tape widths which are not industry standard, the cost is significantly higher.

UD tape does a much better job in translating fiber properties than two-dimensional fabrics. This is due to the inherent anisotropic (single-direction) reinforcing characteristics of continuous fibers. By placing fibers in the 0° orientation, the tape form is taking full advantage of their strength properties [6]. Carbon, glass, and aramid fiber can all be produced as unidirectional tapes.

3.1.4 Prepreg

Prepregs are woven fabrics, tapes, or tows which have been impregnated with resin. Because the resin is in an uncured or semi-cured state, most prepregs have a "tacky" feel at room temperature which has both positive effects (e.g., adhesion) and negative effects (e.g., alignment) in a manufacturing process like hand lay-up. Today, prepregs are made-to-order products which the end user can specifically formulate to suit his or her application. Prepregs differ primarily in fiber form, fiber type, resin type, and resin content. Resin content is usually expressed as a percentage of the total weight of the prepreg.

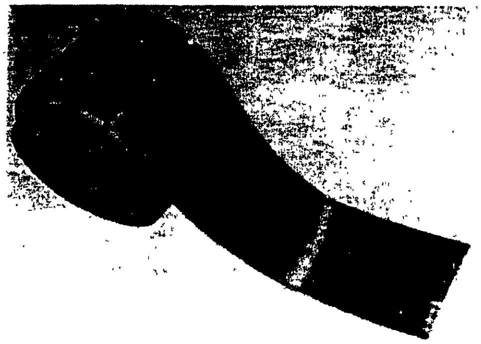


Figure 5: Carbon-Epoxy Prepreg Tape [6]

There are essentially two broad grades of prepregs: those used in high-performance aerospace applications, and those used in lower-performance consumer-good applications. The most common aerospace prepregs are carbon fiber/epoxy resin systems. The lower-performance prepregs are bulk-molding (BMC) and sheet-molding compounds (SMC) [6]. BMC and SMC are typically glass fiber/polyester resin combinations.

In terms of cost, the high performance prepregs are much more expensive than the molding compounds. Within the category of high performance, for a given fiber type, the higher the cure temperature of the resin, the higher the cost of the prepreg. For a given fiber and resin combination, as the width of the prepreg tape or fabric increases, the price per pound decreases. Prepreg tapes are typically less expensive than woven fabric prepregs [6].

3.2 Material Properties

3.2.1 Carbon Fiber

The reinforcement of choice for high-strength composites is carbon fiber. Carbon fiber is derived from three different precursors: rayon, polyacrylonitrile (PAN), and isotropic and liquid crystalline pitches. Rayon and isotropic pitch result in carbon fiber with a relatively low elastic modulus, typically less than $5*10^{10}$ Pascal (50 GPa). PAN and liquid crystalline pitch fibers have much higher moduli, usually greater than 200 GPa. PAN carbon fiber, due to its high strength and relatively high conversion yield (at least 50%), is the most common type of carbon fiber available today. With its low conversion yield (25%), carbon fiber derived from rayon is the most expensive [6].

Carbon fiber has a lower density than glass fiber and a much higher elastic modulus. Its tensile strength is nearly always superior to that of E-glass, which is not necessarily the case with S-glass. Although aramid fiber is less dense than carbon fiber, it is not as strong. Carbon fiber's high strength and light weight make it ideal for those composites with aircraft and space applications.

3.2.2 Glass Fiber

Glass fiber is the most abundant reinforcement found in composites, primarily due to its low cost. It is derived from the same materials (silica, etc.) as bulk glass and is formed by extruding molten glass through an orifice. Compared to carbon and aramid fiber, glass fiber has high density and low elastic modulus. Glass fiber is available in a number of different types, each with slightly different chemical make-ups. The most common types are E-glass and S-glass. E-glass, or electrical-grade glass, has high electrical resistivity and average strength properties. It is primarily used as a reinforcement in plastics. With its high tensile strength, S-glass, or high-strength glass, has a high cost and is typically reserved for aerospace applications [6].

3.2.3 Aramid Fiber

Aramid fibers are the primary organic fibers found in composites today. Their low density and relatively high strength make them good candidates for a wide variety of composite applications. The commercial name for aramid fiber is Kevlar®, which was invented by the Dupont Chemical Company in the early 1970s.

The two most common grades of aramid fiber are Kevlar® 29 and Kevlar® 49. Kevlar® 49 has the higher tensile strength and modulus, and typically higher cost. Both types come in a number of different sizes, denoted by their denier. As the denier increases, the number of filaments increases and the tensile strength decreases. Due to their lower strength, the higher deniers have lower prices. Kevlar® 49 is available in deniers ranging from 55 (25 filaments) to 7100 (5000 filaments), while Kevlar® 29 deniers range from 200 (134 filaments) to 15,000 (10,000 filaments) [6].

3.2.4 Thermoset Resins

Thermosets are polymers which, once cured, cannot be reheated and reformed. They are the most common matrix materials used in composites due to their low initial viscosity which eases the wetting-out of the reinforcing fibers. Once a thermoset is heated past its glass transition temperature (T_g), the temperature at which its coefficient of thermal expansion changes, it begins to degrade and may eventually decompose [19]. Temperature performance is one of the primary criteria for choosing a particular resin over another for a certain application. In general, the lower the temperature performance of the resin, the lower the cost [6].

When it comes to composite matrices, thermoset resins are rarely used in pure form. Different chemicals can be added to achieve better properties, in terms of higher strength, higher temperature resistance, or better corrosion resistance. Thus, a more accurate term for matrix is actually "resin system." Catalysts can be used with a resin to control the rate of cure. A hardener, or curing agent, can also be added to enhance physical properties of the resin in cured state [6].

Three primary thermoset resins are epoxy, polyester, and vinyl ester. Epoxy is the highest performance resin in terms of strength and thermal resistance. It also has the highest cost and is typically used in aerospace applications. Polyester resins, or unsaturated polyesters, are classified according to their chemical constituents. The two types of polyesters listed in the new database contain either isophthalic acid or bisphenol A (BPA) fumarate. Both polyesters have good mechanical strength, and good thermal and chemical resistance. Vinyl esters exhibit all three of these properties to a slightly higher degree than polyesters. Despite their higher cost than polyesters, vinyl esters find themselves used in similar applications [6].

3.2.5 Thermoplastic Resins

Thermoplastics are polymers which can be reformed after curing. They become "rubbery" after being heated past their glass transition temperature, and will eventually melt if heating continues [19]. Their use in composites has lagged significantly behind that of thermosets for many years. Two of the problems are processability, in relation to high viscosity, and cost. Thermoplastics are typically limited to manufacturing processes such as injection molding and compression molding where discontinuous fibers are required. In terms of cost, thermoplastics with composites applications are generally much more expensive than thermosets, sometimes by a factor of 10.

Three common thermoplastics used as matrices in composites are polyamide-imide (PAI), polyetheretherketone (PEEK), and polyethylene (PE). PAI and PEEK are both high-temperature engineering thermoplastics. PE is actually a "commodity" plastic, but due to its rubbery nature at room temperature, it can be used to produce very tough composites. PAI has the highest modulus, tensile strength, and glass transition temperature of these three polymers.

4. Materials Database

4.1 Trademarked Materials

4.1.1 Carbon Fiber

Continuous Roving			
Product	***Manufacturer***	***Description/Applications***	***Price Source***
Hexcel® AS4C, AS4, IM4, IM6	Hexcel Corporation	PAN-based fiber used in weaving, braiding, pultrusion, and prepregging; fiber has been sized* and can be surface treated [9]	Hexcel Fibers
Hexcel® IM7, IM8, IM9, UHM	Hexcel Corporation	PAN-based fiber used mainly in prepregging; fiber has been sized and can be surface treated [9]	Hexcel Fibers
Thornel® T-300, T-650/35	BP Amoco	PAN-based fiber, certified aircraft grade [3]	BP Amoco Chemicals
Thornel® T-300C, T-650/35C	BP Amoco	PAN-based fiber, commercial grade; surface has been treated; used in weaving, pultrusion, prepregging [3]	BP Amoco Chemicals
Thornel® P-25	BP Amoco	Mesophase pitch-based fiber; higher density and higher thermal conductivity than PAN-based [3]	BP Amoco Chemicals
Zoltek Panex® 33 48K	Zoltek Companies, Inc.	Low-cost PAN-based fiber	Zoltek
Woven Fabric			
Hexcel® Schwebel 130, 282, 433, 584 Fabric	Hexcel Corporation	PAN-based carbon fabric used in low-pressure composites and aircraft advanced composites [10]	Hexcel Schwebel
ThermalGraph® EWC-300x	BP Amoco	Pitched-based carbon fabric; certified aircraft grade [3]	BP Amoco Chemicals
Unidirectional Tape			
Zoltek Panex® 33 UD21 48K	Zoltek Companies, Inc.	Low-cost PAN-based carbon tape	Zoltek

* "A sizing is any surface coating applied to a reinforcement to protect from processing damage, aid in processing, or improve mechanical properties" [6].

4.1.2 Glass Fiber

Continuous Roving			
Product	***Manufacturer***	***Description/Applications***	***Price Source***
366 Type 30® Fiberglas®	Owens Corning	Owens Advantex® E-glass for use with epoxy, polyester, and vinyl ester resins; treated with silane-based sizing; used in pultrusion and weaving [15]	Ashland Chemical/FRP Supply
449 S-2 Glass®	Owens Corning	High-strength glass for use with epoxy resins; treated with an epoxy-compatible sizing; used in weaving and unidirectional prepregs [15]	Ashland Chemical/FRP Supply
PPG 1062	PPG Industries, Inc.	E-glass fiber designed for use with epoxy resin systems; treated with silane sizing; applications which require high mechanical strength and corrosion resistance [16]	PPG
PPG 1712, 1764 Multi-End	PPG Industries, Inc	E-glass fiber for use with epoxy, polyester, or vinyl ester resins; treated with silane sizing; designed for pultrusion [16]	PPG
PPG 7065	PPG Industries, Inc	E-glass designed for use in laminating clear/high performance acrylic modified panels; treated with silane sizing [16]	PPG
Hybon® 2006 Direct-Draw	PPG Industries, Inc	E-glass designed for use with epoxy resin; designed for pultrusion; treated with silane sizing [16]	PPG
Hybon® 2022	PPG Industries, Inc	E-glass designed for use with epoxy, vinyl ester, or polyester resin; treated with silane sizing; used in pultrusion [16]	PPG
Woven Fabric			
Hexcel® Schwebel 106	Hexcel Corporation	E-glass fabric used in low-pressure composites, aircraft advanced composites, coated and laminated fabrics, electrical laminate [10]	Hexcel Schwebel
Hexcel® Schwebel 112	Hexcel Corporation	E-glass fabric used in low-pressure composites, aircraft advanced composites [10]	Hexcel Schwebel
Hexcel® Schwebel 120, 1543	Hexcel Corporation	E-glass fabric used in aircraft advanced composites [10]	Hexcel Schwebel
Hexcel® Schwebel 1527	Hexcel Corporation	E-glass fabric used in aircraft advanced composites, coated and laminated fabrics [10]	Hexcel Schwebel
Hybon® Woven Roving	PPG Industries, Inc	E-glass fabric used in aircraft and automotive parts [16]	PPG

4.1.3 Aramid Fiber

<table>
<tr><th colspan="4">Continuous Roving</th></tr>
<tr><th>Product</th><th>Manufacturer</th><th>Description/Applications</th><th>Price Source</th></tr>
<tr><td>Kevlar® 29, 49</td><td>DuPont</td><td>Used in weaving, pultrusion, prepregging</td><td>DuPont</td></tr>
<tr><th colspan="4">Woven Fabric</th></tr>
<tr><td>Hexcel®
Schwebel
328, 345, 348, 351, 352
Kevlar® 49 Fabric</td><td>Hexcel Corporation</td><td>Used in hand lay-up, RTM; used in aircraft advanced composites [10]</td><td>Hexcel Schwebel</td></tr>
</table>

4.1.4 Thermoset Resins

<table>
<tr><th colspan="4">Epoxy</th></tr>
<tr><th>Product</th><th>Manufacturer</th><th>Description/Applications</th><th>Price Source</th></tr>
<tr><td>Araldite® GY 507, GY 6010/GY 6010CSR, GY 6020 Liquid</td><td>Vantico</td><td>High-performance resins for aerospace applications; used in hand lay-up, RTM, pultrusion [22]</td><td>Vantico</td></tr>
<tr><td>DERAKANE D.E.R.® 329 Liquid</td><td>Dow Chemical</td><td>Low-viscosity, good thermal properties, and excellent fatigue behavior; designed for use in RTM [7]</td><td>Dow</td></tr>
<tr><th colspan="4">Polyester</th></tr>
<tr><td>AROPOL™ 7241T-15, 7334T-15</td><td>Ashland Specialty Chemical</td><td>Low-viscosity; used hand lay-up, RTM, pultrusion [1]</td><td>Ashland</td></tr>
<tr><td>HETRON® 700</td><td>Ashland Specialty Chemical</td><td>Excellent corrosion resistance; used in hand lay-up, RTM, pultrusion [1]</td><td>Ashland</td></tr>
<tr><th colspan="4">Vinyl Ester</th></tr>
<tr><td>HETRON® 922, 942/35, 980/35</td><td>Ashland Specialty Chemical</td><td>Good corrosion resistance; used in hand lay-up, RTM, pultrusion [1]</td><td>Ashland</td></tr>
<tr><td>DERAKANE® 411-350</td><td>Dow Chemical</td><td>Good chemical resistance, mechanical strength, and impact resistance; used in hand lay-up, RTM, pultrusion [7]</td><td>Dow</td></tr>
<tr><td>DERAKANE® 470-300</td><td>Dow Chemical</td><td>Excellent chemical resistance; excellent high-temperature properties; used in hand lay-up, RTM, pultrusion [7]</td><td>Dow</td></tr>
<tr><td>DERAKANE® 8090</td><td>Dow Chemical</td><td>Good impact resistance; exceptional tensile elongation (at break); very good processability; used in hand lay-up, RTM, pultrusion [7]</td><td>Dow</td></tr>
</table>

4.1.5 Thermoplastic Resins

Polyamide-imide (PAI)			
Product	***Manufacturer***	***Description/Applications***	***Price Source***
Torlon® 4301	BP Amoco	Exceptional wear resistance, thermal performance and chemical resistance; used in military aircraft wear pads; used primarily in injection molding, extrusion and compression molding [4]	BP Amoco Chemicals
Torlon® 5030	BP Amoco	Exceptional strength at high temperatures; used in air-return grills on commercial aircraft; used in shrouds for directing airflow in jet engines; used in connectors and brackets that support electrical wiring; used primarily in injection molding, extrusion and compression molding [4]	BP Amoco Chemicals
Torlon® 7130	BP Amoco	Exceptional wear resistance, thermal performance and chemical resistance; used in military aircraft wear pads; used primarily in injection molding, extrusion and compression molding [4]	BP Amoco Chemicals
Polyetheretherketone (PEEK)			
PEEK™ 381G, 450G, 450FC30 Pellets	Victrex	Excellent high-temperature performance; excellent mechanical strength, creep and fatigue resistance; Used primarily in injection molding and extrusion; used in engine, aircraft exterior and interior components [23]	Victrex
Polyethylene (PE)			
Marlex® C579 High-Density	Chevron Phillips Chemical	Outstanding impact resistance and chemical resistance; used in multi-layer and mono-layer fuel tanks; automotive applications [5]	Chevron Phillips
Marlex® K605	Chevron Phillips Chemical	Used in a number of applications including automotive parts, piping, and industrial films [5]	Chevron Phillips

4.1.6 Prepregs

Product	Manufacturer	Description/Applications	Price Source
Carbon/Epoxy			
NB-1122	Newport Adhesives and Composites, Inc.	PAN-based woven fabric prepreg designed for laminated structures and one-step assembly of sandwich panels [14]	Northern Fiber Glass Sales, Inc.
NB-1450	Newport Adhesives and Composites, Inc.	Flame-retardant, PAN-based woven fabric prepreg designed for laminated structures and one-step assembly of sandwich panels [14]	Northern Fiber Glass Sales, Inc.
AW370-5H/3501-6*, AW370-8H/3501-6*, AW193-PW/3501-6*	Hexcel Corporation	PAN-based woven fabric prepregs	Hexcel
NCT-303, NCT-1122	Newport Adhesives and Composites, Inc.	PAN-based UD tape prepegs	Northern Fiber Glass Sales, Inc.
AS4/3501-6	Hexcel Corporation	PAN-based UD tape prepreg	Hexcel
Glass/Epoxy			
NB-1100 TIP	Newport Adhesives and Composites, Inc.	E-glass woven fabric prepreg designed for the manufacture of laminates [14]	Northern Fiber Glass Sales, Inc.
NCT-106/8	Newport Adhesives and Composites, Inc.	Flame-retardant, E-glass UD tape prepreg recommended for lightweight sandwich parts [14]	Northern Fiber Glass Sales, Inc.
NCT-306	Newport Adhesives and Composites, Inc.	Flame-retardant, E-glass UD tape prepreg [14]	Northern Fiber Glass Sales, Inc.
Aramid/Epoxy			
NB-1109	Newport Adhesives and Composites, Inc.	Flame-retardant, Kevlar® woven fabric prepreg designed for laminated structures and one-step assembly of sandwich panels [14]	Northern Fiber Glass Sales, Inc.
NB-1122	Newport Adhesives and Composites, Inc.	Kevlar® woven fabric prepreg designed for laminated structures and one-step assembly of sandwich panels [14]	Northern Fiber Glass Sales, Inc.
NCT-321	Newport Adhesives and Composites, Inc.	Kevlar® UD tape prepreg designed for laminated structures and one-step assembly of sandwich panels [14]	Northern Fiber Glass Sales, Inc.

* Price is from 1995. Product name has since changed.

4.2 Database Compilation

Due to the prevalence of composites manufacturing in the aerospace industry, it is most likely that the WEB-Based Cost Estimator will benefit engineers within this field. Thus, the types and grades of materials which have been chosen to be included in the database are typically those with aircraft/aerospace applications.

4.2.1 Sources of Price Information

A high priority in compiling cost data for this estimator is the collection of reliable information. The most reliable cost data can be obtained from the manufacturers themselves (e.g., Hexcel, DuPont). All of the prices in the new database, with the exception of those for the Owens Corning glass fibers, have been garnered directly from the manufacturer. The prices for the Owens rovings have been obtained from Ashland Chemical/FRP Supply, one of their distributors in the northeastern United States. Phone calls and e-mails to sales and technical representatives have been the primary methods for gathering price information. Most product technical data are from the company websites.

There are a number of small businesses which sell composite materials, and their pricing information is much more readily available than that of any manufacturer. Most of these companies have websites with downloadable catalogs which contain all of the prices for their products, be it Kevlar® fibers or carbon/epoxy prepregs. While they sell much of the same products as the manufacturers themselves, the intended customers are low-volume users such as hobbyists or small research groups. The result is a price markup on these materials as high as 100% or more [2].

Obtaining cost information from manufacturers is not always an easy task, especially when they are told that the price inquiry will not be leading to a potential purchase, as is the case in this project. The manufacturers do not post their product prices publicly and generally require a request for a quote. While gathering prices from a manufacturer is much more difficult than browsing a small composite retailer's catalog, it is absolutely necessary in order to compile an accurate cost database. In the case of distributors, pricing information is also tough to come by if one is not intending to make a purchase. Nonetheless, price numbers obtained from distributors are generally as reliable as those from the manufacturer, but they may differ slightly based on geographic location and manufacturer/distributor transaction volume.

Obtaining prices for prepregs is the most difficult of all the materials listed in the database. Prepregs are highly-specialized products which manufacturers typically build-to-order based on the customer's specific application. Thus, it is often difficult to get exact cost figures as opposed to "ballpark" numbers. The prepreg prices obtained from Northern Fiber Glass Sales, Inc., a distributor in New Hampshire, are considered estimates. However, according to their sales representative, they should not be off by more than 10% [17]. The Hexcel prepreg prices listed in the database are from the past records of an individual who has made purchases from the company [11]. These cost figures may be considered out-of-date (1995) in comparison to all of the other prices in the new database, but, nonetheless, they give a general clue as to the cost of prepregs.

4.2.2 Price/Volume Relationship

Nearly all of the prices included in the materials database are volume-dependent. The decision was made to list prices for low-volume purchases of the composite materials. For instance, in the case of dry fibers, prices are quoted for purchases of one to 100 pounds. In the case of resins, prices are quoted for purchases of one to four containers. For thermoset resins, which come in liquid form, the container is a 55-gallon drum. For thermoplastic resins, which come in solid form, the container is a 55-pound box.

The only exceptions to the 100-pound rule for fiber are the prices for the PPG glass rovings and fabrics. These prices are quoted for a "truck-load" volume, or approximately 40,000 pounds. This is a huge volume, but the price difference between 1,000 pounds and 40,000 pounds is most likely very small (less than $0.50 per pound). A much larger price increase ($1 to $2 per pound) can be expected when volume decreases from 1,000 pounds to under 100. Consequently, although a 40,000-pound volume seems as if it would result in an extremely low price, the cost is comparable to a 1,000-pound volume. Thus, the error in the PPG prices listed in the database is essentially the price difference between 100- and 1,000-pound volumes.

There exists valid reasoning behind the choice for low-volume pricing. First of all, it is impossible to know exactly what volumes the typical user of the WEB-Based Cost Estimator will be using. Although one can be certain it will usually be more than one-hundred pounds, just how high the volume will go is unclear. With a database of mostly low-volume prices, it is certain that the cost model will rarely underestimate material cost. In other words, the higher prices for the low volumes adds a small safety factor onto the material cost estimate.

To illustrate how the price of carbon fiber differs based on purchase volume, Table 1 is shown on the following page. The average difference in price between volumes below 100 pounds and those above 100 pounds is between $2 and $3 per pound. So, if an individual using the cost estimator plans for a volume of 500 pounds, the materials cost will be overestimated by an average of less than 10%. This is not a bad estimate, given that a 10-percent figure is normally considered a reasonable level of error for most scientific analyses.

Product Name	*Price/Pound [dollars/lb]*	
	0-99 Pounds	*100+ Pounds*
T-300 1K	128.50	128.50
T-300 6K	26.00	24.00
T-650/35 6K	28.00	26.80
T-650/35 12K	26.00	23.70
P-25 4K	49.50	46.50
T-300C 1K	115.00	115.00
T-300C 6K	19.00	17.00
T-650/35C 12K	11.00	9.00

Table 1: Pricing for BP Amoco Thornel® Carbon Fibers

In the case of resins, two different types of price behavior are witnessed for increasing volumes. Figure 6 on the following page shows how the price of polyamide-imide resin from BP Amoco changes with volume. The behaviors of the plots are typical for volume-dependent pricing. Such prices can be expected to decrease until they reach an asymptotic value close to the cost of production plus profit at some high volume.

The second type of price behavior is shown in Figure 7 for Victrex PEEK™ resin. In this case, one price covers a particular range of volumes, and once a certain threshold is reached, the price drops. For instance, 381G PEEK™ pellets cost $47 per pound for one to 11 boxes, $43.75 per pound for 12 to 23 boxes, and $40 per pound for 24 or more.

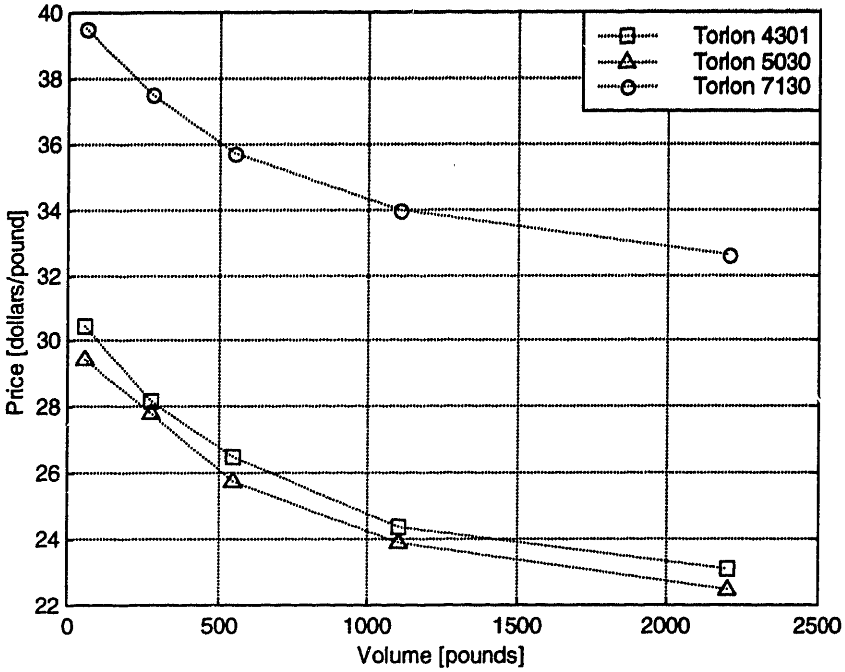


Figure 6: Price of BP Amoco Polyamide-imide Resin vs. Purchase Volume [4]

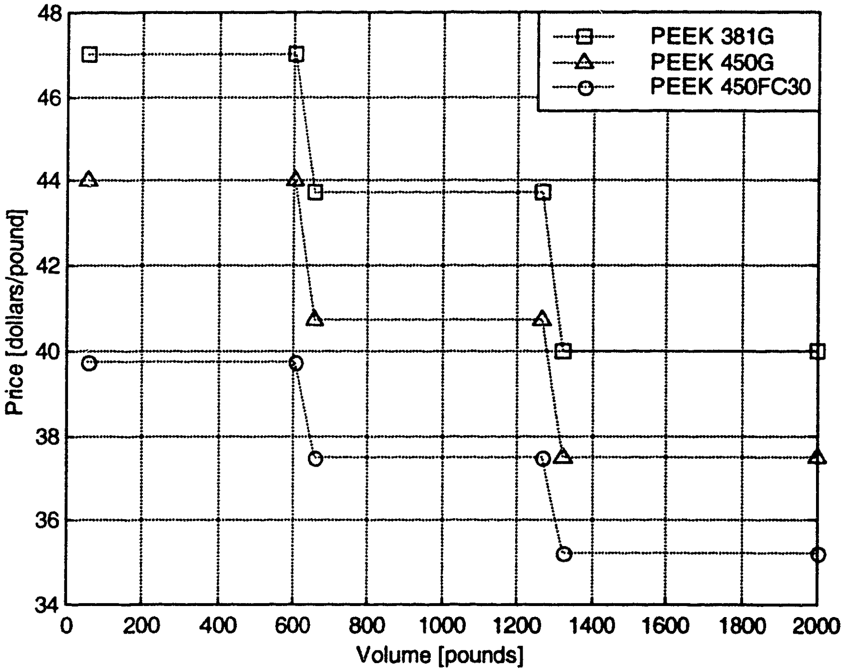


Figure 7: Price of Victrex PEEK^{TM} Resin vs. Purchase Volume [23]

4.2.3 Price/Material-Property Relationship

In addition to purchase volume, material properties can also dictate the behavior of raw-material pricing. As mentioned earlier, the price of reinforcements tends to increase as elastic modulus increases. Figure 8 shows how the price of Hexcel carbon-fiber roving increases with modulus, for each of three different tow sizes. Another point illustrated by Figure 8 is the fact that, for a given modulus, the price per pound increases as the tow size decreases. Although this plot is for carbon fiber, similar behavior can be expected for both glass and aramid fiber.

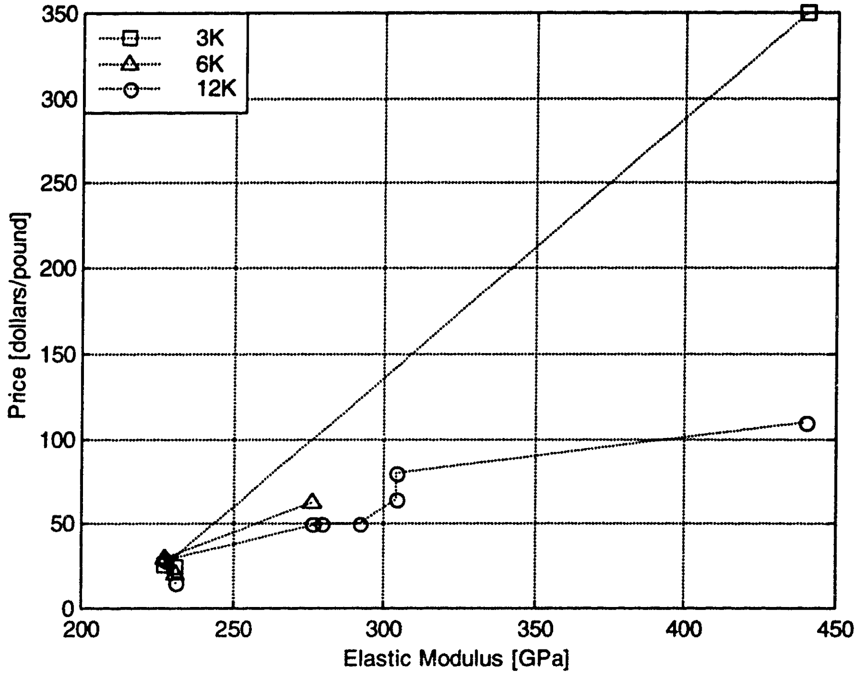


Figure 8: Price of Hexcel Carbon Fiber vs. Elastic Modulus [9]

In the case of resins, temperature performance plays a large role in determining price. Figure 9 shows that customers are willing to pay more for those polymers with higher use-temperatures. In this case, the price is plotted versus the heat deflection temperature (HDT), a value which is determined by an ASTM standard.

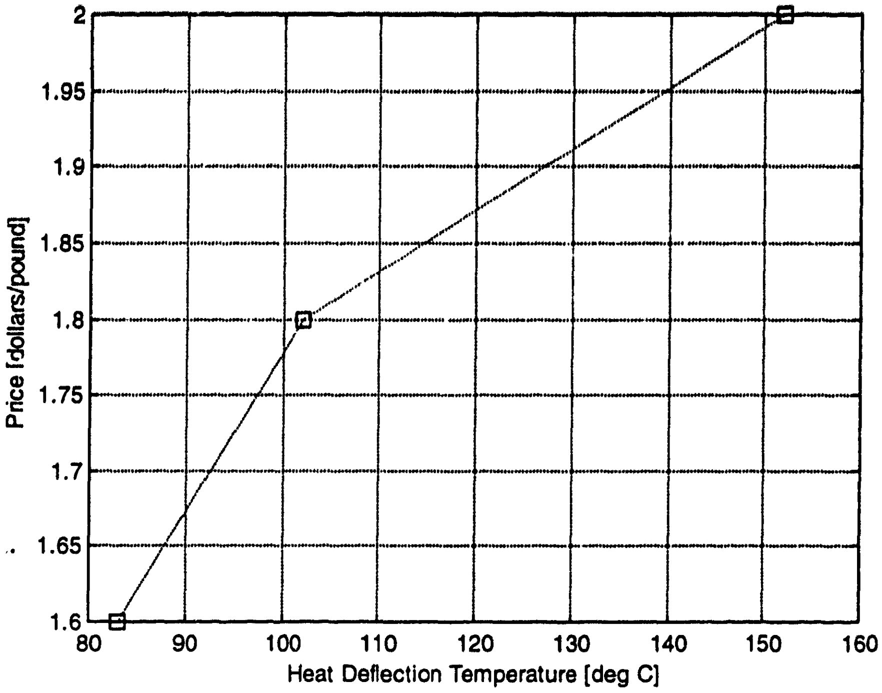


Figure 9: Price of Dow DERAKANE® Epoxy Vinyl Ester Resin vs. Heat Deflection Temperature [7]

5. Manufacturing Processes

5.1 Overview of Processes

Hand Lay-Up

Hand lay-up, or contact molding, is one of the most labor-intensive forms of composites manufacturing. It is an open-mold process in which an operator deposits thin layers of composite material on top of one another, a single ply at a time. The work is performed on a tool, or mold, which has the shape of the final product, as shown in Figure 10 [12].

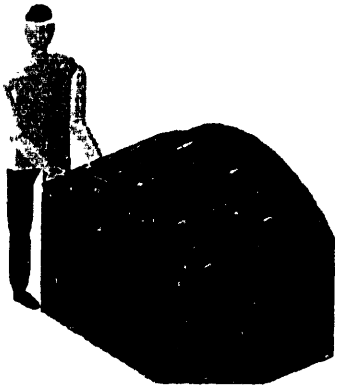


Figure 10: Hand Lay-Up [12]

Since the operator is responsible for placing each layer in the correct orientation and removing any disparities, hand lay-up is not a very repeatable process. It is appropriate for large, high-strength, low-volume composites. The type of hand lay-up operation shown in Figure 10 normally uses woven fiber prepreg or unidirectional tape prepreg [12]. Another type of hand lay-up is wet lay-up. In this process, dry fiber fabric or tape is placed into a mold one layer at a time, and resin is poured on top of each layer and spread by the operator [20].

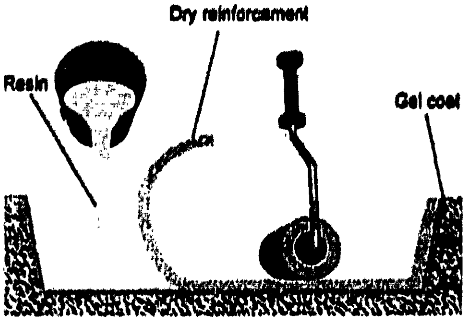


Figure 11: Wet Lay-Up [20]

Automated Tow Placement/Automated Tape Laying

Automated tow placement (ATP) and tape laying (ATL) are processes used to produce laminated composite parts. A computer numerically-controlled machine is used to lay prepreg tapes or tows onto a mandrel to form the desired part. The tapes or tows are carried on spools which are unrolled as the fiber placement head is moving.

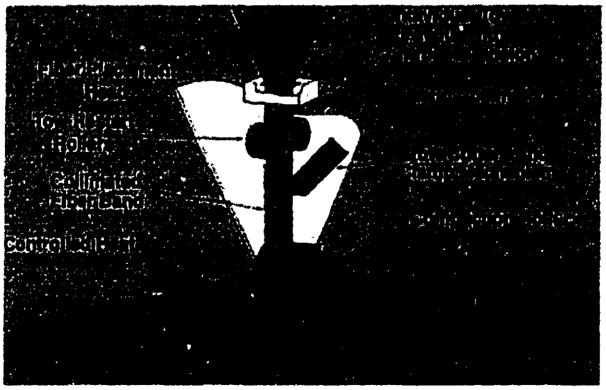


Figure 12: Automated Tow Placement [12]

Due to its high degree of automation, ATP provides both accuracy and repeatability. It is typically used to produce large, low-volume products [12].

Braiding

Braiding is an automated textile process which can weave fiber roving into two-dimensional (2D) or three-dimensional (3D) shapes. Dry fiber tow can be braided into a number of forms with different fiber orientations [6]. The resulting dry fiber preform is then ready for resin impregnation and subsequent processing. Figure 13 shows a two-dimensional braider which can produce tubular preforms.

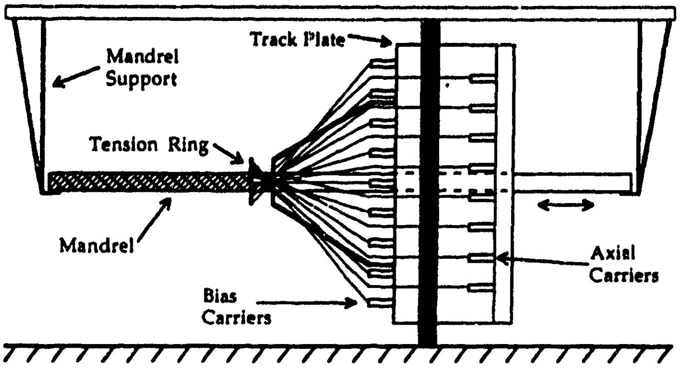


Figure 13: 2D Braiding [12]

Diaphragm Forming

In diaphragm forming, a flat prepreg preform is drawn into vacuum between two thermoplastic diaphragms and clamped onto a mold. After the material is heated to its glass-transition temperature, a hydrostatic pressure difference is produced in order to force the preform into the mold [21]. Diaphragm forming is used for high-volume production of curved parts. The process is much less time-consuming than hand lay-up, and therefore much more economical [12].

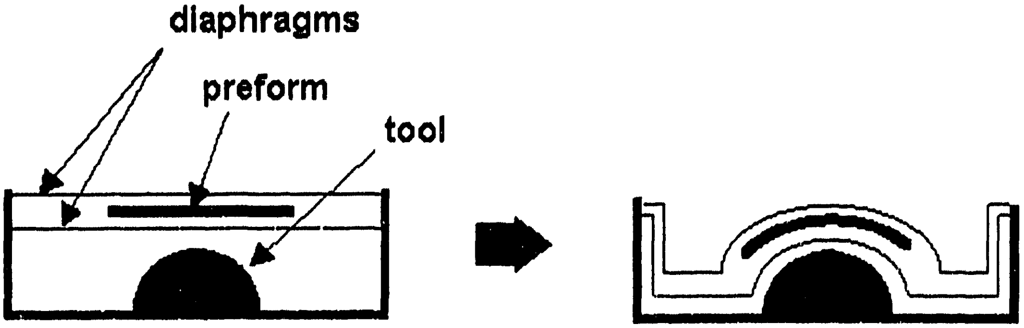


Figure 14: Diaphragm Forming [12]

Pultrusion

Pultrusion is a continuous process for producing linear parts with a constant cross section. Dry reinforcement is spun off creels, impregnated with resin, and then pulled through a heated die which gives the part its cross-sectional shape. Pultrusion is one of the most versatile composites manufacturing processes due to the large variety of raw

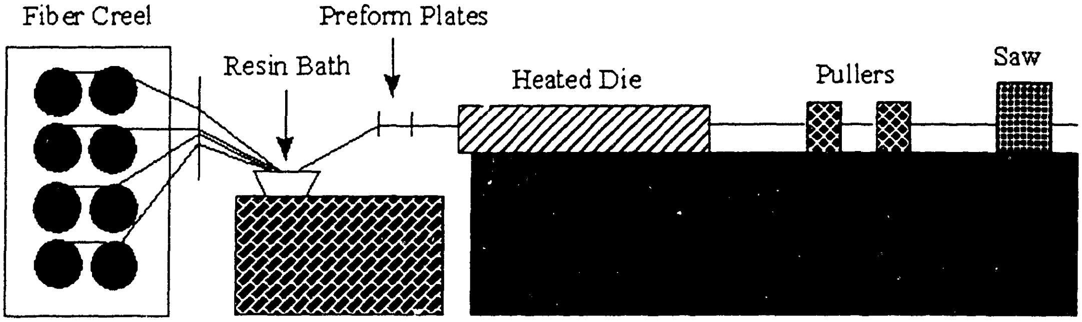


Figure 15: Pultrusion Process [20]

material forms which can be used. Some of the products of pultrusion include rod stock, beams, and tubing.

Resin Transfer Molding

Resin transfer molding (RTM) is a process in which a pre-shaped dry fiber preform is placed within a matched die mold and then impregnated with low-viscosity resin. The resin is injected into the mold under pressure and heat is later applied to cure the part [20].

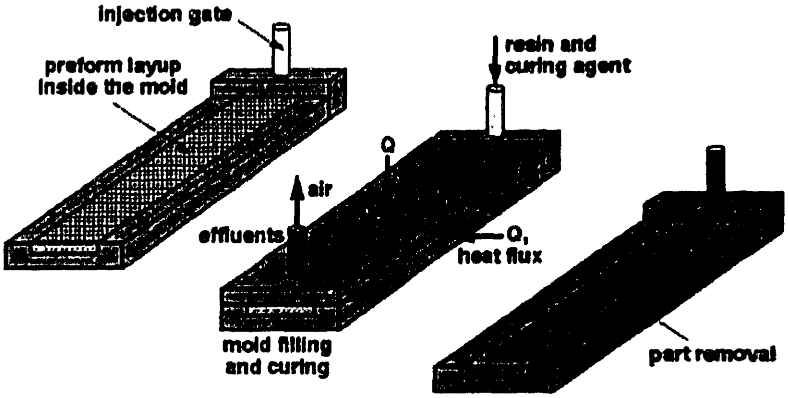


Figure 16: RTM Process [20]

Dry fiber forms typically used include woven roving, continuous-strand mat, and unidirectional tape. Due to their low viscosity, thermoset resins are most commonly used in RTM. This manufacturing process produces composites with a good surface finish and close tolerances. It is typically used for medium to high-volume production [12].

5.2 Material Selection Chart

A goal of this paper is to provide a material selection chart for manufacturing processes as an addition to the WEB-Based Cost Estimator. This chart will enable the user to see what materials are typically used in six common manufacturing processes.

Table 2: Material Selection Chart for Composites Manufacturing Processes

- if material can be used in process: **X**
- if material is commonly used in process: **XX**
- if material is not likely used in process: **O**

Process/Material	**Hand Lay-Up**	**Automated Tow Placement/ Tape Laying (ATP)**	**Braiding (2D/3D)**	**Diaphragm Forming**	**Pultrusion**	**Resin Transfer Molding (RTM)**
Carbon Fiber	**X**	**X**	**XX**	**X**	**X**	**XX**
Continuous roving	O	O	XX	O	X	X
Woven fabric	X	O	O	O	X	XX
Unidirectional tape prepreg	XX	XX	O	X	O	O
Woven fabric prepreg	XX	O	O	XX	X	O
Prepreg tow	O	XX	O	O	X	O
Glass Fiber	**XX**	**X**	**XX**	**X**	**XX**	**XX**
Continuous roving (single/multiple end)	O	O	XX	O	XX	X
Woven fabric	XX	O	O	O	X	XX
Continuous-strand mat	XX	O	O	O	X	XX
Chopped-strand mat	XX	O	O	O	O	X
Unidirectional tape prepreg	XX	XX	O	X	X	O
Woven fabric prepreg	XX	O	O	XX	X	O
Prepreg tow	O	XX	O	O	X	O
Aramid Fiber	**X**	**X**	**XX**	**X**	**X**	**XX**
Continuous roving	O	O	XX	O	XX	X
Woven fabric	XX	O	O	O	X	XX
Unidirectional tape prepreg	XX	XX	O	X	X	O
Woven fabric prepreg	XX	O	O	XX	X	O
Prepreg tow	O	XX	O	O	X	O
Thermoset Resin	**XX**	**XX**	**O**	**XX**	**XX**	**XX**
Epoxy	XX	XX	XX	XX	X	XX
Polyester	XX	X	X	X	XX	XX
Vinyl ester	XX	X	X	X	XX	XX
Thermoplastic Resin*	**X**	**X**	**O**	**X**	**X**	**O**
Polyamide-imide (PAI)	X	X	O	X	X	O
Polyetheretherketone (PEEK)	O	X	O	X	X	O
Polyethylene (PE)	O	X	O	X	XX	O

* The use of thermoplastics in most of these processes is still under scientific development.

5.3 Description of Selection Chart

This material selection chart lists only those manufacturing processes for which the WEB-Based Cost Estimator is capable of performing a cost-model. The materials are listed in general terms (carbon fiber, glass fiber, thermoset resin, etc.) and further delineated based on material form in the case of reinforcements and particular resin type in the case of matrices. The specificity of the fiber material form is important to show how a particular form may be more widely used in a certain manufacturing process as opposed to another form. For example, although continuous roving glass fiber is commonly used in the pultrusion process, glass fiber woven roving is only occasionally used. Although resins within the category of thermosets exhibit similar properties in general, the process-selection chart shows that they also display their own special characteristics based on their use in different manufacturing processes. For instance, epoxy resins are used more frequently in automated tow placement (ATP) and diaphragm forming than polyesters and vinyl esters.

5.3.1 Reinforcement Selection

The choice of a particular reinforcement for use in a composite is typically based on the strength and stiffness of the fiber. In some cases, conductivity and corrosion resistance are also considered. In order to ease processability, the fiber material form does need to change according to the manufacturing process.

5.3.2 Matrix Selection

Choosing which resin to use in a particular composite is not always an easy task. The strength properties of the composite are much more dependent on the selection of the reinforcement. For this reason, it is possible to choose from a number of different resins which are essentially equally-capable of performing at a high level within the composite. Nonetheless, the choice of resin for a particular application depends in large part on the required properties of the final product. Resin selection also depends slightly on the manufacturing process which will be used to produce the composite [6]. For instance, certain processes require resins with low viscosities or fast cure cycles. Table 3 lists the three common thermoset resins and those properties which have the greatest influence on manufacturing process selection.

Resin	*Tensile Strength*	*Continuous Use Temperature*	*Viscosity*	*Reaction*	*Shrinkage*
Polyester	3.4 - 90 MPa	Up to 120° C	Low	Fast	High
Vinyl ester	60 - 90 MPa	Up to 120° C	Low	fast	Intermediate
Epoxy	55 - 130 MPa	Up to 175° C	High	Intermediate	Low

Table 3: General Criteria for Matrix Selection

Appendix

Material	Density [g/cc]	Price [dollars/lb]	Modulus [GPa]	UTS [MPa]	Filament Dia. [um]	Wt./Length [g/m]	Elongation [%]	Yield [m/g]
REINFORCEMENTS								
Carbon Fiber Roving								
Hexcel AS4C 3K	1.78	24.50	231.00	4205	7.0	0.200	1.82	5.100
Hexcel AS4C 6K	1.78	20.50	231.00	4205	7.0	0.400	1.82	2.550
Hexcel AS4C 12K	1.78	15.00	231.00	4205	7.0	0.800	1.82	1.270
Hexcel AS4 3K	1.79	25.50	228.00	4150	8.0	0.210	1.82	4.760
Hexcel AS4 6K	1.79	29.50	228.00	4150	8.0	0.427	1.82	2.340
Hexcel AS4 12K	1.79	29.00	228.00	4150	8.0	0.858	1.82	1.170
Hexcel IM4 12K	1.78	22.50	276.00	4480	N/A	0.723	1.60	N/A
Hexcel IM6 12K	1.76	50.00	279.00	5510	5.0	0.446	1.97	2.140
Hexcel IM7 6K	1.78	63.00	276.00	5080	5.0	0.223	1.84	4.280
Hexcel IM7 12K (5000 spec)	1.78	50.00	276.00	5530	5.0	0.446	2.01	2.140
Hexcel IM7 12K (6000 spec)	1.79	50.00	292.00	5760	5.0	0.446	1.97	2.140
Hexcel IM8 12K	1.79	65.00	304.00	5580	5.0	0.446	1.83	2.140
Hexcel IM9 12K	1.80	80.00	304.00	6120	4.5	0.335	2.01	2.990
Hexcel UHM 3K	1.87	350.00	440.00	3570	4.4	0.085	0.81	11.76
Hexcel UHM 12K	1.87	110.00	440.00	3570	4.4	0.330	0.81	3.080
Thornel® T-300 1K	1.76	128.50	231.00	3750	7.0	0.066	1.40	15.05
Thornel® T-300 6K	1.76	26.00	231.00	3750	7.0	0.395	1.40	2.520
Thornel® T-650/35 6K	1.77	28.00	255.00	4280	6.8	0.391	1.70	2.550
Thornel® T-650/35 12K	1.77	26.00	255.00	4280	6.8	0.763	1.70	1.300
Thornel® T-300C 1K	1.76	115.00	231.00	3750	7.0	0.066	1.40	15.05
Thornel® T-300C 6K	1.76	19.00	231.00	3750	7.0	0.395	1.40	2.520
Thornel® T-650/35C 12K	1.77	11.00	248.00	4280	6.8	0.763	1.70	1.300
Thornel® P-25 Pitch-Based 4K	1.90	49.50	159.00	1380	11.0	0.715	0.90	1.400
Zoltek Panex® 33 48K (45,700 filaments)	1.81	9.00	228.00	3800	7.2	3.300	N/A	0.302
Glass Fiber Roving								
Owens Corning 366 Type 30® Fiberglas®	2.62	1.12	80.00	3100	N/A	N/A	4.60	N/A
Owens Corning 449 S-2 Glass®	2.49	8.00	96.52	4826	10.0	N/A	5.15	N/A
PPG 1062 (TEX 1145)	2.64	1.15	72.39	N/A	13.0	1.145	N/A	0.872
PPG 1062 (TEX 2010)	2.64	1.09	72.39	N/A	13.0	2.010	N/A	0.498
PPG 1062 (TEX 4030)	2.64	1.12	72.39	N/A	13.0	4.030	N/A	0.248

PPG 1712 Multi-End (TEX 4310)	2.64	1.18	72.39	N/A	13.0	4.310	N/A	0.231
PPG 1764 Multi-End (TEX 2300)	2.64	1.01	72.39	N/A	13.0	2.300	N/A	0.435
PPG 7065 Roving (TEX 2350)	2.64	1.34	72.39	N/A	N/A	2.480	N/A	0.403
PPG Hybon® 2006 Direct-Draw (TEX 1985)	2.64	0.95	72.39	N/A	22.0	1.985	N/A	0.504
PPG Hybon® 2022 (TEX 1503)	2.64	0.99	72.39	N/A	20.0	1.503	N/A	0.665
PPG Hybon® 2022 (TEX 1722)	2.64	0.95	72.39	N/A	15.0	1.722	N/A	0.580
PPG Hybon® 2022 (TEX 2205)	2.64	0.95	72.39	N/A	17.0	2.205	N/A	0.439
Aramid Fiber Roving								
DuPont Kevlar® 29 Fiber (1500 denier)	1.44	22.75	70.30	2760	12.0	0.166	3.6	6.00
DuPont Kevlar® 49 Fiber (2160 denier)	1.44	22.50	112.37	2923	12.0	0.240	2.4	4.23
DuPont Kevlar® 49 Fiber (2840 denier)	1.44	22.50	112.37	3000	12.0	0.315	2.4	N/A

Material	Density [g/cc]	Price [dollars/lb]	Modulus [GPa]	UTS [MPa]	Weight [g/m^2]	Width [cm]	Thickness [mm]
REINFORCEMENTS							
Carbon Fiber Woven Fabric							
Hexcel® Schwebel 130 Plain Weave 1K Fabric	1.79	201.00	228.0	N/A	125	106.7	0.14
Hexcel® Schwebel 282 Plain Weave 3K Fabric	1.79	36.65	228.0	N/A	197	106.7	0.22
Hexcel® Schwebel 433 5H Satin Weave 3K Fabric	1.79	34.25	228.0	N/A	285	106.7	0.32
Hexcel® Schwebel 584 8H Satin Weave 3K Fabric	1.79	37.02	228.0	N/A	373	106.7	0.42
ThermalGraph® EWC-300x Plain Weave (4K Pitch-Based)	2.10	250.00	275.0*	689*	610	89.0	0.94
Carbon Fiber Unidirectional Tape							
Zoltek Panex® 33 UD21 48K	1.81	15.00	228.0	3800	N/A	127.0	1.02
Zoltek Panex® 33 UD25 48K	1.81	15.00	228.0	3800	N/A	127.0	1.15
Glass Fiber Woven Fabric							
Hexcel® Schwebel 106 Plain Weave Fabric	2.57	73.82	68.94	N/A	25	96.5	0.04
Hexcel® Schwebel 112 Plain Weave Fabric	2.57	19.78	68.94	N/A	71	96.5	0.06
Hexcel® Schwebel 120 4H Satin Weave Fabric	2.57	19.70	68.94	N/A	107	96.5	0.09
Hexcel® Schwebel 1527 Plain Weave Fabric	2.57	7.59	68.94	N/A	417	111.8	0.38
Hexcel® Schwebel 1543 4H Satin Weave Fabric	2.57	8.40	68.94	N/A	292	96.5	0.20
PPG Hybon® Woven Roving Plain Weave (610 g/m^2)	2.64	1.61	301.0*	N/A	610	106.7	N/A
PPG Hybon® Woven Roving Plain Weave (814 g/m^2)	2.64	1.54	301.0*	N/A	814	106.7	N/A
Aramid Fiber Woven Fabric* **							
Hexcel® Schwebel 328 Plain Weave Kevlar® 49 (1420 denier)	1.44	33.50	124.00	2760**	217	96.5	0.30
Hexcel® Schwebel 345 4H Satin Weave Kevlar® 49 (195 denier)	1.44	154.20	124.00	2760**	58	96.5	0.08
Hexcel® Schwebel 348 8H Satin Weave Kevlar® 49 (380 denier)	1.44	84.85	124.00	2760**	166	96.5	0.20
Hexcel® Schwebel 351 Plain Weave Kevlar® 49 (380 denier)	1.44	94.84	124.00	2760**	75	127.0	0.10
Hexcel® Schwebel 352 Plain Weave Kevlar® 49 (1140 denier)	1.44	43.60	124.00	2760**	173	127.0	0.25

* in laminate

** approximate value

*** product made-to-order

Material	Density [g/cc]	Price [dollars/lb]	Modulus [GPa]	UTS [MPa]	Viscosity [mPa.s] at 25C	Tg [C]	Heat Deflection Temp. [C]
RESINS							
Liquid Epoxy Thermoset Resin (Bisphenol A)							
Vantico Araldite® GY 507	1.14	2.11	N/A	N/A	600	N/A	<200*
Vantico Araldite® GY 6010/GY 6010CSR	1.17	1.70	N/A	N/A	12,500	N/A	<200*
Vantico Araldite® GY 6020	1.17	1.70	N/A	N/A	18,000	N/A	<200*
Dow DERAKANE D.E.R.® 329	1.16	1.80	N/A	N/A	1100	N/A	N/A
Epoxy Vinyl Ester Thermoset Resin							
Ashland HETRON® 922	1.04	2.01	3.17	86.20	N/A	105.00	105.00**
Ashland HETRON® 942/35	1.08	2.08	3.58	91.70	N/A	121.11	121.11**
Ashland HETRON® 980/35	1.08	2.20	3.31	87.56	N/A	132.22	132.22**
Dow DERAKANE® 411-350	1.05	1.80	3.10	79.00	350	N/A	102.00**
Dow DERAKANE® 470-300	1.08	2.00	3.60	85.00	300	N/A	152.00**
Dow DERAKANE® 8090	1.04	1.60	2.90	66.00	320	106.00	83.00**
Polyester Thermoset Resin							
Ashland AROPOL™ 7241T-15 Isophthalic Polyester	1.07	1.59	3.65	62.74	solid	N/A	98.88
Ashland AROPOL™ 7334T-15 Isophthalic Polyester	1.10	1.57	3.44	86.18	solid	N/A	93.88
Ashland HETRON® 700 Bisphenol A	0.97	2.12	3.17	68.94	solid	N/A	142.22
Polyamide-Imide Thermoplastic Resin							
BP Amoco Torlon® 4301	1.46	30.45	6.60	164.00	solid	260	279.00
BP Amoco Torlon® 5030	1.61	29.45	10.80	205.00	solid	260	282.00
BP Amoco Torlon® 7130	1.48	39.50	22.30	203.00	solid	260	282.00
Polyetheretherketone Thermoplastic Resin							
Victrex PEEK™ 381G, Depth Filtered Pellets	1.30	47.00	3.50	97.21	solid	142.77	160.00
Victrex PEEK™ 450G, General Purpose Pellets	1.30	44.00	3.50	97.21	solid	142.77	160.00
Victrex PEEK™ 450FC30, Lubricated Pellets	1.44	39.75	8.30	141.95	solid	142.77	276.66
Polyethylene Thermoplastic Resin							
Chevron Phillips Marlex® C579 High-Density	0.945	0.60	1.10	22.06	solid	N/A	72.77***
Chevron Phillips Marlex® K605	0.959	0.60	1.59	30.33	solid	N/A	N/A

* for laminate, depends on hardener

** clear castings (HDT at 1.82 MPa)

*** HDT at 0.455 MPa

PREPREGS

	Dry Reinforcement	Price [dollars/lb]	Fiber Areal Weight [g/m^2]	Modulus [GPa]	UTS [MPa]	Resin Content [%]	Cure Temp. [C]	Width [cm]	Cured-Ply Thickness [mm]
Woven Fabric/Epoxy									
NB-1100 TIP	Hexcel® Schwebel 106 Glass	2.75*	25	69**	N/A	34	121-148	127	N/A
NB-1109	Hexcel® Schwebel 328 Kevlar® 49	3.75*	217	124**	N/A	34	121-148	127	N/A
NB-1122	Hexcel® Schwebel 282 Carbon 3K	4.25*	197	228**	N/A	34	148-190	127	N/A
NB-1122	Hexcel® Schwebel 348 Kevlar® 49	3.75*	166	124**	N/A	34	148-190	127	N/A
NB-1450	Hexcel® Schwebel 433 Carbon 3K	5.50*	285	228**	N/A	34	112-135	127	N/A
AW370-5H/3501-6	5H Satin Weave Carbon 6K	43.00	370	69	827	42	176	124.5	0.36
AW370-8H/3501-6	8H Satin Weave Carbon 6K	73.00	370	69	N/A	42	176	124.5	0.36
AW193-PW/3501-6	Plain Weave Carbon 6K	69.00	193	69	758	42	176	124.5	0.20
UD Tape/Epoxy									
NCT-106/8	Owens Corning S-2 Glass®	19.00	125	96**	4826**	34	112-148	30.5	N/A
NCT-303	Hexcel AS4 Carbon 3K	23.00	150	228**	4150**	34	121-148	30.5	N/A
NCT-306	Owens Corning S-2 Glass®	19.00	200	96**	4826**	34	121-140	30.5	N/A
NCT-321	DuPont Kevlar® 49 Fiber (2160 denier)	20.00	150	112**	2923**	34	135	30.5	N/A
NCT-1122	Hexcel AS4 Carbon 6K	22.50	250	228**	4150**	34	171-190	30.5	N/A
AS4/3501-6	Hexcel AS4 Carbon 6K	45.00	150	141	2139	36	176	30.5	0.13

* price in dollars/square foot

** properties of the dry fiber

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