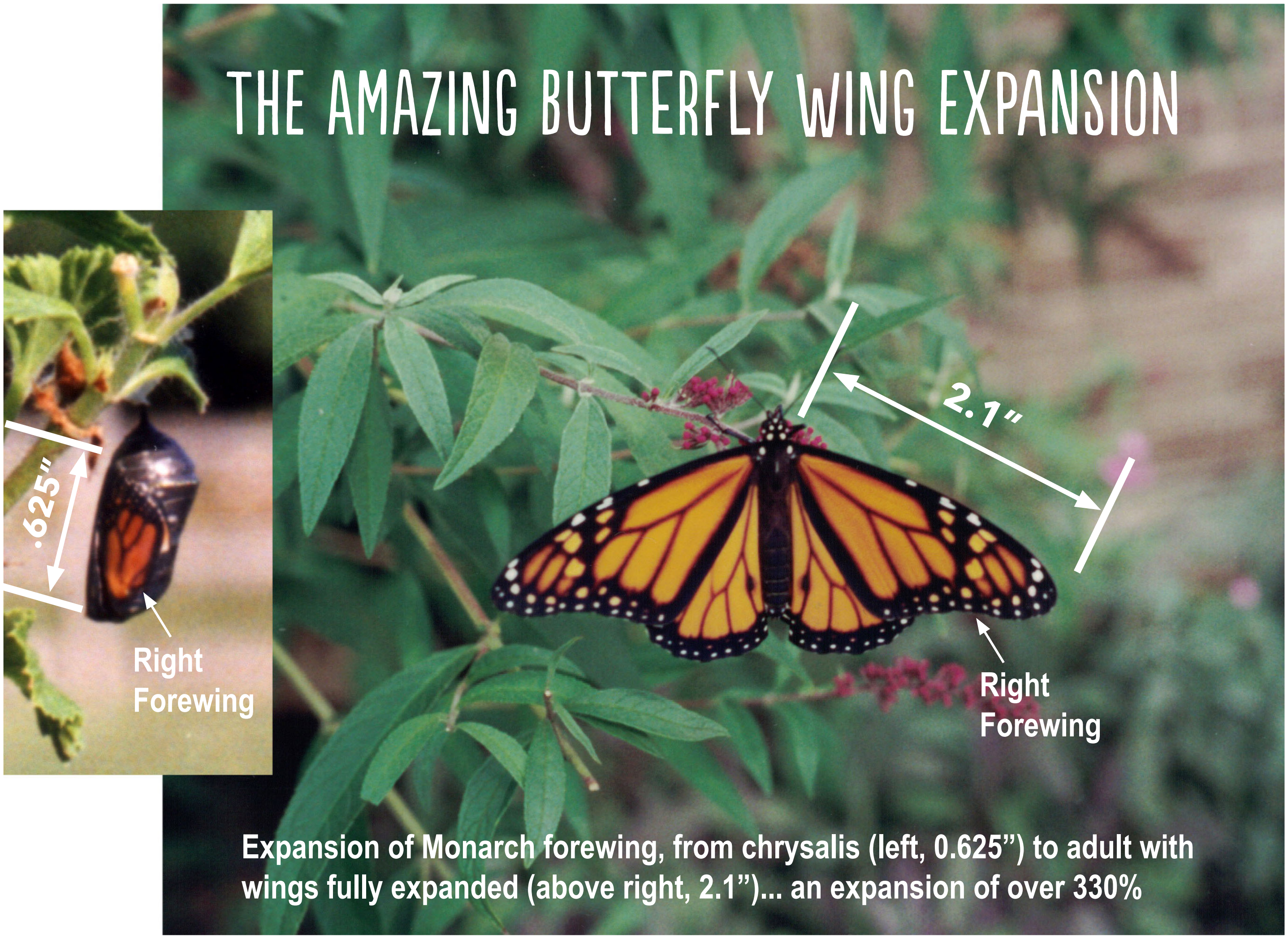
Materials Selection Process for a Butterfly Wing Design,

with extensions to scuba fin design and other applications

Figure 1 - ***Monarch Butterfly, Danaus plexippus, on Asclepias tuberosa***
August 8, 1993 - photographed by Marsha Tufft
(Photo # 1993-8A3-24A, CD image #10).

TERM PAPER for MAT 508, *Materials Selection*
Dr. James Snide, Fall, 1993

Submitted by Marsha Tufft
December 15, 1993



Expansion of Monarch forewing, from chrysalis (left, 0.625") to adult with wings fully expanded (above right, 2.1")... an expansion of over 330%

Butterfly Wing Expansion Observed

Approximately 24 hours before emerging, the monarch chrysalis turns transparent. In the photo, above left, the right forewing of the monarch can be clearly observed. The "hypoteneuse" of the right forewing was measured at 5/8" (0.625") through the side of the chrysalis.

After emerging, the hypoteneuse of the monarch, above right, was measured at 2.1", an elongation of roughly 330%.

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Marsha Tufft
December 15, 1993

Overview:

The idea for this paper began with the observation of a Monarch butterfly, Danaus plexippus, emerging from its chrysalis or pupa. What I observed led me to wonder about the material characteristics of the wings, and it seemed like an interesting idea to see if I could characterize the unique properties of the butterfly wing, which meet the necessary development constraints of the insect and support flight in the adult. What started as a materials selection quest got a bit sidetracked into flight mechanics, butterfly morphology, and numerous other issues (which needed to be explored in order to develop the design and selection criteria, of course).

During my researches, I found numerous articles on animal flight mechanics, including humming birds and insects. One diagram of hovering flight looked like the sculling pattern they teach to swimmers to tread water. I made the connection to my scuba fins, which allow preferential bending in one direction (or preferential stiffness in the other), and I concluded that butterflies might use the same trick to get more work out of the power stroke, and less resistance out of the recovery stroke. So, at least I had a starting point and an application.

As you might expect, I found that I'd bit off a bit more than I could possibly handle. But, I'd like to share what I was able to find. I'll try to share some of the chronology of events, more as an explanation of how and when I discovered the gaps which still need plugging.

The Initial Observation(s):

The chrysalis of the Monarch becomes transparent the morning or evening before the butterfly emerges, showing the detail of the forewings clearly through the membrane. From the time it first starts to peel back the edge of the chrysalis and emerge, to the time that the wings are expanded to full size (still soft, not hardened) is only about 4-5 minutes. The forewings are roughly shaped like a right triangle. Before emerging, the hypotenuse measures about 5/8", with the other two sides measure about 7/16". After emerging, the hypotenuse measures about 2.1", over 330% elongation, while the other sides measure about 1.3" (about 300% elongation). Figure 2 shows a transparent Monarch chrysalis, approximately one hour before the butterfly emerged. You can make out the wing venation of a right forewing through the chrysalis. Compare this with the right forewing of the Monarch in Figure 5. You can see that the wing is not folded up, but condensed in the chrysalis. Figure 3 shows a Monarch immediately after clearing the membrane of the chrysalis, with a swollen abdomen and shriveled wings. Again, you can make out the wing venation in the forewings and barely in the hindwings. Figure 4 shows a side view of the Monarch. You can see some corrugation in the shadows on the wings between veins - the wing is not perfectly flat, there is still some elasticity or flex in the structure.

I also observed a few drops of meconium, or colored waste products, being discharged (around ~5-10 minutes after emerging). But this was followed by drops of clear fluid around ~28 minutes after emerging, and continuing over the next 1-2 hours until the first flight. Figure 6 shows some colored drops of meconium which I caught on a sheet of paper, surrounded by a larger amount of clear fluid.

At this point, I was fascinated by the pure elasticity of the wing structure, and the rapidity of the process of developing and expanding the wings to flight readiness. I was able to observe six Monarch emergences (three female, three male) during August-September, 1993. On average, the Monarchs required between 1.5 to 3 hours after emerging before they were ready to take their first flight.

During this time, I was also rearing Black Swallowtail caterpillars, but I was expecting them to winter over in the chrysalis form and emerge next spring, as last year's brood had. A female apparently emerged during one night and was found downstairs with my cat Tottenham in the morning on 9/15/93. Her wings were deformed. At first I thought they were still soft and in the process of filling out and hardening. Later I realized that Tottenham had found her while the wings were still soft, and that they had set. Figure 7 shows a picture of the butterfly, "Ginger I." You can clearly see the bend in the left forewing. The hindwings were also folded in thirds, and the right forewing was also deformed. I couldn't reset the wings. They appeared to have undergone a "polymerization" process. I later wondered if the excess clear fluid that is emitted during the emergence process was water and actually a by-product of a condensation polymerization process.

At this point, I was hooked. A few conversations with Dr. Snide made me aware of other researches into aspects of insect structure (elliptical fibers in beetles), and I conducted a literature search on butterfly wings. I got a few leads, which got me more references, and soon I was pulling a string which led me to a number of articles about insect/animal/butterfly flight mechanics in both biological journals and fluid mechanics journals.

This led me to attempt some photos of Monarchs in flight. Later, I selected some photos to be transferred to a photo CD in November. When the CD came back in December, I started processing the images using Adobe Photoshop. My initial objective was to crop and enlarge specific sections for use in this paper. But, I discovered a few things about the wing deformation during flight that wasn't obvious from the photos.

I hope this gives you an idea of where I headed and why. Before rambling further, let me try to chart out a more methodical, if not logical, progression for the remainder of this paper:

- *Characterization of the Monarch butterfly*
- *Palatability and other defense mechanisms*
- *Maneuverability*
- *Aerodynamics & flight mechanics*
- *Wing structure & corrugation*
- *Power and energy requirements*
- *Summary of wing characteristics & requirements - knowns and unknowns*
- *Materials selection process and criteria*
- *Conclusions and questions to be explored*

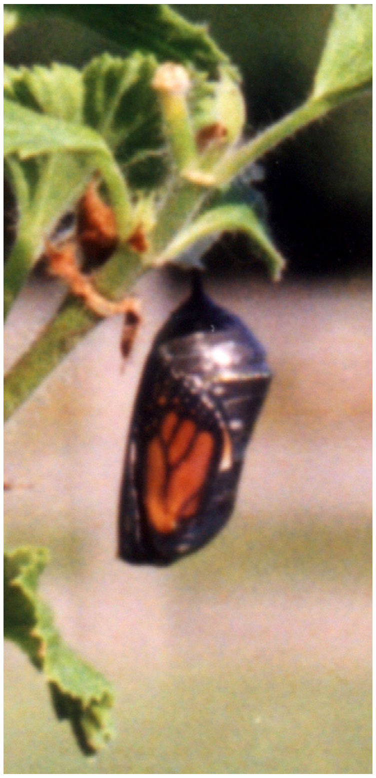

Figure 2 - Monarch butterfly, Danaus plexippus, in chrysalis approximately 1 hour prior to emerging from chrysalis. *September 3, 1993, Cincinnati, Ohio. Photographed by Marsha Tufft (Photo # 1993-9B1-5)*

Figure 3 - Monarch butterfly, emerging from chrysalis. *August 28, 1993, Cincinnati, Ohio. Photographed by Marsha Tufft (Photo # 1993-8F1-22, CD image #20)*

Figure 4 - Monarch butterfly, Danaus plexippus, shortly after emerging from chrysalis. Wings have expanded to full size, prior to first flight. *August 28, 1993, Cincinnati, Ohio. Photographed by Marsha Tufft (Photo # 1993-8F2-11, CD image #33)*

Figure 4 - Monarch butterfly, wings spread, shortly after emerging from chrysalis. Wings have expanded to full size. Photo taken approximately 5 minutes prior to first flight. *September 5, 1993, Cincinnati, Ohio. Photographed by Marsha Tufft (Photo #1993-9B2-23A).*

Figure 6 -
Paper beneath emerging Monarch showing traces of colored meconium and a clear fluid.
August 28, 1993, Cincinnati, Ohio.
Photographed by Marsha Tufft
(Photo # 1993-8F3-22).

Figure 7 -
Deformed wings of female Black Swallowtail ("Ginger I") caused by interaction with cat (Tottenham) prior to hardening of wings.
October 3, 1993, Cincinnati, Ohio.
Photographed by Marsha Tufft
(Photo roll # 1993-9D3).

Characteristics of the Monarch butterfly

I found myself limited by my knowledge of butterfly physiology and morphology. During my investigations, I discovered a wealth of studies conducted on the flight mechanics aspect, but relatively little on structural or materials aspects. It's possible that some exists, but that I didn't stumble onto the sources. The major work appears to be done with an aerodynamic perspective (some work dates from 1973-1979, and even earlier). I don't have enough background in aerodynamics currently to know how much of this is directly applicable to aircraft and propeller design, and to what extent this knowledge has already been applied. There are still a number of current articles being published in biological journals continuing with these investigations. These studies even addressed mechanical power requirements to sustain flight, location of center of gravity relative to maneuverability and palatability. So many factors began to fit into place. I'll summarize some of the findings that relate to wing structure, design and function. First, let me try to provide a reference frame about the butterfly life cycle.

Butterflies have four life phases:

1) **egg**, which is laid on the appropriate larval food plant by the female,
2) **larva or caterpillar**, a rapid growth phase where the caterpillar is basically an eating machine, processing food and storing energy; most species require a specific larval food plant, (Monarchs feed on milkweed plants, asclepias family.)
3) **pupa or chrysalis**, an apparently dormant phase during which the wings are developed,
4) **adult or imago**, where the butterfly emerges, with wings to feed on flower nectar, reproduce, and continue the life cycle.

Table 1 summarizes some typical life spans for some local butterflies. These numbers were tabulated from Stokes [reference 36], but other sources have listed the Monarch adult life span as ranging as high as 3-9 months in some cases. The Monarch has one of the longest life spans of all butterflies, and is the only butterfly with a true migration pattern. This is even more intriguing when you consider that no one individual makes the entire cycle of the trip.

Table 1: Comparison of Some Butterfly Life Cycle Spans [1]

Species	***Egg***	***Caterpillar***	***Pupa***	***Adult***	***Winter Stage***
Monarch (Danaus plexippus)	4-6 days	2-3 weeks	5-15 days	**1-3 months**	Adult
Swallowtails, including Black Swallowtail, Tiger Swallowtail, etc.	4-10 days	3-4 weeks	10-20 days	6-14 days	Pupa
Cabbage white	4-7 days	2-4 weeks	8-14 days	6-10 days	Pupa
Admirals, including Viceroy	4-9 days	3-4 weeks	7-14 days	6-14 days	Larva
Angelwings and Tortoiseshells, including Mourning Cloak, Question Mark	4-14 days	3-4 weeks	7-18 days	6-20 days	Adult
Blues, including Spring Azure	3-6 days	2-3 weeks	8-12 days	4-10 days	Pupa

[1] Stokes, 44-91.

Although I've been able to study both Black Swallowtails and Monarchs at close hand, I chose to focus on the Monarch butterfly for the following reasons:

- It's migration pattern and life span make it the most notable flyer of all butterflies (at least from a durability perspective, if not a maneuverability perspective)
- Opportunities to observe the Monarch during the actual pupation process as well as the emergence from the chrysalis have given me more insight into this butterfly than any other.
- Observations of Black Swallowtails (a palatable butterfly) contrasted by those of a Monarch (an unpalatable butterfly) gave me even more insight into the strategies and design considerations of both.

Palatability and other defense mechanisms

Butterflies are relatively defenseless. In order to survive, they've evolved some unique defense mechanisms, which I'll mention briefly because this also affects the flight characteristics.

Caterpillars are relatively defenseless, and rely on camouflage and numbers for survival. Females lay hundreds of eggs, relatively few make it to maturity. Few butterfly caterpillars are considered serious pests, unlike moths and other insect larva. The cabbage white butterfly is perhaps the only one (noticed because it munches happily on some of our food plants). Butterflies tend not to over saturate larval food plants with eggs - the developing caterpillars will munch on the leaves, but not to the extent that health and vigor of the plant is jeopardized. Caterpillars of the swallowtails have an "osmeterium" or forked projection that they can erect out of their forehead when provoked. It's supposed to have a foul odor, and make them appear like a small snake (my nose isn't sensitive enough to comment on this).

Larva of the Monarch, and a few other species such as the pipevine swallowtail and zebra longwing, feed on larval plants that make them poisonous to birds, retaining enough of the chemicals even as adults so that ingesting even a portion of a wing is enough to cause vomiting and nausea in most birds. The strategy is to enable both butterfly and bird to survive these experiences, so that others may benefit: one experience is enough to teach the bird to avoid orange colored butterflies (in the case of the Monarch), thereby giving protection to many other Monarchs. The Monarch, like most butterflies, is designed to be able to fly even with significant wing loss, so there's margin for surviving bird attacks. Other species of butterfly which are not poisonous, like the Viceroy, try to get protection by mimicking the coloration of a poisonous species.

Maneuverability

What does this have to do with flight mechanics? Well, I ran across a study which compared the location of the butterfly center of mass with maneuverability and palatability [Marden, reference 23; Srygley and Dudley, reference 35]. Dudley reported that the center of mass, cmbody, was located closer to the wing base in palatable butterflies, and lower in poisonous butterflies. This had the effect of increasing the flight speed and maneuverability of the palatable butterflies, enabling them to evade more bird attacks. Thus, palatable butterflies are more like the "fighter jet" - extremely maneuverable, even unstable flight characteristics. Fighter jets are basically aerodynamically unstable - control surfaces must be computer controlled to maintain stable flight, but the basic instability is what makes this class of aircraft so maneuverable. By comparison, civil commuter aircraft employ more stable designs. They're not designed for evasive maneuvers. These are analogous to the Monarchs of the butterflies. Of the butterflies which were caught or grasped by birds, Dudley noted that a higher percentage of poisonous butterflies survived grasping encounters than palatable butterflies. Thus, the insect body itself was tougher. It appears to me that poisonous butterflies like the Monarch, are designed to be caught and to survive "grasping" by birds. The butterfly gains its defense by being attacked and teaching the bird to avoid its species.

Aerodynamics & Flight Mechanics of Butterfly Flight

Apparently there was great furor over insect flight in the early studies. Measurements of body weight, wing size, and calculations of lift coefficients for various insect wings could not explain how enough lift was generated to achieve flight in several insects. Apparently, insects use principles of unsteady aero which were not previously recognized or understood. Weis-Fogh [reference 38] was one of the first to study this, and described the process as the "clap-and-fling" mechanism. It isn't exhibited by all insects, but butterflies are among those that use this technique.

Many birds taxi or use strong legs to launch them into flight. Some insects also use this approach. But many, including butterflies, possess legs that aren't well equipped for walking, let along running or jumping. Another mechanism was needed to explain how they achieved initial lift upon takeoff. The "clap-and-fling" involves vortex shedding and interaction between the two wings. To illustrate this in simpler terms, picture a butterfly with both wings clapped behind its back. The wings form a single surface, with one atmosphere of pressure action on the outside of both surfaces. At the instant that the butterfly flings the wings apart, there is still 1 atmosphere of pressure underneath both wings, but instantaneously nothing on the top surface, creating a net pressure differential upwards. This isn't a rigorous explanation, but the aerodynamicists have generated one with mathematical rigor. The clap-and-fling mechanism would also explain why so many butterflies sip nectar with their wings folded behind their backs and are reluctant to open them out. At a moment's notice, they can escape - if they're in the "starting position." This also explains why the hind side of the butterfly wing is used for camoflage. Many species are able to blend into bark, or simulate eyespots at the tails of their wings, away from the more vulnerable parts (thus allowing them to survive an attack, with only the loss of a small amount of wing). The position with their wings clapped back is their safest, most defensive position.

However, this doesn't account for all the aspects of butterfly flight. Betts and Wootton [reference 4] note that the "Weis-Fogh" or "clap-and-fling" mechanism is explained in terms of "vortex shedding during rotational motion of the wing at stroke extremes."[2] They also noted that there is still much to be learned about the aerodynamics of flapping flight. They noted that rotational mechanisms may also be operating in some butterflies which exhibit strong wing twisting during flight.

Betts and Wootton also mention a "flap-glide" technique in which fast forward flight is interspersed with periods of gliding. I've observed this often. It seems possible that the elastic nature of the wing membranes, coupled with the body structure might be ideally suited for "parasailing" - the abdomen contains a small sac at the rear which acts as a depository for nutritive substances, but which can also be filled with air.[3] In the gliding sequences observed by Betts and Wootton, they noted that the wings of each specimen (forewing & hindwing) appeared to be unlinked during gliding, perhaps delaying stall at low speeds or high angles of attack. Also, they noted that the wing loading of butterflies appeared to be several orders of magnitude lower than for vertebrates. Although their study of butterfly flight patterns agreed broadly with predictions based on other insect studies and theories, they noted that butterflies behaved in unexpected ways. They exhibited great versatility in switching between flight modes, and ability to shift maneuvers by "startling shifts in frequency, amplitude and stroke plane angle, in a manner quite unlike that of most insects whose flight has been investigated. Inter-and intraspecific differences in kinematic parameters suggest that a wide variety of aerodynamic tricks are in use, whose implications on wing design are quite unknown." [4]

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[2] Betts and Wootton, p. 283 [reference 4].
[3] Daccordi, p. 19 [reference 9].
[4] Betts and wooton, p. 287 [reference 4].

I attempted to capture a few photos of butterfly flight myself. Figures 8-13 show the actual photos. These were transferred to photo CD, and I was able to zoom in further (black and white laser printer output follows for some of the photos, in various magnifications. This gave me further insight into the mechanics of Monarch flight. Figure 8 shows a downstroke, which resembles the "butterfly stroke" of swimmers greatly (this was the first time that I understood how that stroke was named). Note the body position above the wings.

Figure 9 again shows a Monarch from below. The zoomed view (figure 9X) shows more clearly that the abdomen is hidden by the wings, and that the wings appear clapped together below the abdomen. Thus, this appears to be a downstroke or glide. You can see the corrugation in the wings - these could be acting as miniature parasails, enhancing glide.

Figure 10 shows extreme deformation in the wing. When viewed in color on the Macintosh, it was clear that the upper tip of the butterflies left forewing is pointed directly down. Figure 10X (the photo CD zoomed view) shows this more clearly than the photo, but it's not as easy to see as it is on the monitor in color. If you look at figure 9X, you can see that no other section of the wing which has the distinctive pattern of the upper corner of the forewing. That's the same pattern seen on the lower most portion of the wing in figure 10X. Thus, the wing is undergoing more extreme deformation than observed in other insects. This is shown more clearly in figure 14, which is a composite of figures 8, 9 and 10.

The body of the butterfly consists of a head, thorax, and abdomen. The wings are attached to the thorax. Specifically, the forewings are attached to the second segment of the thorax, and the hind wings to the third segment of the thorax. Butterflies have exoskeletons. Their muscles can only pull, not push. To extend one part of their body, they must contract another. Perhaps the forewings are used to control the downstroke, or power stroke, and the hind wings are used for the recovery stroke. This could explain figure 10, but it's only my hypothesis.

Figures 11 and 11X show the Monarch in a hovering vertical orientation. Like figure 9, the hind wings are tightly sealed together at the base, however this time the body is in front of the wings. This looks like a sculling or swinging type motion to me. Again, corrugation in the wings is particularly evident at the base of the hind wings. This characteristic of butterfly wings was not noted in other insects, most of which have completely uncoupled wings during flight.

Figure 12 shows a Monarch from a nearly horizontal position, apparently in a down stroke. On the monitor, it appears that a section of the hindwing is bowed out, like a parasail. This can be seen partially in figure 12X.

Figure 13 shows a Viceroy (a mimic of the Monarch) in flight. This is viewed at an angle showing the top side of the butterfly. Unfortunately, the printout doesn't show the detail as clearly as the color monitor. But, corrugation of the hind wings is fairly evident in figure 13X.

Figure 8 -
First flight of newly emerged Monarch butterfly, downstroke viewed from side (male, named "Henry V")
September 5, 1993, Cincinnati, Ohio. Photographed by Marsha Tufft (Photo # 1993-9B2-24A, CD image #57).

Figure 8i -
Illustration of first flight of newly emerged Monarch butterfly–downstroke viewed from side (cleaned up version of Figure 8).
Note that abdomen is above the sealed wing surface.

Figure 9 -
Monarch butterfly in flight. Downstroke viewed from below. Note that the abdomen is hidden by the sealed wing surface.
September 3, 1993, Cincinnati, Ohio. Photographed by Marsha Tufft (Photo # 1993-9D4-21A).

Figure 10 -
Monarch butterfly in flight. Upstroke viewed from side.
September 3, 1993, Cincinnati, Ohio. Photographed by Marsha Tufft (Photo # 1993-9D1-36A).

Figure 11 -
Monarch butterfly in flight. Backstroke viewed from side (butterfly in "hovering" vertical position immediately after takeoff, while flying between flowers).
Note abdomen is below sealed wing surface.
September 3, 1993, Cincinnati, Ohio.
Photographed by Marsha Tufft
(Photo # 1993-9D1-32).

Figure 12 -
Monarch butterfly in flight. Downstroke viewed from back side (aft looking forward).
September 3, 1993, Cincinnati, Ohio.
Photographed by Marsha Tufft
(Photo # 1993-9D4-20A).

Figure 10 -
Monarch butterfly in flight. Upstroke viewed from side.
September 3, 1993, Cincinnati, Ohio.
Photographed by Marsha Tufft
(Photo # 1993-9D1-36A).

Figure 9X

Figure 10X

Figure 11X

Figure 12X

Figure 13X

Figure 14 -
Mapping of Movement of Left Forewing between Figures 8, 9 & 10
Observe deformation that occurs during flapping flight.

Figure 8, illustration

Tip of butterfly's right forewing, viewed from top side of wing

Figure 9

Tip of butterfly's left forewing, viewed from below

Figure 10

Tip of butterfly's left forewing, viewed from side
note wing has folded over during the recovery upstroke (reduced stiffness in this direction)

Wing structure and corrugation

Other papers dealt with wing structure and corrugation, speculating that at low Reynolds numbers, the roughness did not adversely affect flight, and that the corrugation provides needed stiffness [Hertel, reference 17; Rees, references 33, 34; Wootton, reference 39]. Wootton noted that can also enhance deformability, and considered wing deformability to be an essential aspect contributing to insect's ability to generate enough lift for flight. He also noted that insects have no intrinsic wing muscles, unlike birds which can control their wing tips directly. Insects can exert forces on the bases of their wings by muscles and neighboring skeletal elements. There is also a possibility - unconfirmed - of hydraulic pressure acting in the veins. Wootton used the analogy of the wings acting more like the sail of a sailboat, than an airfoil. This again, would take more advantage of the elastic nature of the membrane that I observed. However, Wootton cautioned against taking the analogy too far. But, consider the wing as a cross between sail or parasail, and airfoil, with characteristics of both.

Power and energy requirements

Other studies [Casey, reference 7; Dudley, reference 11; Ellington, references 12 & 13] discussed the energy requirements of flight, the efficiency of muscles, and flight performance as a function of muscle mass. It appears that butterfly muscles are not very efficient, or they do not have elastic storage mechanisms. Although a hard conclusion was not formed, the consensus was that it was more likely that the butterfly muscle was less efficient than expected. This might indicate that the wing had to be more efficient in generating propulsive thrust and lift, something that might be noteworthy for a human adaptation, like a scuba fin. If butterflies can fly when their muscles aren't particularly effective, then the principles they use might have tremendous payback to a scuba diver, for example, to allow maximum thrust with minimum exertion and cramping.

Another study by Dudley [reference 11] noted that the energetic costs of erratic flight trajectories increased the mechanical power flight requirements by an average of 43%, assuming elastic storage, primarily due to fluctuations in horizontal kinetic energy. Now, if I connect this to the previous discussion about the effect of the center of mass position on flight performance, I come to the conclusion that palatable butterflies are more maneuverable (and unstable) in their flight patterns, and that they use this ability to evade predators, but at enormous energy costs (also like the fighter jet). The Monarch, with a more stable flight profile and lower center of mass, is able to maintain a more stable trajectory, which would be needed by an endurance flyer. These observations might also explain the extreme difference in average life spans (6-14 days versus several months). So, everything seems to be adding up. Thus, I would expect the Monarch to waste much less energy then many other species of butterflies.

Let me throw in one more miscellaneous fact. Insects are incredible evolvers. They have six legs, while most serious walkers have only 2 - 4. So, the other two aren't really needed for walking. As a result, they're available for customization. The preying mantis uses two for catching prey. Grasshoppers have developed strong legs for jumping. The list goes on. However, some butterflies, like the Monarch, have only 4 usable legs. The front pair are vestigial. Thus, the Monarch has eliminated excess drag and hauls around only the minimal amount of baggage - very sensible for a long distance flyer.

Summary of wing characteristics & requirements - knowns and unknowns

All right. This is supposed to be a materials selection paper. Let me summarize the criteria that I developed for the wing material (this focused mostly on the vein material, although the wing membranes should also be considered).

The wing must be stiff enough to support flight, but flexible enough to deform. In fact, I believe that the structure must be designed to give differential stiffness - a tendency to bend more in one direction than the other. This would require a material with a stiffness in a very specific range, and would also require a special design or shape. The shape factor is probably a function of vein cross-sectional design, vein layout, and membrane connectivity. I had hoped to do some rough sizing calculations, and did measure a Monarch leading edge vein as having a thickness of .003", compared with .006" for a dragonfly. However, the literature suggests that the veins are hollow and transport hemolymph, and I didn't have enough information to establish likely parameters.

I did find a reference to the primary material composing the exoskeleton, as "chitin"

> "Chitin resembles the cellulose of plants, but instead of being composed of chains of glucose molecules it is made up of chains of acetyl-glucosamine residues. It is associated and perhaps chemically combined with protein; in this form it is colourless, tough and elastic, and composes the innermost layer of "endocuticle." In the outer parts of the rigid areas of the cuticle the protein present is hardened (probably as the result of "tanning" by quinones) to produce a resistant brown or amber coloured material, "sclerotin"; this layer is called the "exocuticle." Outside this there is an extremely thin layer, the "epicuticle," which contains no chitin; this layer is probably complex in structure, but an important constituent of it is a film of waxy material which is responsible for the waterproofing of the cuticle as a whole. Delicate cytoplasmic filaments extend from the epidermal cells, through the substance of the endo- and exocuticle, up to but not penetrating the epicuticle. These are the "pore canals"; they enable the cells to exert their action by the secretion of enzymes, etc. upon the outermost layers of the cuticle.[5]

So now I've opened up the whole field of biomaterials. I found some additional clues to material properties and characteristics in an old chemistry book and in a biomaterials book. Condensation polymerization is often associated with biological polymers. And, of course, many polymers are essentially biological materials, or biologically based. Here's some information I found about natural polymers: [6]

> "Most natural polymers like cellulose (polysaccharides) and proteins are made by condensation polymerization ... Cellulose can be polymerized from the common monosaccharide, glucose, by condensing out a water molecule: [figure given in text]. Hyaluronic acid, chondroitin, and chondroitin sulfate are important polysaccharides present in connective tissues. These polysaccharides lubricate the joints and fibrous tissue layers like collagen and elastin.
>
> Collagen and elastin are proteins composed of amino acids which can be considered as monomers. There are about 20 naturally occurring amino acids (Table 6-2) which are polymerized into (poly) peptides by the condensation process."

The chemistry given by these examples appeared to be closest to the "Aldehydes," which include formaldehyde, HCHO, and Acetaldehyde. Nebergall [reference 27] notes that formaldehyde is sold in an aqueous solution known as formalin.

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[5] Encyclopaedia Brittanica, Volume 12. "Insect." 396-397, 416-417 [reference 15].
[6] Park, 266 [reference 28].

> "The solution contains 7 per cent methyl alcohol which is added to inhibit the reaction of formaldehyde molecules with each other to form an insoluble polymer (compound of high molecular weight). The formaldehyde polymer is Bakelite, an important material which makes formaldehyde an industrially important compound. Formaldehyde causes coagulation of proteins, making it a useful preservative of anatomical specimens and in embalming fluids." [7]

Unfortunately, I ran out of time. Among the questions remaining, are those of polymer chemistry and biochemistry. Perhaps the butterfly circulates an enzyme through the wings which causes them to expand and which triggers and controls the polymerization process, and which generates a condensation polymerization by-product of water, which is emitted after the meconium during the hardening of the wings.

Material selection process and criteria

Table 2 summarizes my criteria, as developed, for a material selection process. It was my intention to use the criteria in Table 2 (which are somewhat incomplete, material properties are not well enough defined at this point) to evaluate different material systems, and then specific candidates.

Table 3 shows an initial screening process. Metals and ceramics are eliminated immediately because they are too stiff. Only polymers and polymeric composites offer the range of characteristics needed.

Table 4 shows a rough attempt at starting to get specific about the types of polymers which might best meet these needs. Based on the little information I found on chemical content, the acetals looked the closed in composition to chitin. Thus, I selected the flexural modulus of acetal homopolymers and copolymers as target for the wing. I would need to do more work to confirm this, or narrow this down further.

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[7] Nebergall, 671-672 [reference 27].

Table 2 - Material Selection Criteria for Butterfly Wing Design

Weight	*Criteria / Requirement*	*Design Parameter Affected*	*Material Parameter Affected*
Req.	***Temperature Range*** • Environmental temperatures between -50 to 150 F, approx. • Flight tempeatures between 32 to 140 F, approx.		Max service temperature. Glass transition temperature.
Req.	***Operating Environment*** • Humidity, between 0 to 100% • Air or sea air exposure • Water and salt water/spray exposure • Constant exposure to UV radiation - sunlight		Chemical composition, reactivity. UV resistance.
8	***Stiffness*** • Material must be stiff enough to support wing in down stroke, yet provide differential flexibility. • Estimate flexural modulus requirement in the range of 350-450 ksi @ 75 F.	Vein configuration (cross-section and layout). Wing membrane and scale design.	Modulus of flexion - vein material. Modulus of tension - wing membrane.
5	***Durability / Structural Integrity*** • Design must sustain flight with up to 30% wing loss. • Wing must be able to provide lift after part has been broken or torn off. • Wing must be durable, impact resistant, tough. Wing must survive bird attacks and weathering with minimal impact on flight performance. • Require "ductility" of about 25-75% elongation minimum at break.	Wings must be designed with excess lift capacity - excess wing surface.	Fracture toughness. Ductility, % elongation @ break. Material must be durable and tough, not brittle.
3	***Color / Aesthetics*** • Wing must support identifying coloration to attract members of the opposite sex for reproduction. • Warning coloration necessary to ward off predators.	Wings must support "scales" to provide color.	
8	***Functionality / Life Cycle*** • Must support flight with minimum weight. • Must last for approx. 1 year constant service • Supports other required biological functions (circulation of hemolymph and oxygen through wings, support scales, scent glands - provide identification).	Design weight. Construction of vein. Loading mission - design for vibrations.	
Req.	***Chemical compatibility*** • Must not be toxic to the insect • Must be compatible with typical organic life forms		Chemical composition.
9	***Formability, processability*** • Must be easily processed. Polymerization must be completed within 2 hours of initiation. Acceptable by products are water, possibly alcohol. Polymer must be able to flow through small veins readily. • Cannot use high cure temperatures or pressures.		Viscosity, formability, processing methods
Req.	***Cost, availability of materials*** • Inspect must be able to generate its own materials from typical biological resources: aire, plant materials, water (C, H, O, N, P, K available; F, Cl not likely available).		Chemical composition

Table 3 - Rating of Material Families against Selection Criteria for Butterfly Wing
(✔ = feasible, ✘ = not feasible)

Weight	*Criteria / Requirement*	*Metals*	*Polymers*	*Ceramics*	*Polymer Composites*
Req.	***Temperature Range*** • Environmental temperatures between -50 to 150 F, approx. • Flight tempeatures between 32 to 140 F, approx.	✔	✔	✔	✔
Req.	***Operating Environment*** • Humidity, between 0 to 100% • Air or sea air exposure • Water and salt water/spray exposure • Constant exposure to UV radiation - sunlight	✔? possible- need prot.	✔? possible- dep. on specific polymer	✔	✔? possible- dep. on specific polymer
8	***Stiffness*** • Material must be stiff enough to support wing in down stroke, yet provide differential flexibility. • Estimate flexural modulus requirement in the range of 350-450 ksi @ 75 F.	✘ too stiff	✔?	✘ too stiff	✔?
5	***Durability / Structural Integrity*** • Design must sustain flight with up to 30% wing loss. • Wing must be able to provide lift after part has been broken or torn off. • Wing must be durable, impact resistant, tough. Wing must survive bird attacks and weathering with minimal impact on flight performance. • Require “ductility” of about 25-75% elongation minimum at break.	✔?	✔?	✘ too brittle	✔?
3	***Color / Aesthetics*** • Wing must support identifying coloration to attract members of the opposite sex for reproduction. • Warning coloration necessary to ward off predators.	? difficult	✔	? difficult	✔
8	***Functionality / Life Cycle*** • Must support flight with minimum weight. • Must last for approx. 1 year constant service • Supports other required biological functions (circulation of hemolymph and oxygen through wings, support scales, scent glands - provide identification).	? difficult	✔		✔
Req.	***Chemical compatibility*** • Must not be toxic to the insect • Must be compatible with typical organic life forms	? difficult	✔	? difficult	✔
9	***Formability, processability*** • Must be easily processed. Polymerization must be completed within 2 hours of initiation. Acceptable by products are water, possibly alcohol. Polymer must be able to flow through small veins readily. • Cannot use high cure temperatures or pressures.	? difficult	✔	? difficult	✔
Req.	***Cost, availability of materials*** • Inspect must be able to generate its own materials from typical biological resources: aire, plant materials, water (C, H, O, N, P, K available; F, Cl not likely available).	? difficult	✔	? difficult	✔

Table 4 - Rating of Polymer types against Selection Criteria for Butterfly Wing

(✔ = feasible, ✘ = not feasible)

Weight	*Criteria / Requirement*	*ABS*	*Acetal*	*Melamine*	*Nylon*	*Polyure-thane*
Req.	***Temperature Range*** • Environmental temperatures between -50 to 150 F, approx. • Flight tempeatures between 32 to 140 F, approx.	✔	✔	Ther-moset		
Req.	***Operating Environment*** • Humidity, between 0 to 100% • Air or sea air exposure • Water and salt water/spray exposure • Constant exposure to UV radiation - sunlight	✔	✔			
8	***Stiffness*** • Material must be stiff enough to support wing in down stroke, yet provide differential flexibility. • Estimate flexural modulus requirement in the range of 350-450 ksi @ 75 F.	130-420 ksi @ 73F bit low?	380-430 ksi @ 73F	1100 ksi too stiff	390 ksi	700-4500 ksi
5	***Durability / Structural Integrity*** • Design must sustain flight with up to 30% wing loss. • Wing must be able to provide lift after part has been broken or torn off. • Wing must be durable, impact resistant, tough. Wing must survive bird attacks and weathering with minimal impact on flight performance. • Require "ductility" of about 25-75% elongation min. at break.	20-100%	25-75% homopoly 40-75% co-polymer	.6-1% ✘	30-100%	100-1000 too stiff for this app? ✘?
3	***Color / Aesthetics*** • Wing must support identifying coloration to attract members of the opposite sex for reproduction. • Warning coloration necessary to ward off predators.					
8	***Functionality / Life Cycle*** • Must support flight with minimum weight. • Must last for approx. 1 year constant service • Supports other required biological functions (circulation of hemolymph and oxygen through wings, support scales, scent glands - provide identification).					
Req.	***Chemical compatibility*** • Must not be toxic to the insect • Must be compatible with typical organic life forms		compa-rable to organic			
9	***Formability, processability*** • Must be easily processed. Polymerization must be completed within 2 hours of initiation. Acceptable by products are water, possibly alcohol. Polymer must be able to flow through small veins readily. • Cannot use high cure temperatures or pressures.	extrusion requires 350-420F ✘				
Req.	***Cost, availability of materials*** • Inspect must be able to generate its own materials from typical biological resources: aire, plant materials, water (C, H, O, N, P, K available; F, Cl not likely available).					

Best candidates appear to be Acetal & Nylon

* Best Candidates *

Conclusions and questions to be explored

I was not able to complete a material selection process with the information I discovered. Much more work needs to be done on understanding the wing structure and biological functions, as well as biomaterial composition and processing methods.

However, I was able to do a preliminary screening, and identify some of the key characteristics of the butterfly wing. The most interesting aspect to me was the idea that the structure needed some range of deformability, even elasticity, as well as stiffness.

The analogy I think of is scuba fins. When I started scuba diving (1982), I used some hard rubber fins with slots in them for lessons. They were very heavy, hard to push, and gave me leg cramps easily. When I purchased my own pair, I bought a pair of "Power Plana" scuba fins. The salesman explained to me (and this is one case where my subsequent experience confirmed the salesman), that the material - probably a polyurethane - allows the flex naturally on the recovery stroke. The trick is that they're slightly stiffer in one direction (the power stroke), and deform more readily in the other (the recovery stroke). As a result, my legs are more effective in doing work on the power stroke, but don't pay the same penalty on the recovery stroke, because they don't have to move as much water. The projected area of the fin is smaller normal to the plane of water resistance. The net effect is that I can propel my self very quickly in full scuba gear, with minimal leg fatigue.

This is where the material selection is critical. The material must be stiff enough, but not too stiff. Hard rubber fin cause much more severe leg cramps than the flexible Power Plana fins - polyurethane?- because the hard rubber fins don't give on the recovery stroke, and your leg is working as hard in both directions.

The shape or design of the component also has to be right. I'd guess that the butterfly wing may have some slight curvature, which is reinforced by the corrugated membrane. When air pushes against the inside of the curvature (on the downstroke), the curvature and reinforcing membrane would catch the air and hold lift, like a parachute. When air pushes against it in the opposite direction, on the outside of the curvature, it would help to deform the wing out of the path of resistance. With curvature, I can envision how the corrugation could provide the necessary stiffness in one direction, and the necessary flexibility in the opposite direction.

As a side note, the "Power Plana" fin is also corrugated slightly, like the butterfly wing. I think that both designs cleverly exploit some unique material characteristics. Both seem to provide means of propulsion which is less taxing to the limited muscle available. But it requires a careful balance of design (shape) and material.

In summary, the butterfly wing appears to be a marvellous combination of adapted material properties and structural design.

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B= Butterfly/Insect Flight Mechanics*   F= Flight Mechanics & Aerodymanics*   G= other published references   M= Materials References   U= Unpublished observations

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Journal articles numbered in chronological order within this category

Figure A1

Self-photo of author with "Henry II", a newly emerged male Monarch butterfly.
August 19, 1993, Cincinnati, Ohio.
Photographed by Marsha Tufft (taken in mirror, Photo # 1993-8C3-13A).

Figure A2

Assistant naturalists, Putney and Tizer, shown with Elizabeth II, a newly emerged female Monarch butterfly.
August 28, 1993, Cincinnati, Ohio.
Photographed by Marsha Tufft
(Photo # 1993-8F3-6).

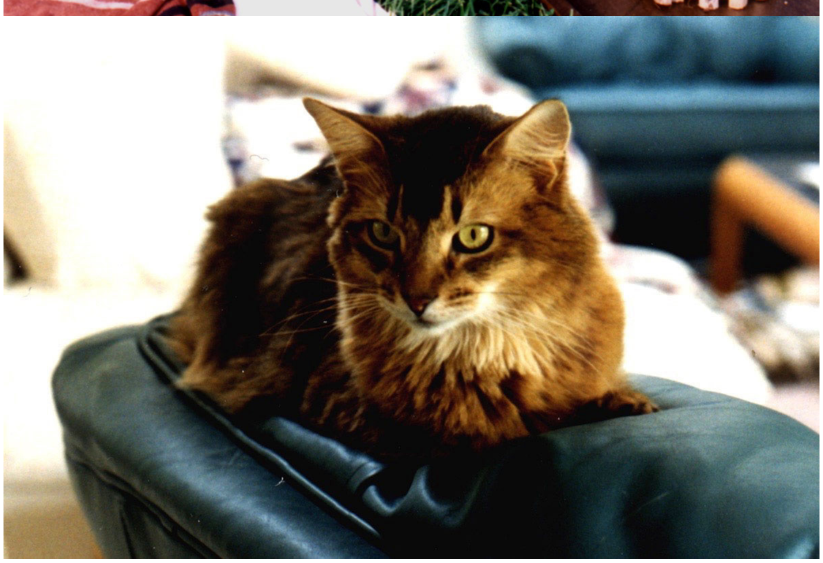

Figure A3

Tottenham, principal investigating feline.