CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter introduces the methods employed to conduct the experiments and simulations in this research project. It is ordered as follows: wing model overview, topological optimization, method and types of analysis used, wing frame fabrication process, static stress experiments, the flapping mechanism and the high speed imaging technique set up.

3.2 Wing model overview

The dragonfly species used in this study is called Diplacodes Bipunctata. This species has a distinct red discoloration with a wing span and body length of approximately 0.055 m and 0.035 m, respectively. A digital image (resolution 1600 dpi) was taken of this dragonfly using a Nikon D7000 camera (Figure 3.1). Both the fore and hind wings were modeled from this digital image.
Figure 3.1  Main parts of a dragonfly wing

a) Radial; b) Costa-leading edge (rectangular pattern throughout) the stiffest pattern of all parts; c) Nodus (part of the vein which is much thicker than the others, plays a pivotal role in the dissipation and storage of mechanical energy); d) Pterostigma (behaves as a dampener);

e) Anal margin and supercosta; f) Small hexagonal patterns which are compactly arranged ranging from 0.0001 to 0.0002 m in size; g) Large quadrilateral and hexagonal patterns ranging from 0.0002 to 0.0004 m in size. 1-15) Dragonfly wing patterns that are divided into several regions for further study.
3.3 Spatial network analysis

Spatial network analysis as mentioned in Chapter 2 is a graphical topological optimization method that is used in various fields involved with geographical maps. A spatial network (sometimes also called geometric graph) is a graph in which the vertices or edges define spatial elements associated with geometric objects, which means the nodes are located in a space within a specified unit (e.g. radius or distance). There are various methods of conducting spatial network analysis. Geographical Information Systems used this method to explore geographic spatial patterns (Angel, 2010). Our methodology is similar, but we are applying this algorithm (based on shape, angle and density) to a biological structure (a dragonfly wing). The idea of simplifying a dragonfly wing based on spatial network analysis was inspired by observing its compactly arranged geometrical patterns. Although there are a variety of methods available to conduct a spatial network analysis, the proximity proposition method was chosen for this analysis because of its conformity of use to a wing structure. The proximity proposition states that among all shapes available, the circle has the shortest average distance to its center (Angel, 2010). Since there are many possible centers for a known shape, it is essential to define at least one appropriate center of a shape before defining a Proximity Index: The Proximate Centre is defined as the center of gravity of a shape. The Proximity Index: ratio of the average distance from all points in the equal-area circle center: average distance to the Proximate Centre from all points in the shape.

Frolov (1975) computed that the mean distance to the centre of a circle is equal to two thirds of its radius and suggested that it would be quite accurate to be used as a measure of compactness. The Proximity Index therefore uses Frolov’s equation. In our case, this new approach is initiated due to the fact that after close observations, it could be noted that the
3.3.1 Canny edge detection algorithm

The image was imported into Matlab and segmented using the Canny edge detection algorithm, resulting in a logical image illustrated with point clouds. This grayscale image was then smoothed with a Gaussian filter to suppress noise. The main vein structures were manually traced out and divided into sections using splines and polygons. An edge detection algorithm was required to define the different regions separated by veins in the image of the wing. The Canny edge detection algorithm is one of the most popular algorithms, because of its detection of edge at a low error rate. The algorithm runs in five steps which are:

1) Using Gaussian filter to smooth the image and remove noise;

   All camera digital images will possess some amount of noise (blurry lines or edges, dots, etc). Noise must be reduced to avoid errors caused by wrongly assuming the noise as a part of the edge. This is an essential first step for Canny edge detection algorithm. The image must then be smoothed using a Gaussian filter. The filter is applied using a matrix quadrant as shown in (1) below:

\[
\begin{bmatrix}
a & b & c & b & a \\
b & d & e & d & b \\
c & e & f & e & c \\
b & d & e & d & b \\
a & b & c & b & a \\
\end{bmatrix}
\]

(3.1)

2) Edges are detected where the computed intensity gradients are the largest;

   The Canny algorithm finds edges where the grayscale intensity of the image changes the most. These areas are found by determining pixel gradients in the image. Sobel-operator (feature detection filter in Matlab) is applied to determine the pixel gradients in the smoothed image. Gradients are approximated in the x- and y-directions by applying the kernels shown in (3.2) and (3.3). In these equations \(K_{GX}\) and \(K_{GY}\) represent the kernel
matrices and $a$ and $b$ are unknowns;

$$K_{GX} = \begin{vmatrix}
-a & 0 & a \\
-b & 0 & b \\
-a & 0 & a \\
\end{vmatrix} \quad (3.2)$$

$$K_{GY} = \begin{vmatrix}
a & b & a \\
0 & 0 & 0 \\
-a & -b & -a \\
\end{vmatrix} \quad (3.3)$$

The strongest edges can then be assumed as an Euclidean distance. This can be measured by applying the law of Pythagoras. It can also be simplified by applying Manhattan distance formula as shown in Equation 3.2. The Euclidean distance value is then applied to the image. The computed edge stresss are then compared to the smoothed image;

$$|G| = \sqrt{G_x^2 + G_y^2} \quad (3.4)$$

where Gx and Gy are the gradients in the x- and y-directions respectively.

Equation 3.5 shows the method to determine the direction of the edges.

$$\theta = \arctan \left( \frac{|G_y|}{|G_x|} \right) \quad (3.5)$$

3) Local maxima are marked as edges;

The blurred edges are converted to sharp edges in this step. The highest value (maximum) gradient is preserved and the others are deleted. The algorithm for each pixel in the gradient image is outlined below:

1. Convert or round all the nearest $\theta$ (gradient) to the nearest 45°.

2. The edge stress of the current pixel in both positive and negative directions are compared. For example, if the gradient direction is north (90°), compare with the pixels to the north and south.
3. Check to see that the edge stress of the current pixel is the largest. If not, remove the value.

4) Use double threshold to detect potential edges;

   The non-maximum values of the gradients may be the true edges of the image but they were not strong due to the large effect of noise or color variation. The simplest way to distinguish them is to use a threshold. The Canny edge detection algorithm uses a double thresholding method (Matlab)

5) Track edges via hysterisis whereby final edges are determined by suppressing all non-connected edges to a prominent edge.

   Strong edges can immediately be included in the final edge image. Even if there is a lot of noise interference, this noise will not be strong enough to mask strong edges. (for threshold levels that are properly adjusted). Weak edges are included if they are deemed to be a part of the true image and only if they are connected to strong edges. BLOB-analysis (Binary Large Object) was used for edge tracking. This preserves strong edges are preserved while suppressing weak edges.

3.3.2 Proximity index

   The smaller vein structures were then modeled, in a similar way, to match the detailed patterns and densities shown in the logical image. The spatial network analysis method (proximity index) was employed to perform the segmentations. Although there are a variety of methods available to conduct a spatial nework analysis, the proximity proposition method was chosen for this analysis because of its conformity of use to a wing structure. A circle is the most compact geometric shape possible, so this was selected as a reference defining the specified unit (radius) (de Smith et al. 2007). The proximity
proposition is defined as the shortest average distance of a circle in a given area of symmetrical shapes. The proximity index is the ratio of the proximate center from all points in the shape. Where \((x_i, y_i)\) are the coordinates of a particular node \((i)\), \(n\) is the total number of nodes, and \((x_c, y_c)\) are the fixed coordinates of \(b_{ref}\) (point of reference).

The mean distance \((d_{CA})\) of any point bounded by the circle (of radius \(R_A\)) to its center is given in Eq. 7 (de Smith et al. 2007):

\[
d_{CA} = \frac{1}{\pi R^2} \int_0^{R_A} 2\pi r^2 \, dr = \frac{2}{3} R_A\]

Since

\[
R_A = \sqrt{\frac{A}{\pi}}
\]

Where \(A\) is the area of the proximity circle

Therefore:

\[
d_{CA} = \frac{2\sqrt{\frac{A}{\pi}}}{3}\]

The proximity index \((I_y)\) is the ratio of the proximate center from all points in the shape.

The \(d_{CS}\) is the radius of the circle. The equation for calculating the proximity index can be written as:

\[
I_y = \frac{d_{CA}}{d_{CS}} = \frac{2\sqrt{\frac{A}{\pi}}}{3d_{CS}}
\]

Nodes were manually placed at the vein structure intersections on the dragonfly wing model selected for biomimicry (Figure 3.2). The nodes were only placed on intersections of veins that are \(3.0 \times 10^{-7} \text{ \mu m}\) thick or lesser. Each circle was manually sized to be the minimum radius required to encompass all of the minor vein patterns (thickness less than
3.0 \times 10^{-7} \mu m) surrounding a single node. In this manner, all of the minor vein patterns were encompassed in one of the many proximity circles inserted.

A fixed wing reference point (bref) is defined as the midpoint of the maximum spanwise length of a single wing (from root to tip). The averaged distance to the fixed reference point (bref) from all nodes is defined by (de Smith et al. 2007):

**Figure 3.2:** Spatial Network Model

[Note: nodes are widely spaced in an exaggerated manner for figure clarity]
3.3.3 CAD model

An initial wire frame, two-dimensional scaled model was constructed using a CAD software Rhinoceros 5.0. This was then exported into AutoCad 2015 to create a three dimensional solid model (Figure 3.3 (a) and (b)). Although there is a difference in thickness across the wing, it is small. For example, the vein at the base and the tip of the wing differ by only $2 \times 10^{-6}$ m (Li et al, 2009). Therefore in order to simplify the model, average vein and membrane thicknesses of $2.5 \times 10^{-6}$ m and $3.0 \times 10^{-7}$ m were used, respectively (Maria, 2011, S. Combes 2010, Jerzy, 2008).

Figure 3.3: (a) Digital image of the forewing of a dragonfly; b) Forewing created by Canny edge algorithm; c) Canny edge forewing created after noise minimization and main pattern identification; d) Forewing CAD model
3.4 Finite element analysis (FEA)

FEA or more commonly known finite element analysis modeling follows three general rules: pre-processing, analysis and post processing. Equation (3.11) is a general structural equation (Bucalem, 1997):

\[ [M] \ddot{u} + [C]u + [K]u = F \cos(At + \gamma) \tag{3.11} \]
Where $|M|$ is the mass matrix, $\ddot{U}$ is the acceleration, $C$ is the damping matrix, $K$ is the stiffness matrix and $F$ is the force vector. The software shall assemble the matrix equation of the structure. The first part would be to solve the matrix equation below:

$$|M| \ddot{U} + |K|u = 0$$  \hspace{1cm} (3.12)

This equation was used to solve the free vibrations of structure. The solution to the equation above gives the natural frequencies (eigenvalues) and the undamped mode shapes (eigenvectors). These are the parameters needed to define the basic dynamical properties of a structure. Since, the main focus is natural frequency, which is a dynamic response, these values are needed in subsequent analysis for dynamic displacements and stresses. For harmonic motions:

$$\ddot{U} = -\omega^2 u$$  \hspace{1cm} (3.13)

In this equation $\omega$ is circular frequency. Substituting equation (3.14) into equation (3.13) gives the matrix eigenvalue expression of:

$$|K| - 1 = |M| u = |I| u$$  \hspace{1cm} (3.14)

In this equation $|I|$ is the identity matrix. The back substitution method is used to obtain the corresponding matrix of eigenvectors $|\Theta|$. The matrix equation of motion for the structure contains off-diagonal terms. The matrix equation may be deduced by introducing the following transformation:

$$u = |\Theta| x$$  \hspace{1cm} (3.15)

and writing the following expressions:
In these equations $\Theta$ is modal displacement matrix, $M^*$ is modal mass matrix, $K^*$ is modal stiffness matrix and $C^*$ is modal damping matrix. The expressions contain only diagonal terms. The damping matrix may be uncoupled on the condition that the damping terms are proportional to either the corresponding stiffness matrix terms or the corresponding mass matrix terms. The uncoupled matrix expressions are:

$$|M^*|x + |C^*|x + |K^*|x = |\Theta|T F \cos (At + r)$$  \hspace{1cm} (3.19)

Each equation in this expression then has the form:

$$M_r x_r + C_r x_r + k_r x_r = d_r \cos (At + r)$$  \hspace{1cm} (3.20)

to which the solution is:

$$n_r = \frac{d_r \cos(At + x_r)}{\sqrt{k_r - m_r X^2} + (c_r X)}$$  \hspace{1cm} (3.21)

where $c$ is modal damping coefficient, $k$ is modal stiffness, and $m$ is modal mass. The dynamic displacements, $u$ at frequency $\omega$ may then be obtained from the transformation.

$$u = |\Theta|\eta$$  \hspace{1cm} (3.22)

where $\eta$ is modal displacement.
3.4.1 Element and mesh

The purpose of building an Autodesk model was to calculate the natural frequency and displacement of the wing under a load. The mesh sizes of the elements were viewed visually to ensure the mesh distribution was fine throughout the structure. The mesh was chosen based on the results of a grid study. A grid study was performed to determine the mesh size required for accurate results. The program was run with both coarse and fine grids, with mesh sizes of 0.001 m and 0.0001 m respectively. The difference in results between the coarse mesh and a fine mesh was found to be less than 2%. However, a comparison of the run times of these mesh sizes was 70% faster for the detailed model and 50% faster for the simplified models. (4 hours for detailed and 2 hours for simplified in the former mesh size). Therefore a mesh size of 0.001 m was used for all subsequent runs.

Shell based elements are often used in finite element analysis models to calculate the displacement. Each element in this model was specified as a shell, in order to simulate the highly efficient load bearing capabilities of an insect wing (Jiyu et al, 2012, Combes, 2010, Tu Delft, 2013, Du Mont, 2009). Teflon was specified as the material for each shell. This is because past research has identified Teflon as possessing similar characteristics to a real dragonfly wing (made up of chitin and chitosan) (Antonia et al, 1998). The model is assumed to have identical material properties in all directions with a single modulus of elasticity and Poisson Ratio value. The properties are summarized in Table 3.1.

Table 3.1: Properties of Teflon

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1260 kg/m³</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>6.0 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Autodesk’s Algebraic Iterative Multi-Grid Scheme, with a third order Newton Raphson integration method, was used as the finite element solver. A general element formulation was selected, because this provides a robust solution for thin and thick elements. This was necessary because the wing model is designed with two different type of thickness (vein and membrane). The analysis formulation is set to nonlinear for natural frequency analysis and linear for static stress analysis. The shell element model is set to be isotropic, as it is assumed that the parts will only experience deflection in the elastic region of the material.

3.4.2 Modal analysis: Mode shapes and MAC

A fixed constraint was placed at the base of the wing. This mimics a real dragonfly which flaps with a fixed joint at the base. The modal analysis computes the natural frequencies, mode shapes, the |M|, |C| and the response analysis matrices. Ten modes of interest were computed in this experiment. The cut-off frequency was set to 100Hz as a constraint for the simulation results. A lumped mass representation is used with an allocated ratio of 0.2 percentage of data storage (S. Combes, 2003).

Correlation analysis of the similar mode shapes between the detailed and simplified model were carried out. MAC (Modal assurance criterion) requires mode shape data from two similar modes of the structure. Due to the large size of the finite element models in terms of their number of nodes, it is not practically possible to include all the nodes into analysis. Therefore 30 nodes were chosen, along the center of the wing span, at an interval of 0.0002 m (distance between each node) were chosen as the representative of the mode shape. The modal assurance criterion was calculated based on the mode shapes obtained from the simulation results which will be discussed in Chapter 3. Mode was calculated
using MathCAD Prime Express 3.0 (Parametric Technology Corporation, 2013) based on this formula:

\[ MAC_n = \frac{(u_n^T D_n^T)^2}{(u_n^T u_n)(D_n^T D_n)} \]  

(3.23)

where \( u_n \) stands for detailed mode shape matrix of the \( n^{th} \) similar mode, \( D_n \) stands for the simplified mode shape matrix of the \( n^{th} \) similar mode, \( u_n^T \) and \( D_n^T \) is the transpose of the detailed and simplified mode shape matrices respectively and \( MAC_n \) is the value for the \( n^{th} \) similar mode shape (the dots represent multiplying these variables).

### 3.5 Artificial wing frames and nano-composite chitosan membrane

Several geometrically identical wings were fabricated based on the simplified model created. The frames were fabricated from seven different materials: stainless steel (Type 321), balsa wood, black graphite carbon fiber laminates, red prepreg fiberglass laminates, polylactic acid (PLA), acrylic sheet and acrylonitrile butadiene-styrene (ABS). Three samples of each wing type were tested to determine their tensile stress and bending performance. The same nano-composite was used as a membrane for each wing frame (which will be discussed in section 3.5.8). The mechanical properties of these materials are as stated in Table 3.2. The compromise between minimizing the weight and maintaining adequate tensile and bending stresss are critical for BMAV wings.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m$^3$)</th>
<th>Modulus of Elasticity (N/m$^2$)</th>
<th>Poisson Ratio</th>
<th>Shear Modulus of Elasticity (N/m$^2$)</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel (Type 321)</td>
<td>7920.0</td>
<td>1.90 x 10$^{11}$</td>
<td>0.3</td>
<td>7.7 x 10$^{10}$</td>
<td>0.01</td>
</tr>
<tr>
<td>Balsa wood</td>
<td>130.0</td>
<td>3.00 x 10$^9$</td>
<td>0.5</td>
<td>1.5 x 10$^{8}$</td>
<td>0.02</td>
</tr>
<tr>
<td>Black graphite carbon fiber</td>
<td>1750.0</td>
<td>2.00 x 10$^{11}$</td>
<td>0.5</td>
<td>2.4 x 10$^{11}$</td>
<td>4 x 10$^{-4}$</td>
</tr>
<tr>
<td>Red prepreg fiberglass</td>
<td>1522.4</td>
<td>2.00 x 10$^{11}$</td>
<td>0.5</td>
<td>3.0 x 10$^{10}$</td>
<td>3 x 10$^{-4}$</td>
</tr>
<tr>
<td>Polylactic acid (PLA)</td>
<td>1190.0</td>
<td>3.50 x 10$^9$</td>
<td>0.36</td>
<td>3.37 x 10$^9$</td>
<td>2 x 10$^{-4}$</td>
</tr>
<tr>
<td>Acrylic</td>
<td>1180.0</td>
<td>3.32 x 10$^9$</td>
<td>0.35</td>
<td>6.20 x 10$^7$</td>
<td>2 x 10$^{-4}$</td>
</tr>
<tr>
<td>ABS</td>
<td>1050.0</td>
<td>2.80 x 10$^9$</td>
<td>0.35</td>
<td>1.03 x 10$^8$</td>
<td>2 x 10$^{-4}$</td>
</tr>
</tbody>
</table>

3.5.1 Fabrication of stainless steel (Type 321) wing frames

![Figure 3.4: Stainless steel type 321 wing frames; a) forewing, b) hindwing](image)

Stainless steel (Type 321) is in the high carbon grade category, meaning that it contains a minimum and maximum of 0.04% and 0.10% carbon, respectively. Higher carbon helps the material retain stress at extreme temperatures. Type 321 is commonly used in aircraft applications; because it is low in density (e.g. relative light weight) and high temperature resistance. In our experiment, the stainless steel was subjected to solution annealing. This is a common process done to ensure the smoothness of the grain structure. This means only the carbides which may have precipitated to the grain boundaries are
dispersed into the metal matrix by the annealing process. Type 321 stainless steel offer higher creep and stress rupture properties.

The stainless steel wing frames were laser cut from sheet metal. These frames were then coated with an anti-rust layer and spray painted using an acrylic lacquer spray. This was necessary because the nano-composite film membrane will expose the wing frame to oxidation. This is because the film contains concentrated glacial acetic acid and tannic acid as a cross-linker. The anti-rust layer and acrylic lacquer spray hinder the oxidation due to the presence of the acids. Oxidation is visibly indicated by purple blotches appearing on the frame. After these processes, the frames were then immersed in the nano-composite suspension which formed a film membrane coating the entire wing, as previously described. Figure 3.4 shows the finished stainless steel wings.

### 3.5.2 Fabrication of balsa wood wing frames

Balsa wood is the most widely-used material used in hobby remote-controlled aircraft. This is because of its extremely low density (making it very lightweight) and high mechanical stress. Balsa wood was chosen for this study because it represents a minimum weight solution. The balsa wood wing frames were cut manually with wood carving knives and then immersed into the nano-composite solution. Figure 3.5 shows the finished balsa wood wings.

![Figure 3.5: Balsa wood wing frames; a) forewing, b) hindwing](image-url)
3.5.3 Fabrication of black graphite carbon fiber wing frames

Black graphite carbon fiber sheets were purchased and visually inspected to make certain they were uniform in appearance and free from foreign material. The specifications are listed in Table 3.3.

Table 3.3: Specifications of black graphite carbon fiber

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>0.04 mm</td>
</tr>
<tr>
<td>Carbon yarn spacing</td>
<td>Four per 0.45 kilograms per strand</td>
</tr>
<tr>
<td>Warp tracer weave spacing</td>
<td>0.3 ± 1 m across the fabric width</td>
</tr>
<tr>
<td>Fill tracer weave spacing</td>
<td>0.6 ± 1 m apart</td>
</tr>
<tr>
<td>Length to diameter ratio (L/D) (See Figure 3.6)</td>
<td>&gt; 10</td>
</tr>
</tbody>
</table>

The woven laminate was hardened using an epoxy resin with a hardener (Araldite rapid kit). Both epoxy resin and hardener were mixed with a ratio of 1:1 and then applied evenly to the laminate in a thin layer. The laminate was then left to cure in a Memmert UNB 300 convection oven for about two hours at a constant temperature of 45°C. The forewing and hindwing shapes were then carved out of the hardened laminates manually with a knife, using the stainless steel wings as a reference. The only difference between the black graphite wings and the others, were that the inner gap regions were not carved out according to the simplified model. Attempts to do so proved impossible, because it resulted...
in delamination of the material. However, the overall size and shape of these wings are the

![Figure 3.7: Black graphite carbon fiber wing frames; a) forewing, b) hindwing same as the others. Figure 3.7 shows the finished black graphite carbon fiber wings.](image)

### 3.5.4 Fabrication of red prepreg fiberglass wing frames

Red prepreg fiberglass plies with a thickness of 0.03mm were purchased and visually inspected. After curing, the red prepreg fiberglass exhibits a plastic-like characteristic unlike carbon fiber which will retain its strand-like properties. This increases the chance of delamination if a resin and hardener is not applied. The red prepreg fiberglass (after curing) does not require an extra application of resin or hardener. In order to create the wing frame structure, the material was warmed as necessary to enable easier manual carving with a knife. Figure 3.8 shows the finished red prepreg fiberglass wings.

![Figure 3.8: Red pre-preg fiberglass wing models after immersion in chitosan nano-composite solutions; a) forewing, b) hindwing](image)
3.5.5. Fabrication of polylactic acid (PLA) wing frames

The PLA wings were fabricated using a Maker Bot Replicator 2X 3D printer. PLA is chosen for its biodegradability, lightweight, flexibility and elasticity (Joong, 2013). The fabricated PLA wing models are shown in Figure 3.9.

![Figure 3.9: PLA wing models after immersion in chitosan nano-composite solutions; a) forewing, b) hindwing](image)

3.5.6 Fabrication of acrylic wing frames

The acrylic wings were fabricated using micro laser machining. Acrylic or polyacrylate are generally known for their resistance to breakage, elasticity and flexibility (David, 2014). Fabricated acrylic wing models are as shown in Figure 3.10.

![Figure 3.10: Acrylic wing models after immersion in chitosan nano-composite solutions; a) forewing, b) hindwing](image)
3.5.7 Fabrication of acrylonitrile butadiene styrene (ABS) wing frames

Models made out of ABS are constructed from a thermoplastic. ABS is very useful for functional applications because it matches 80% of the properties of the real injected production material. ABS models are very accurate and have intermediate level of printed details. You have a lot of freedom for the design of your model. However, the surface quality of the models is rougher compared to other materials. The ABS wings were fabricated using a Maker Bot Replicator 2X 3D printer. ABS is chosen due to its stress, flexibility, and machinability (Hwan, 2012). The fabricated ABS wings are shown in Figure 3.11.

![ABS wing models after immersion in chitosan nano-composite solutions; a) forewing, b) hindwing](image)

Figure 3.11: ABS wing models after immersion in chitosan nano-composite solutions; a) forewing, b) hindwing

3.5.8 Chitosan nano-composite solution (membrane)

The chitosan nano-composite suspension as mentioned earlier was made up of a chitosan suspension reinforced with nano-sized chitin whiskers and cross-linked using tannic acid. This nano-composite film was processed by our research team for this specific purpose and is featured in another article (Rubentheren et al, 2015). The suspension was transformed into a thin 3 mm film by the casting evaporation method. This film was chosen because it closely mimics the material properties of a dragonfly wing membrane. The
mechanical properties and water resistivity of chitosan film can be controlled by the addition of chitin whiskers and tannic acid as a cross-linker. Utilizing nano-sized whiskers as a filler material elevates the composite film’s mechanical property (rigidity). A crosslinking agent is also added to alter the mechanical properties of the film created. Tannic acid is fully biodegradable and less expensive to produce, compared to the other chemical derivatives. Tannic acid also has a high antioxidant capacity and can interact with other biological macro-molecules. Addition of tannic acid as a cross-linking agent reduces the swelling behavior, solubility and the rigidity of the nano-composite film. In order to ensure that the immersion is uniform, the structure was submerged in the solution. This also ensures that both sides of the frame structure are evenly coated with the solution. Once cured, the film created a shiny, transparent film layer that adheres firmly to the frame structure.

Figure 3.12: Wing structure immersed in chitosan nanocomposite solution; (a) fore wing, (b) hind wing
3.6 Numerical Bend-Twist Coupling and Static Stress Simulation Analysis

3.6.1 Numerical bend-twist coupling analysis

The bend-twist coupling is one of the most relevant analyses for a wing cross section. The effect of the bend-twist coupling appears in a wing structure as a link between its two deformation states – bending and torsion. A static bend-twist coupling analysis was performed for further validation of the models created. As previously described, the analysis was set up with a constraint fixed at the base to mimic an actual dragonfly flapping mode. Figure 3.13 shows the placement of constraints for a natural frequency analysis.

![Figure 3.13: Placement of constraints fixed in a natural frequency analysis](image)

3.6.2 Static stress simulation analysis

A fixed constraint was placed at the base of the wing tip to mimic the hinge of an actual dragonfly wing. Nodal forces were applied at the tip of the wing to mimic the tensile and bending test experiments. Simulations were done for all eight wings (forewing and hindwing fabricated from all four materials). In addition, simulated bending and tensile tests were done for the frame structures without the membrane to record the effects of the chitosan nano-composite film on the frame structure. The stresses computed in the static analysis are used to form the stress-dependent contribution to the tangent-stiffness.
matrix. Static stress analysis, enables the study of stress, strain, displacement, and shear and axial forces that result from static loading. Figure 3.14 shows the static stress simulation model for a static stress analysis. Numerical analysis was not constructed until failure due to the fact that dragonfly wings do not flap until they fail. Hence, a linear model was used.

![Figure 3.14: Constraints for a static stress analysis](image)

3.7 Experimental Set Up

Tensile and bending experimental tests were done on the physical models using the Instron Universal Testing Machine (Model 5569). Increasing loads were incrementally applied to the wings until they failed. The data was compiled and integrated by Instron MERLIN software. A specific jig was designed for both bending and tensile test to clamp the fabricated models, whereby the slots were used to clamp the thin structures firmly. All testing was repeated three times for each wing type, necessitating the fabrication of three identical copies of each wing type. Since the wing frame test specimen is a sheet-like structure, the same ratio of width-to-gage length (18:18 for forewing and 20:20 for hindwing) was maintained in order to compensate for the elongation that occurs during diffuse necking. ASTM test specifications were followed throughout the experiment. Each base of the wing models were clamped at a fixed point and the tips were clamped at the
moving point. The load was then increased gradually with a speed rate of 0.013 m/s. The rate of extension and the stress-strain curve was observed until the wing model experienced a structural failure. This point can be observed in the collected data as a sudden decrease in the load. Data obtained in RAW file (not processed) was then converted to Microsoft Excel for further analysis. The high speed camera imaging technique was then employed after close observation of all these seven materials, and three best materials were chosen based on performances. The main criteria of selection were the ability to withstand high tensile stress and possess a high compression stress vs strain. Due to the complexity of an actual dragonfly wing (due to the corrugations and veins) it was impossible to conduct tensile testing on an actual wing. However, previous research has provided sufficient values to aid in setting a benchmark for the criteria of the suitable material. Referring to previous research, the value of tensile and compression stress for an actual dragonfly wing was found to be 285 MPa and 16.87 GPa, respectively (Rupan et al, 2013). As mentioned earlier, in order to test the aero-elastic properties of the dragonfly wings, the final step of the research was two test it on an actual flapping mechanism. This is a static mechanism which is able to produce a flapping motion frequency up to 250 Hz.

Previous researchers have conducted studies using high speed camera. Gui et al. (2010) applied simple optical modifications to replace an expensive two-camera system for taking stereo videos of fire ant alate wingbeat motion. Many have utilized the high speed camera technique to capture wing motion of birds and insect flights. (Norris 2001; Sudo et al. 2001, 2005; Dalton 2002; Gorman 2003). Recent advances in high-speed imaging technique make it possible to capture insect wing motion not only at high phase resolution but also at high digital resolution, e.g. the Photron Ultima APX high-speed camera used in our lab is capable of capturing partial frames of 1024\( \times \)256 pixels at 8,000 frames per second (fps). High digital resolution and high phase resolution together enable a precise analysis of
the wing motion within a wingbeat period. However, at least two images from different view angles, e.g. provided by a stereo imaging system, are necessary to determine the three dimensional shape and orientation of the wing surface. A stereo imaging system requires at least two cameras that view an object from two different directions, and in an ideal situation, these two view directions should be perpendicular to each other, (Sudo et al. 2001, 2005).

**Figure 3.15**: Schematic diagram of Gui et al (2010) of fire ant alate wing motion

In order to capture the motion of the wing motion of the wings, two Phantom Miro 310 (Vision Research) high frame rate cameras were used to view the flapping wings from two different directions in Figure 3.15. The camera’s high frame rate enables a precise sequence of images to be captured of the flapping wing motion within a single wing beat. Two cameras were necessary in order to determine the three-dimensional shape and orientation of the wing surface (Figure 3.16 (a) and (b)). The cameras were placed perpendicular to one another following the procedures established by Gui et al. (2010).
Both cameras were equipped with a Nikon F lens. A multiple LED lighting system was used to provide sufficient illumination. Imagery was recorded at a resolution of 320 x 240 pixels and a frame rate of 35000 per second, which allowed the wing beat motion to be precisely captured. The motion video was stored in a computer via two high speed Ethernet cables. It was played-back and analyzed using the Vision Research Phantom Camera Control Software (version 2.6.749.0).
Figure 3.16: (a) Actual experimental set up of the high speed camera imaging technique, (b) Schematic diagram of the experimental set up

Figure 3.16: (continued) (a) Actual experimental set up of the high speed camera imaging technique, (b) schematic diagram of the experimental set up
Figure 3.17: Front view (a) and side view (b) of the wing motion captured and measurement axes.

Measurements were taken using each of the three wings while flapping at varying frequencies: 10, 20, 30, 70, 120, 200 and 250 Hz. Figure 3.17 shows the front and side view of the wing motions that were measured and recorded from captured imagery. Figure 3.17(a) illustrates the bending angle (θ) and displaced distance or deflection (d). Figure 3.17 (b) defines the wing tip angle (α) and the wing tip rotational twist speed (ω).

3.8 Flapping mechanism

The wing flapping mechanism used in this study is an electromagnetic flapping wing actuator. The power supply used in this flapping wing drive is 9 volts DC. A LM555 crystal clock oscillator integrated circuit (shown in Figure 3.18) is used to generate a stable oscillation. The free running frequency and duty cycle are accurately controlled with two resistors and one capacitor. The generated oscillation is fed to a Power MOSFET fast switch. The output of the Power MOSFET is used to actuate the miniature PC Board Relay. The frequency of the switch (corresponding to the wing beat frequency) can be adjusted by a 22 kW potentiometer. Each of the different wings is attached to a flat iron plate (2 mm long and 2.75 mm thick) using super glue. This plate (wing platform) is oscillated by an electromagnetic actuator (3 x 3 mm). Figure 3.18 shows the wing structures attached to the actuator. The plates are attached to the hinge of the wing to mimic the joint of an actual
dragonfly. This flapping mechanism is able to create a linear up-down stroke motion at variable wing beat frequencies, up to a maximum frequency of 250 Hz. The flapping degree was set to be 60° which corresponds with an actual dragonfly wing flapping angle during hovering flight (Jane, 2004 and Xinyan, 2008).

Figure 3.18: Flapping mechanism used in this research