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# Effect Of Lift Force On The Adhesion And Bonding Strength Of A Model Airplane Wing - Fuselage Interface

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**Abstract**

In order to understand the effect of lift force on the adhesion and bonding strength of airplane wing –fuselage interface, this investigation was undertaken. Two airplanes with same wing cross section were designed using a computer aided design program. The wings, although had the same area of cross section, the wing of one plane is solid where as the second plane had a hollow wing with 0.003 m thick skin. In addition, the plane with solid wings were attached at right angle to the fuselage while the wings that were hollow inside, were attached to the airplane at angle of about $75^o$. Both the airplanes were produced using Accura SI 40 epoxy resin. The airplane performance characteristics (viz. the lift and drag) were measured in a subsonic wind tunnel as a function of the air speed and the angle of attack. The air speeds were in the range 65 – 215 kmph and the angle of attack was in the range 0 – 15 $^o$ (both in ascending and descending positions).The results suggest that the plane with wings at $75^o$ has better performance characteristics. The plane with hollow wings failed at 215 kmph speed, and the wings tore apart due to lift force generated by the wings at an ascending angle of 12.5 $^o$. The plane with solid wings on the other hand survived the maximum speed of 215 kmph and the angle of attack. The calculations based on fracture mechanics indicated that the dynamic pressure produced by the airplane with its hollow wing configuration at 215 kmph has generated stresses (at the wing-fuselage interface) that are greater than the fracture stress of Accura SI 40 epoxy resin (79 MPa). The second plane with solid wings survived because the stresses generated by the lift forces at the interface are far below that of the fracture strength of Accura SI 40 epoxy resin.

**Keywords:** Model airplane, lift and drag, hallow and solid wings, epoxy resin, dynamic pressure, fracture strength of resin

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## 1. Introduction

When a plane moves the air molecules near the airplane are disturbed and generate aerodynamic forces [1,2]. The aerodynamic forces create a layer of air near the surface and this layer is important in determining the lift and drag of the airplane. The lift depends upon the shape size and angle of inclination and flow conditions. For lifting the wing, the airflow over the top of the wing will be at lower pressure than that of the flow under the wing. Near the tips of the wing, the air is free to move from high pressure to lower pressure region. This produces a pair of counter rotating vortices at the tip of the wings. The wingtip vortices produce a down wash of air behind the wing, thus putting a drag on the forward motion of the plane. The location and the influence of both lift and drag changes with the angle of inclination. The position for which the lift is maximum and the drag is low is called the critical angle of lift. The lift force produces great upward thrust on the wings and the lift force increases with an increase in the wingspan. However, the larger the wingspan the higher the lead acted on the hinges and or the joining of the wings to the fuselage The aim of this project is to investigate the effect of wing position and the wing design parameters on the lift and drag, and the maximum amount of stresses the wings impose on the wing – fuselage joint of an airplane.

## 2. Theory

**Dynamic Pressure:**

The air molecules are in constant and random motion and they collide with each other and therefore changes in the air molecules momentum take place. The change in the momentum is related to the gas pressure [5,6]. The pressure is the force times the surface area in a direction perpendicular to the surface. If the air is moving, the measured pressure depends upon the motion and one can define the pressure as a "dynamic pressure" as follows:

$(P_s) + (½) (\rho) X (u)^2$ = Constant ………………………………………………… (1)

Where

The constant is the Total Pressure ($P_t$),

($P_s$ ) is the Static Pressure, ($\rho$) is the Density of air and (u) is the velocity of air

At high speeds we can ignore static pressure. Therefore, the total pressure is defined as Dynamic Pressure (q) which is given as

Dynamic Pressure (q)= $(½) \rho X (u^2)$ ………………………………………(2)

The dynamic pressure (q) is a pressure with units $Kg/(m.s^2)$

**Lift Equation:**

In a controlled environment such a wind tunnel, the lift produced under a given set of conditions of velocity, density and wing surface area, can be calculated using the dynamic pressure (q), as follows.

At low speeds (< 360 kmph), the compressibility effects are negligible. Therefore the lift (L) is given as

Lift (L) $\propto$ q

Where 'q' is the dynamic pressure.

Lift Force (**L** $(kg/m^2)$**)** = [constant] [ $(½) \rho X (u^2)$] = $(½) C_{CL} / \rho X (u^2)$…………….. (3)

Where $C_{CL}$ is the coefficient of lift and it is expressed as the ratio of lift force to the force produced by the dynamic pressure.

The total lift load (**$T_L$** (kg)) acting on the wing = lift force X area of the wing …….. (4)

**Fracture Mechanics:**

The total lift force exerted under the wing has to be supported by the adhesion and bonding strength of the wing/fuselage interface. If we assume that the strength of the wing - fuselage interface depends primarily upon the adhesion and bonding strength of the interface, then the failure process of the interface can be treated as a similar process that is often seen during the fiber pull out during the deformation of fiber reinforced composite materials. The fracture mechanics models developed to explain the deformation of a fiber reinforced composite materials [3,4] can also be applied for this system. From the fracture mechanics models, the total stress generated by the lift force acting on the wingspan can be calculated. If the integrity of the airplane will be maintained only when the total stress on the wings is supported by the adhesion and bonding strength of the wing – fuselage interface. That is if the load (**$T_L$** ) (that acted on the wing due to the lift force) is distributed on the total contact area (**$T_{ca}$**) of the wing, then the stress acting on the wing fuselage interface ( $\sigma_{\textbf{interface}}$ $(kg/m^2)$) is given as:

$\sigma_{\textbf{interface}}$ $(kg/m^2)$ = total load (**$T_L$** ) / total contact area (**$T_{ca}$**) ………………(5)

If the stress acting on the wing-fuselage interface {$\sigma_{\textbf{interface}}$ $(kg/m^2)$} is less than the fracture strength/adhesion and bonding strength of the material {$\boldsymbol{\sigma}_{\textbf{Fracture}}$ $(kg/m^2)$}, the wing – fuselage joint will sustain the lift force and will maintain the structural integrity of the airplane. On the other hand, if the $\boldsymbol{\sigma}_{\textbf{interface}}$ $(kg/m^2)$ **>** $\boldsymbol{\sigma}_{\textbf{Fracture}}$ $(kg/m^2)$, the wing fuselage joint will not support the exerted lift force. The consequence is that the wings will be separated from the main airframe. It has to be pointed out that the above conclusions are based on simple stress analysis calculations and they do not take the thermal effects into consideration.

## 3. Experimental Procedure

**Airplane Models:**

Two different airplanes with wing attached at $75^o$ and $90^o$ to the plane normal of the fuselage. The planes were first designed using "Rhinoceros" computer aided design and computer aided manufacturing (CAD & CAM) software. Once the model shapes were designed, the models were built using a "3D Systems" Stereo Lithography Apparatus (Model SLA 5000). The models were made out of a commercial epoxy resin called the "Accura" SI 40 resin. The epoxy models were later cured under UV light. The mechanical properties and other details of the epoxy resin are given in Table 1.The length of the airplane with wings attached at $75^o$ angle is about 0.45 meters. The diameter of the fuselage is about 0.05 meters and the wing span is about 0.40 meters.

The second plane was 0.3375 m long. The diameter of the fuselage is about 0.0375 meters, and the total wingspan is about 0.30 meters. The strength of the wings of the airplanes was enhanced by reinforcing the wing structure with 0.00625, 0.00625 and 0.003125 meter diameter steel rods. These rods were placed inside the airplane model after the resin was cured. Figure 1 shows the airplanes as they were produced using the Stereo Lithography Apparatus.

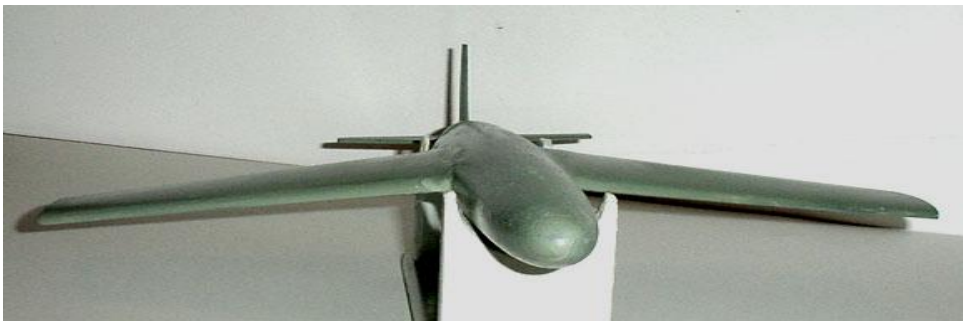
Table 1. Typical Properties of "Accura SI 40" Epoxy Material [Ref. (7)]

| **Liquid Material** | | **Post Cured Material** | | |
|---|---|---|---|---|
| **Property** | | **Property** | **90 min UV Cure** | **90 min UV Cure + Thermal** |
| **Appearance** | **Clear Amber** | **Tensile Strength (MPa)** | **57.2 – 58.7** | **73.9 – 74.2** |
| **Density at $25^oC$** | **$1.1 gm/cm^3$** | **Elongation at Break** | **4.8 – 5.1 %** | **4.8 – 5.1 %** |
| | | **Flexural Strength (MPa)** | **93.4 – 96.1** | **116 – 118** |

**Cross Section Of The Airplane Wings:**

When an airplane is flying at a constant speed, the airplane experiences lift and drag. The decrease in the weight of the plane not only increases the lift but also reduces the power requirement for maintaining the cruise condition. The most weight saving location of an airplane is the wing structure. However, a reduction in the wing cross-section will impose large stress on the wing fuselage interface. The present airplane models incorporated two different wing designs. The first air plane wing [that corresponds to the airplane in Figure 1 (A)] has hollow wing characteristics, while the wing of second plane [shown in Figure 1 (B)] has a solid wing cross section. The hollow wing has a wall thickness of 0.003125 meters. The overall thickness of the wing near fuselage side is about 0.0125 meters and near the wing tip is 0.0067 meters. The solid wing is 0.009375 meters thick near the fuselage, and 0.005 meters thick near the wing tip respectively.

**A**



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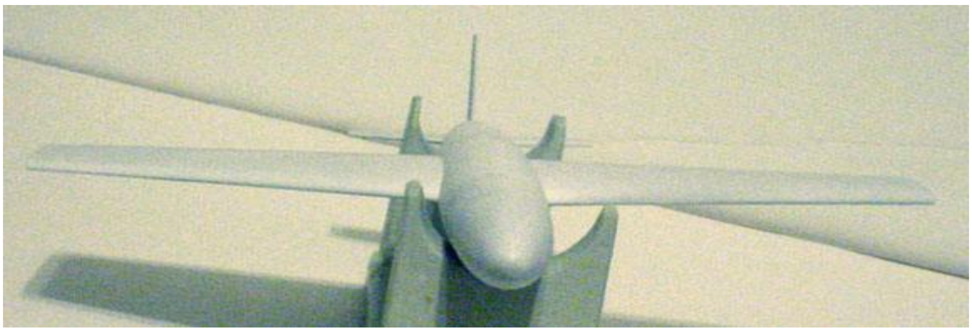


Figure 1. Typical airplane models (A) hollow wings attached at $75^o$ and (B) solid wings attached at $90^o$ to the plane normal to the fuselage respectively.

## 4. Aerodynamic Studies:

### Wind Tunnel Experiments

The important parameters that affect the stability of a flight system are the lift and the drag. Therefore during this year, the wind tunnel studies were limited to make the measurements of lift and drag. The present experiments were conducted in a horizontal wind tunnel. The positioning of the model airplane in the wing tunnel is shown in Figure 2 [(A) plane positioned parallel to the direction of air flow, (B) the airplane in ascending position and (C) in descending position respectively). The maximum air speed of the wind tunnel used in the present study is 215 kmph. The wind tunnel has the capability to move the model in any direction. The maximum tilt that can be achieved is about $45^o$. The wind tunnel experimental chamber was augmented with sensors that will monitor the lift and drag effects and send the output as an electrical current signal. In the wind tunnel, the lift and drag that is created on a model (as a result of flowing wind of different speeds) is converted as an electrical signal and the electrical signal output is recorded as a function of angle of inclination (angle of attack) and the wind speed. After the experiment is over the electrical signal output data (mill volt (mV)) is converted to determine the lift and drag as a force (Newton). The models were clamped to the wind tunnel mounting unit with a special attachment. The wind tunnel experiments were carried out at speeds ranging from 65 – 215 kmph and the angle of inclination (ascending and descending) was studied in the range 0 – $15^o$.
First, the airplane models with no tilt were subjected to wind to the maximum speed of 215 kmph. At the maximum speed, the airflow was continued for about 15 minutes. After the initial treatment, the air speed was decreased and the models were brought to room air pressure. The wind tunnel was switched on and the models were subjected to air flow. Once, a specific required air speed is achieved, the airflow was kept at that speed for 5 minutes and the output current value for the lift and drag were noted. The airflow was then increased with 30 kmph increments until the maximum of 215 kmph was achieved. Then the air speed was decreased with a stepwise decrease of 30 kmph. The actual value of the lift and drag force was determined using the current (in milli amperes) versus lift or drag force plots. The lift or drag force values were plotted as a function of air speed and the angle of attack. From those plots, the critical angle of attack for maximum lift or drag was determined.

## 5. Results

### Airplane with Hollow Wing Design

The airplane model was studied at four different ascending positions with angle of attack 0, 5, 10 and $12.5^o$. At an angle of attack $12.5^o$, and the maximum air speed of 215 kmph, the airplane wings collapsed due to crack nucleation and growth on the underside of the wing at the wing – fuselage interface. Figure 3 shows the collapsed plane. The reinforcing steel rods that were placed inside the model airplane did not break, and the broken wings did not separate from the model. Since, the airplane failed, no additional lift and /or drag could be determined for this plane with descending position.

The lift and drag plots for the airplane models are given in Figure 4. The results on lift suggest that the lift increased with an increase in the angle of attack between 0 – $10^o$. Any increase in angle of attack above $10^o$ will cause the force of lift tends to decrease. Similarly, while the airplane is ascending, an increase in angle of attack initially (between 0 – $5^o$) will increase the drag. Above $5^o$, the drag decreased. For example, at an airplane speed of about 212 kmph, as the plane is ascending from $0^o$ to $5^o$ inclination, the drag on the plane increases significantly from 13.3 N to 36 N (nearly 170% increase) while the lift is increased from 66.7 N to 89 N (33% increase). However, if the angle of attack is increased from 5 to $10^o$, the drag force decreases nearly 40% (from 36 N to nearly 22 N) while the lift increased from 89 N to about 102 N. This would mean that the plane has enough force to lift at this angle of inclination.

### Airplane With Solid Wings:

The airplane with solid wings is shown in Figure 2. The lift and drag characteristics of the plane was studied both during ascent and descent. The maximum angle of attack studied was "+" (ascent) or "–" (descent) 15 degrees. The lift and drag plots for the airplane models are given in Figure 5 (A) and (B) respectively. The results on lift suggest that the lift increased with an increase in the angle of attack between 0 – $7.5^o$. Any increase in angle of attack above $7.5^o$, the force of lift tends to decrease. For example, while the airplane is ascending at 200 kmph, an increase in angle of attack initially (between 0 – $7.5^o$) has increased the lift force by nearly 30% [82 N – 105 N]. At higher angle of attack (7.5 – $15^o$ angle), the lift force decreased by 14 % [105 N – 90 N]. The drag during the airplane ascent has continuously increased with an increase in the angle of attack. However, the rate of increase in drag force appears to be dependent on the angle of attack. The drag force increased 200% between 0 – $5^o$ [2.4 N – 5.9 N] and nearly 1600 % for an increase in the angle of attack from $5^o$ to $15^o$ [5.9 N – 31 N].

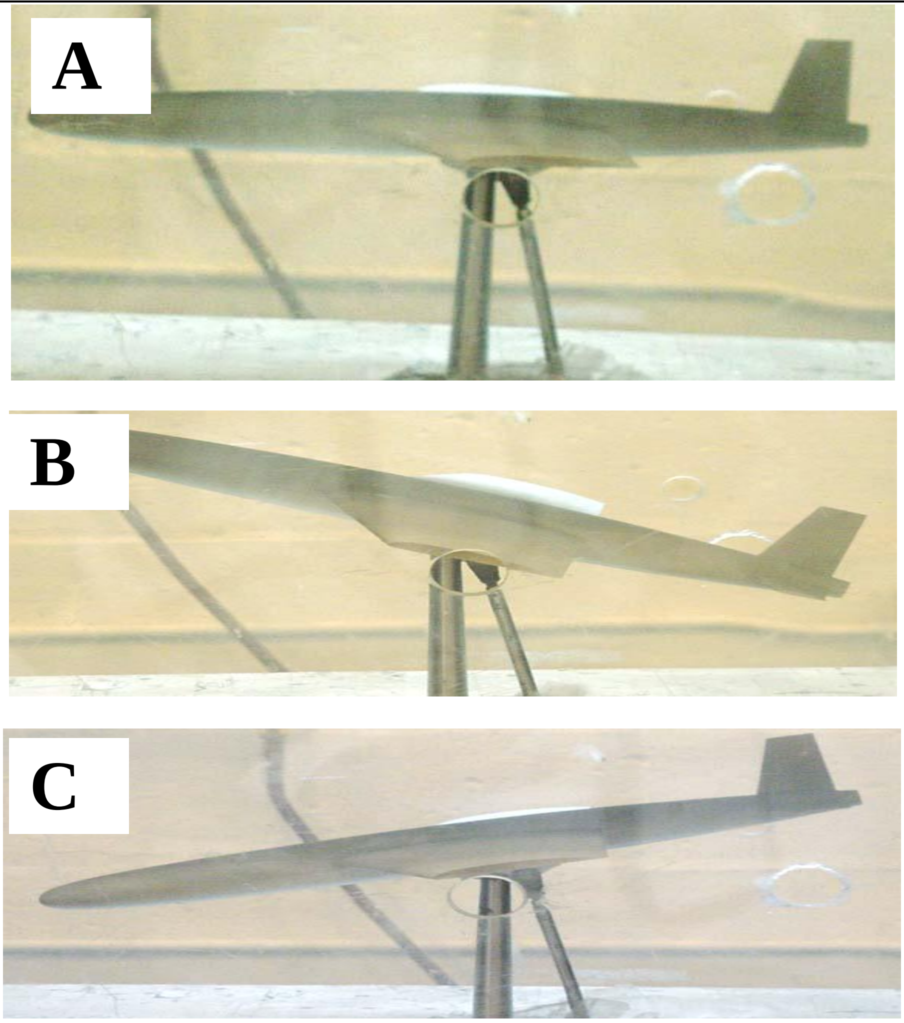



Figure 2. Model airplanes with solid wings during wind tunnel experiments.
Angle of attack (A) $0^o$, (B) $15^o$ ascending and (C) $15^o$ descending.


Figure 3. Model airplane with hallow wings. The airplane wings failed during testing in the wind tunnel. The airspeed is 215 kmph and the angle of attack for ascending was $12.5^o$.

The interesting results are the behavior of the lift and drag force during the planes descent. The results suggest that as the plane is descending at 200 kmph, the lift force decreases with an increase in the angle of descent. The data indicates that the value of the lift force changes from positive (82 N at $0^o$ angle) to negative [ -1.4 N for $5^o$ angle of descent]. The magnitude of the force increases with an increase in the angle of attack [ -1.4 N at $5^o$ and – 70 N at $-15^o$]. The results of the drag force suggest that as the angle of attack during descent increases, the lift force also increases.

The results on lift force during descent of the airplane indicate that at 200 kmph and angle of descent of 15$^o$, it is not possible to maintain stability and proper descend. It is because the drag force is increasing while the lift force is exerting an upward force. Without further detailed experimental analysis, the interpretation of these results is very difficult.

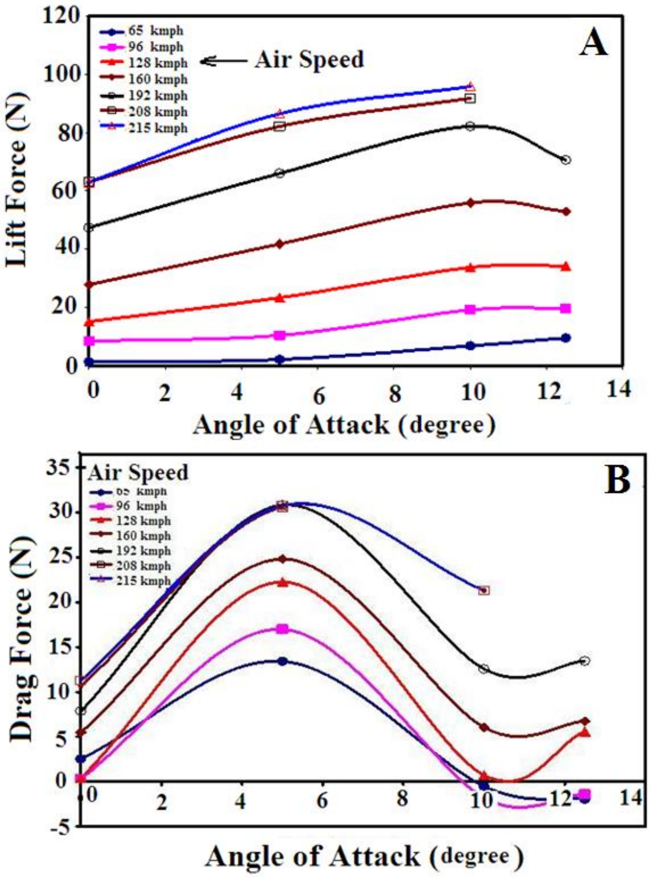



Figure 4. Angle of attack versus (A) lift, and (B) drag plots for airplane model with hollow wings and at different air speeds.

## 6. Disussion

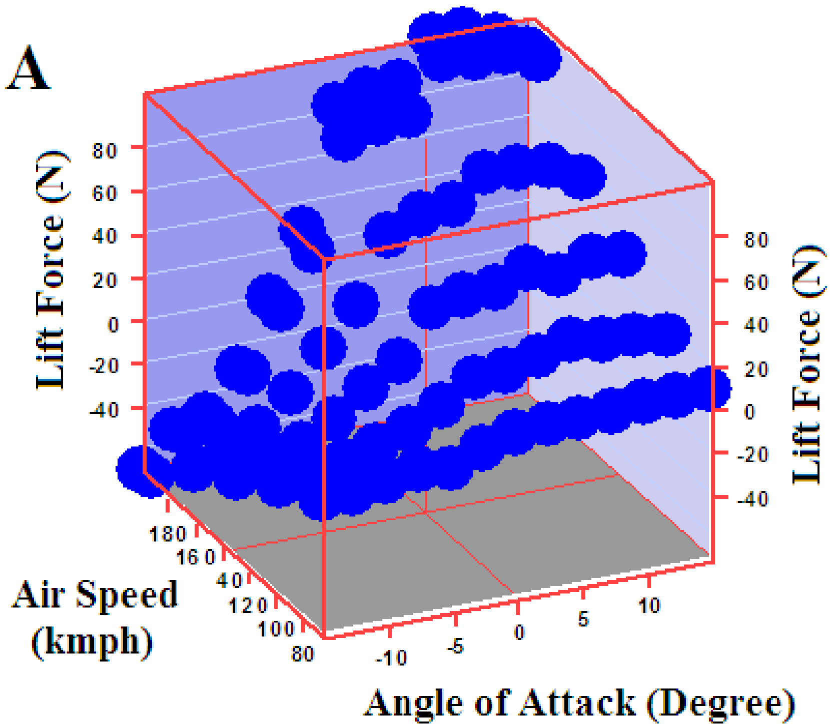
One of the main purposes of testing models in a wind tunnel is to estimate aerodynamic forces that a full scale vehicle experiences during operation [6]. The wind tunnel experiments deal with much higher speeds. The results on the airplane models suggest that the behavior of the lift and drag represented as a function of angle of attack and the wind speed shows a classic trend. That is, as the angle of attack is increased, the lift increases and once an optimum/critical force value of the total lift is reached, any further increase in the angle of attack has a negative effect on the lift. The results on the drag indicate that at higher angles of attack the drag force is lower. This is because under these angle of attack conditions, the lift force is high. The failure of the wings of the airplane model appears to be due to sudden increase in the stress level, above and beyond the fracture stress of the epoxy materials “Accura SI 40” at the wing – fuselage interface. In order to unequivocally attribute the failure of the wings to the poor design of the wings or the poor selection of the material for the fabrication of the model airplane, simple fracture mechanics based stress analysis calculations on the stress at the wing – fuselage joint were made. The analysis can be summarized as follows:

Figure 6 shows the one of the cracked wing of the airplane with hallow wing design. The airplane is inclined at an angle of 12.5$^o$ to the direction of airflow. The air speed at which the airplane wings failed was 215 kmph. From a careful examination of the crack morphology, two possible failure mechanisms can be suggested as follows:

1. The dynamic pressure induced crack initiation and growth; and
2. the lift induced stress on the wing – fuselage interface or joint.

**Dynamic Pressure Induced Crack Initiation And Growth:**

As the airplane is subjected to 215 kmph, air current, the surface/skin temperature of the airplane has increased. As a result, the epoxy resin might have become soft. The continued dynamic air pressure might have introduced fine crack (perhaps due to erosion of the epoxy) at the corner of the wing (Point 1 in Figure 6). The stress concentration at the crack tip is so large that the crack has continued to progress along the entire length of the wing joint.



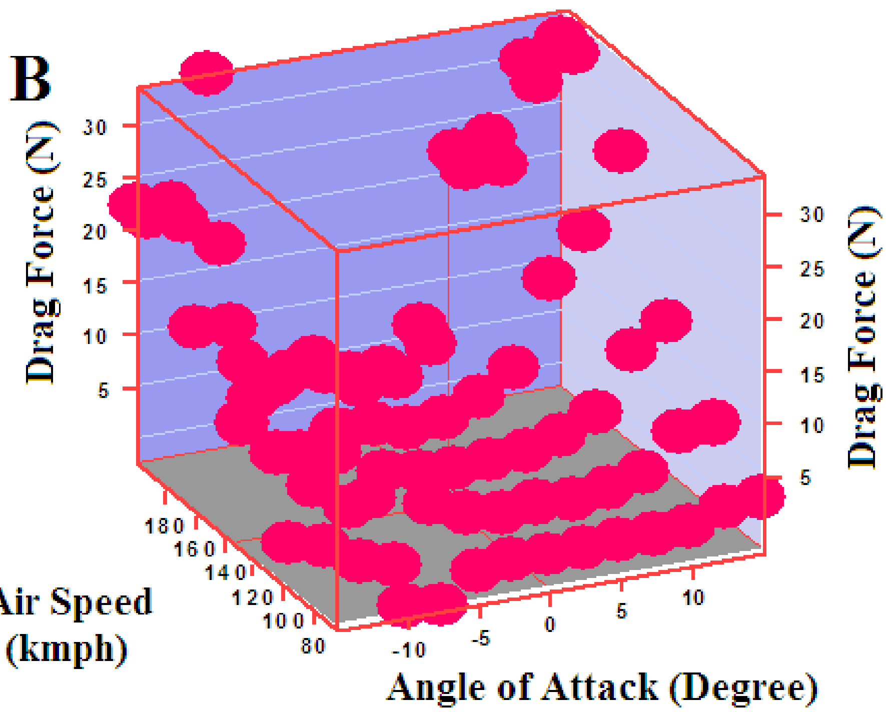




Figure 5. (A) Lift Force or (B) Drag Force versus Air Speed versus Angle of Attack Plots obtained for Model Airplane with Solid Wings.

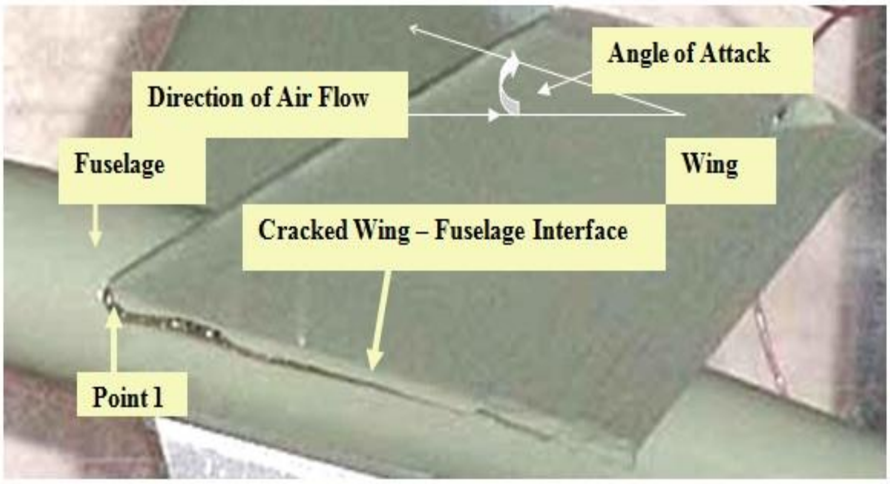



Figure 6. Photograph of the fractured wing of the airplane with hollow wings. The air speed was 215 kmph and the angle of attack was 12.5$^o$.

The dynamic pressure at 215 kmph speed was calculated using the equation

Dynamic Pressure (q) = (½) ρ X ($u^2$)

Where 'ρ'and 'u' are the density of air and speed of air respectively. The dynamic pressure (q) is a pressure with units Kg/(m.s$^2$). Assuming that the dynamic pressure is exerting uniform pressure on the wing, the total force can be calculated as

Total load on the wing = Dynamic pressure X Length of the wing.

The total force acting on wing has to be balanced by the adhesion and binding strength of the wing – fuselage interface/joint (i.e., the total contact area of cross section of the wing with the fuselage).

Stress acting on the wing – fuselage interface or joint =

(Total load on the wing)/(total contact area of the wing – fuselage interface or joint)

The stress at Point 1 was estimated and the stress was found to be in the range of 4 – 2.4 MPa. The stress value is much lower than the tensile strength of the cured Accura SI 40 epoxy resin(Table 2). In addition, the airplane with solid wings model did not show any indication of erosion or material lost near and around wing region. Therefore, it is reasonable to suggest that that the wing failure did not occur as a result of dynamic pressure induced crack initiation and growth.

**Lift Induced Stress on the Wing – Fuselage Interface / Joint:**

During wind tunnel experimentation, the airplane wing failed at 215 kmph air speed and at 12.5$^o$ angle of attack. The wing area was 0.0337 m$^2$ and the contact area of the wing fuselage joint is 4.2 X 10$^{-4}$ m$^2$. Assuming that the dynamic pressure is equal to the actual pressure on the plane, the stress acting on the joint can be calculated using the equation

The stress acting on the wing fuselage interface/joint ( $\sigma_{\textbf{interface}}$ (kg/m$^2$))
= total load ($\mathbf{T_L}$ )/ total contact area ($\mathbf{T_{ca}}$)

The stress value for the airplane with hallow wing configuration is found to be 81.68 MPa. In a similar calculation for the second airplane with solid wings, was found to be about 45.2 MPa.

The airplanes were fabricated using "Accura SI 40" Epoxy resin. From the materials data provided by the manufacturer (Table 1), it can be realized that maximum the tensile strength of cured epoxy using UV light followed by thermal treatment is about 74 MPa. The values are well below the stress levels that are imposed on the wing joint of the first airplane with hallow wing design, while the stress levels imposed on the second plane with solid wing cross section is well below the fracture strength of the cured epoxy resin. It is possible that the first airplane would have survived the air speed on 215 kmph and angle of attack of 12.5$^o$, provided a proper design of the airplane was made taking into consideration the stresses on the plane at various locations. The program goal for the future is to design better wing geometry and / or augment the airplane wings with winglets in order to generate better lift, and reduce the stress on the wing – fuselage interface. The current experimental evidence indicates that the airplane design based on the stress analysis, and a proper selection of material (based on the knowledge of the mechanical properties of materials) will not only improves the strength and performance of the airplane, but also enhances the structural integrity of the airplane. It is planned to design new planes based on the stress analysis data and incorporate winglets to reduce the drag and increase the lift and test them for their structural integrity.

**Table 2. The air speed, wing surface area, dynamic pressure, lift force and stress on the wing for model airplanes tested in the wind tunnel.**

| Properties | Plane 1 (Hollow wings) | Plane 2 (solid wings) |
|---|---|---|
| Air speed (kmph) | 215 | 215 |
| Wing surface area ($m^2$) | 0.0337 | 0.0252 |
| Dynamic Pressure at 215 kmph($Nm^{-1}s^{-2}$) | 2.1 X $10^4$ | 2.1 X $10^4$ |
| Estimated stress value on the edge of the wing using dynamic pressure model (MPa) | 4 | 2.4 |
| Lift Force at 215 kmph and at an angle of inclination 12.5$^o$ (N) | 99 | 99 |
| Estimated stress value on the wing – fuselage joint due to lift force (Mpa) | 81.68 | 45.2 |
| Tensile strength of Accura SI 40 Epoxy (UV Curing followed by thermal treatment) (MPa) | | **73.9 – 74.2** |

## 7. Summary

The wind tunnel experiments with models conclude that the lift and drag increased with an increase in the air speed. The lift increased with an increase in the angle of attack initially, once an optimum lift value is reached, further increase in the angle of attack has decreased the amount of lift. The drag continuously increased with increase in the angle of attack. The results also conclude that the angle at which the wings are attached to the fuselage has an effect on the critical angle of attack. The integrity of the airplane wings also depend upon the wing design. The wings that are solid survived air speed of 215 kmph and at 12.5$^o$ inclination. However, the airplane model with hollow wing cross-section did not survive those conditions. It is probable that the failure was initiated at underside position of the wing, and at the wing – fuselage interface / joint. The possible causes for the failure can be attributed to the design flaws and the selection of material for the fabrication of the model airplane. Airplane design based on the stress analysis and a proper selection of material based on the mechanical properties will not only improves the strength and performance of the airplane, but also enhance the structural integrity of the airplane.

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