

Kinematic and Dynamic Variations in Cam and Follower Made of Composite Material under Hygrothermal Environment

Shailendra Singh¹, S. Sanyal²

Ph.D. Research Scholar, Department of Mechanical Engineering, N.I.T. Raipur, (C.G.), India and Head of The Department of Mechanical Engineering, Government Polytechnic College Kanker, (C.G.), India¹

Professor and Dean (Research and Consultancy), Department of Mechanical Engineering, N.I.T. Raipur, (C.G.), India²

ABSTRACT: Advancement in materials used in construction of cam and follower for reducing the weight, noise, vibration, stresses and higher strength plus rigidity for efficient and accurate operation is going on throughout the globe since long. The usual materials used for Cam and follower are steel, forged steel, alloy steel, aluminum, alloys and composites. Nowadays, Cam and follower mechanisms are also fabricated from Composite materials or Plastics instead of conventionally used metals with higher specific strength and specific stiffness and thus less weight therefore less inertia forces, stresses, deflections, vibrations and noise. The self-lubricating composite Cam- Follower system requires no lubrication between the cam follower and rail therefore saving on grease and maintenance hence are the best choice for clean-room operations. It is seen from the literature review that every composite material absorbs moisture under high temperature and high moisture condition i.e. hygrothermal environment, consequently material's properties deteriorates. Cam and Follower are also very often used in extreme atmospheric conditions i.e. high temperature and humidity with the requirement of accuracy and precision. Due to absorption of moisture volume, mass and moment of inertia will enhance thus kinematics and dynamics of Cam and follower mechanism will alter. Heretofore, no attempt has been made to find out Kinematic and Dynamic variations of Cam and Follower mechanism made of composite material under hygrothermal environment. So, this is an attempt to find out, Kinematic and Dynamic variations that will take place in cam and follower mechanisms made of composite material under hygrothermal environment. Degradation in the properties of composite material under hygrothermal environment is evaluated using Chamis Equation. Kinematic analysis is carried out to determine the variation in displacement, velocity and acceleration. Dynamic analysis is also carried out to find out variations in inertia force, spring forces, resultant force and torque of the follower for the full range of motion of cam under hygrothermal environment, made of composite material. In kinematic analysis of cam and follower mechanism, it is observed that the displacement, velocity and acceleration changes because of variation in pitch circle radius of cam due to hygrothermal expansion. In dynamic analysis of Cam and follower mechanism under hygrothermal environment, it is observed that mass of Cam and follower increases thus inertia forces enhance which leads to enhancement in resultant forces thus higher torque. This erroneous behaviour of Cam and Follower mechanism under hygrothermal environment can be rectified by estimating exact magnitude of variations under hygrothermal environment and compensating it by accordingly reducing overall dimension of cam and follower . So, it is obligatory that effect of hygrothermal atmosphere should be taken into consideration while analyzing kinematic and dynamic performance of cam and follower mechanism.

KEYWORDS: Fickian diffusion, Chamis Equation, Hygrothermal effect, Kinematic variations, Epoxy resin, Cam

NOMENCLATURE: m : Moisture content (%), Δm : Enhancement in moisture content from dry condition (%), ΔT : Enhancement in temperature (in °C), α : Coefficient of thermal expansion (mm / °C), β , β_L , β_T : Coefficient of moisture expansion in longitudinal and transverse direction in (mm / %moisture absorption), ϵ , ϵ_{hygro} , $\epsilon_{\text{thermal}}$: Strain, strain due to hygro (moist) environment, strain due to elevated temperature in (mm/mm), P_{wT} = Matrix property at the use

temperature T and moisture content M , P_o =Matrix property at reference temperature. T_{gd} = Glass Transition temperature in the dry condition, T_{gw} =Glass Transition temperature in the wet condition.

I. INTRODUCTION

A cam is a rotating machine element which gives reciprocating or oscillating motion to another element known as follower. The cams are usually rotated at uniform speed by a shaft, but the follower motion is pre-determined and will be according to the shape of cam. The cam and follower is one of the simplest as well as one of the most important mechanisms found in modern machinery today. A cam is an element of the cam-follower mechanical system that compels the movement of the follower by direct contact. Genius, The Leonardo da Vinci that produced a modern design cam applied to a machine for pumping water. Cam-follower mechanisms are found in almost all mechanical devices and machines viz. agriculture, transportation equipment, packaging, machine tools, printing, presses, automobile internal combustion engines, food processing machines, switches, ejection molds, and control systems, and more recently in micro -machines such as micro-electromechanical systems. The cam-follower system may be designed for path, motion or function generation. Cams are classified in three ways, (i) In terms of their shape, such as wedge, radial, cylindrical, globoidal, conical, spherical or three-dimensional; (ii) In terms of the follower motion, such as dwell-rise-dwell (DRD), dwell-rise-return dwell (DRRD), or rise-return-rise (RRR); or (iii) In terms of the follower constraint, which is accomplished by either positive drive or spring loaded.

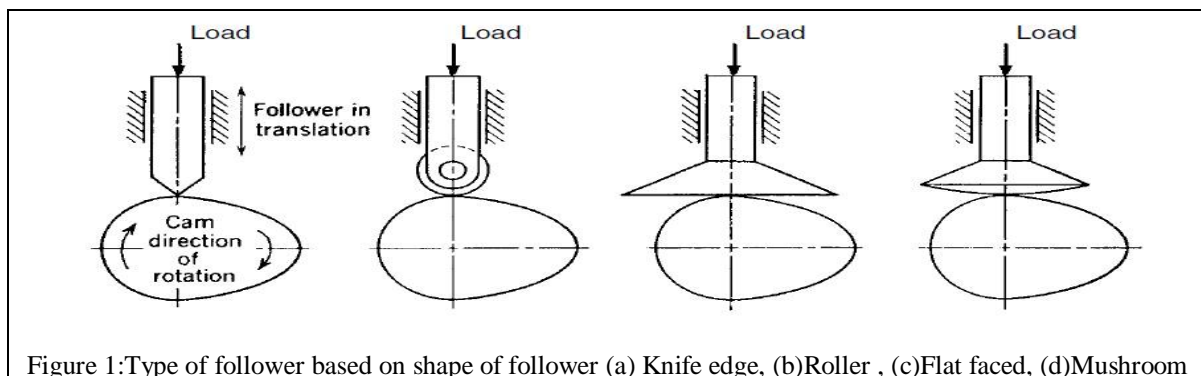


Figure 1: Type of follower based on shape of follower (a) Knife edge, (b) Roller, (c) Flat faced, (d) Mushroom

In recent years, with the development of new polymers, many cams are made of various plastic/composite materials. Advantage associated with composite material are light weight, weight distribution, high specific Strength and Stiffness, directional strength and/or stiffness, improved smooth surface Properties, corrosion resistance, tailored surface finish, low thermal conductivity, low coefficient of thermal expansion, high dielectric strength, non-magnetic and radar transparency. Cam and Follower are also very often used in extreme atmospheric conditions i.e. high temperature and humidity with the requirement of accuracy and precision. Due to absorption of moisture volume, mass and moment of inertia will enhance thus kinematics and dynamics of Cam and follower mechanism will alter. Heretofore, no attempt has been made to find out Kinematic and Dynamic variations of Cam and Follower mechanism made of composite material under hygrothermal environment. So, this is an attempt to find out, Kinematic and Dynamic variations that will take place in cam and follower mechanisms made of composite material under hygrothermal environment.

II. RELATED WORK

Thompson et al [1-4] proposed an alternate philosophy by designing mechanism component using fiber reinforced composite materials possessing high specific strength and high specific stiffness. Weight saving upto 70% and good fatigue life and high damping that is thirty times greater than aluminium is an added advantage of using composite material for mechanisms. Xianmin Zhang and Wenfeng Zhang [5] has published a paper and claimed that

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

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Vol. 6, Issue 3, March 2017

deformation and stresses are produced not alone by mechanical forces but by temperature variations as well. Li et al [6] analyzed large thermal deflections of a Timoshenko beam subjected to transversely non uniform temperature rise by using the shooting method. Analysis of moisture absorption data for epoxy or matrix shows that the moisture concentration increases initially with time and approaches an equilibrium (saturation) level after several days or sometimes several months of exposure to humid environment is referenced in [7, 8, 9, 10, 11]. Chamis [12, 13, 14, 15 and 16] proposed the empirical equation for estimating the hygrothermal effect on the properties of matrix. The Hygrothermal effect should not be ignored when analyzing the Kinematic and Dynamic performance of mechanisms made of composite materials. Singh and Sanyal investigated about effect of hygrothermal environment on various mechanisms, two Research-paper, the first one is "Deviations in coupler curve due to hygrothermal environment in four bar planar mechanism made of neat resin" in *Discovery Engineering*, 2016 [17] and second one is "Variations in Geometry, Volume, Mass and Moment of Inertia of a Four Bar Mechanism link made of Neat-resin under Hygrothermal Environment", in *IJIRSET*, 2016 [18]. Apart from these works not much is done to evaluate, that how performance of mechanisms made of composite material will alter under hygrothermal environment. Heretofore, no attempt has been made to find out Kinematic and Dynamic variations in Cam and Follower mechanism made of composite material under Hygrothermal environment.

Some part of the literature review related to Hygrothermal environment is as follows, Hiroshi Saito et.al [19], evaluated the damage evolution behavior by considering the effect of the textile structure and water absorption. Damage observation was conducted by the integration of non-destructive and direct observation methods. Toshio Ogasawara et.al [20], examined the effect of fullerene dispersion on the mechanical properties of carbon-fibre reinforced epoxy matrix composites. Mechanical properties such as tension, compression, open-hole compression, compression after impact, bending, short beam shear, and inter laminar fracture toughness were evaluated for laminates. B. Kolesnikov et.al [21], explained about the structural joining essential for the development of composite aerospace structures. Alaattin Aktas et.al [22], investigated about the effect of sea water on the bearing strength behaviour of the woven glass fibre composite in this paper. Z. Sereir et.al [23], worked for the reduction of the hygroscopic stresses at the edges of the hybrid composite for the symmetrical and constant environmental conditions in this paper. B. Pradhan and Panda [24], has given about their investigation on the influence of ply layup and the interaction of residual thermal stresses and mechanical loading on the inter laminar asymmetric embedded delamination crack growth behavior in this paper. B. Pradhan and Panda [25], published a paper on effect of material isotropy and curing stresses on interface lamination propagation characteristics in multiple laminated FRP composites. E.C Botelho, et.al [26], studied about the environmental factors, such as humidity and temperature, can limit the applications of composites by deteriorating the mechanical properties over a period of time.

Some part of the literature review related to Cam and Follower is as follows, H. D. Desai et.al [27], State that in "Computer Aided Kinematic and Dynamic Analysis of Cam and Follower", he said analysis becomes more complex when the engine does not have an overhead cam shaft, or when there is an overhead cam shaft that operates the valves by rockers. Khin Maung Chin [28], State that high accelerations are needed to give rapid opening and closing, too rapid a change in acceleration – the 'jerk' or 'jerk rate' will give rough operation due to the sudden changes in forces. M. Teodorescu et.al [29], presented an analysis of a line of valve trains in a four-cylinder, four-stroke in-line diesel engine in order to predict the vibration signature taking into account frictional and contact forces. A. Cardona et.al [30], presented a methodology to design cams for motor engine valve trains using a constrained optimization algorithm in order to maximize the time integral of the valve area opened to gas flow. He observed that profile errors can have a large influence on the dynamic performance of such high-speed follower cam systems. H. S. Jeon et.al [31], stated that with experimental and simulation results that optimizing a cam profile can increase the valve lift area while reducing the cam acceleration and the peak pushrod force. Yu, Z.W. et.al [32], state that, factographic features indicate that multiple origin fatigue fracture was dominant failure mechanism, the camshaft gear fracture first followed by the camshaft gear.

International Journal of Innovative Research in Science, Engineering and Technology

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III. MATERIALS AND LUBRICATION OF CAM AND FOLLOWER MECHANISM

Engineering design is the art of compromise. Engineers typically select components by weighing criteria such as function, reliability, availability, and cost. In the case of cam followers, however, engineers generally don't have much choice. Depending on the application, the designer may choose from materials such as composite materials /plastics, bronze, gray cast iron, nodular and malleable iron, Meehanite iron, a range of low medium and high alloy steels; and stainless steels. In addition, there are different ways of modifying or processing the materials to improve their properties or to reduce the cost of manufacture (Zaretsky, 1997). These include reinforcements for plastics, processing for titanium, and hardening for many of the iron-based materials. When selecting a material for an application, the cam designer will first determine the requirements for the cams being considered. The design requirements for a cam in a given application will depend on such things as accuracy, load, speed, material, and noise limitations. The more stringent these requirements are, the more costly the cam will become. Some of the considerations in the choice of a material include allowable Hertzian stress, wear resistance, impact strength, water and corrosion resistance, manufacturing cost, size, weight, reliability, and lubrication requirements. Steel, under proper heat treatment, meets most of these qualifications for roller followers, while cast iron is excellent for sliding followers. The most widely acceptable metal characteristic reducing the tendency to gall is *selflubrication*. Self-lubrication is exemplified by porous powder metals (oil-impregnated), gray cast iron, Meehanite, ductile cast iron, graphitic steels (graphite-lubricated), and leaded bronze (lead-lubricated). These materials suffer less damage when galling takes place. There has always been a need for lightweight, low-cost cam material for light-duty applications. In the past, cams were made from phenolic-resin-impregnated cloth. However, in recent years, with the development of new polymers, many cams are made of various plastic/composite materials. Advantage associated with composite material are light weight, weight distribution, high specific Strength and Stiffness, directional strength and/or stiffness, improved smooth surface Properties, corrosion resistance, tailored surface finish, low thermal conductivity, low coefficient of thermal expansion, high dielectric strength, non-magnetic and radar transparency. For example, conventional metal cam followers are built for relatively high loads, and that will overkill in light-duty applications. Rail or cam surfaces have to be hardened. And users have to provide lubrication or the bearing and rail can catastrophically fail. Yet excessive grease can contaminate surrounding products and lead to cam-follower skidding and wear. The shock and vibration caused by metal-to-metal impact is also a hazard and the metal particles often contaminate grease, restricts use in the growing clean-room market. Finally, the relatively low rotating speed of the needle bearings in these devices, combined with high rolling resistance and inertia, may limit their use in high-speed equipment. Cam followers that use plastic-composite are a viable alternative to traditional designs. They are especially helpful when the cam follower's primary function is to transmit motion rather than carry high loads. Today's trend is toward high-speed, lightweight, and light-duty machines in food processing, packaging, medical, pharmaceutical industry and semiconductor equipment. Plastic/composite Cam and follower are the best choice for clean-room operations. The self-lubricating composite Cam- Follower system requires no lubrication between the cam follower and rail, saving on grease and maintenance. Two possible sources of contamination – excess grease and metal particulates due to metal-on metal contact are eliminated due to the self-lubricating material of the roller. The plastic cam followers are a cost saving alternative, providing years of maintenance free operation without damaging rails. Less maintenance, greaseless, high load ratings, high-speed capacity, clean operation, can support axial load Low-rolling resistance, pre-lubricated for life, light-weight compared to metal are certain other advantages associated with Plastic/ Composite cam and follower Composite/Plastic cam and follower absorb shock and vibration and run up to 10 dB quieter than comparable metal followers. A Composite/plastic Cam follower weighs about 40% less than a same-size metal cam follower, thus less inertia, which becomes especially important at high speeds. Low rolling resistance and lack of external lubrication also contribute to high-speed capabilities.

Table 1 lists plastic materials used for molded cams. The most common molded plastic cams are made of acetate and nylon resins. These materials are limited in strength, temperature resistance, and accuracy. The nylon and acetate resins have a room-temperature yield strength of approximately 10,000 lb/in². This is reduced to approximately 4000lb/in² at their upper temperature limit of 250°F. Nylon resin is subject to considerable moisture absorption, which reduces its strength and causes considerable expansion. Plastic cams can operate for long periods in adverse environments, such as

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

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dirt, water, and corrosive fluids, where other materials would tend to wear excessively. They can also operate without lubrication or can be lubricated by the processed material as in the food industry. Plastic cams can run in combination with a steel roller follower to give dimensional control and quiet operation. Polyimide is a more expensive plastic material than nylon or acetate resin, but it has an operating temperature limit of approximately 600°F. This makes polyimides suitable for many adverse applications that might otherwise require metal cams. Polyimides can be used very effectively in combination with a metal follower without lubrication because of polyimide's good sliding properties. Properties of Plastic Cam Materials, is reproduced in Table1, is taken from Cam Design Handbook by Rothbart [38].

TABLE 1: PROPERTIES OF PLASTIC CAM MATERIALS

Property	ASTM	Acetate	Nylon	Polyimide
Yield strength, lb/in ²	D638	10,000	11,800	10,500
Shear strength, lb/in ²	D732	9,510	9,600	11,900
Coefficient of linear thermal Expansion in./in. °F	D696	4.5x10 ⁻⁵	4.5x10 ⁻⁵	2.8x10 ⁻⁵
Water absorption (24 h), %	D570	0.25	1.5	0.32
Specific gravity	D792	1.425	1.14	1.43
Temperature limit	-----	250	250	600

IV. PROPERTY DEGRADATION OF COMPOSITE MATERIAL UNDER HYGROTHERMAL ENVIORNMENT

The branch of composite mechanics which provides the formal structure to relate ply properties to constituent properties is called composite micromechanics. Composite micromechanics inputs consist of constituent material properties of fiber and matrix, geometric configuration, and the fabrication process. The outputs consist of ply thermal, mechanical and hygral properties. The formal structure of composite micromechanics i.e. concepts, math-models and equations are developed based on certain assumptions consistent with the physical situation and the principles of solid mechanics. Properties along the fiber direction (1-axis, Figure 2) are conventionally called longitudinal; those transverse (2-axis, Figure 2) to the fiber direction are called transverse; the in-plane shear is also called intra laminar shear (1-2 plane, Figure 2). Micromechanics equations for some geometric relationships including density (ρ) are summarized in Table-2. Here, fiber diameter and the fiber volume ratio are important parameters. The weight percentage can be used to determine the fiber or resin volume ratio from the equations. These equations are expressed in terms of weight ratio (λ_m or λ_f) and constituent densities ρ_m and ρ_f .

TABLE 2 : GEOMETRIC RELATIONSHIP		TABLE3: MECHANICAL PROPERTIES ELASTIC CONSTANTS	
Partial Volume: $k_f+k_m+k_v = 1$	Longitudinal Modulus: $E_{111} = k_f E_{f11} + k_m E_m$	Transvers Modulus: $E_{122} = E_{133} = \frac{E_m}{(1-E_m/E_{f22})(1-\nu_{ff})}$	Ply Density: $\rho_1 = k_f \rho_f + k_m \rho_m$
Resin Volume Ratio: $k_m = \frac{(1-k_f)}{[1+(\frac{\rho_m}{\rho_f})(\frac{1}{\lambda_m}-1)]}$	Shear Modulus: $G_{112} = G_{113} = \frac{G_m}{(1-G_m/G_{f12})(1-\nu_{ff})}$	Shear Modulus: $G_{123} = \frac{G_m}{(1-G_m/G_{f23})(1-\nu_{ff})}$	Fiber Volume Ratio: $k_f = \frac{(1-k_v)}{[1+(\frac{\rho_f}{\rho_m})(\frac{1}{\lambda_f}-1)]}$
Weight Ratio: $\lambda_f + \lambda_m = 1$ Inter Ply thickness: $\delta_1 = [1/2][(\pi/k_f)^{1/2} - 2]$	Poisson's Ratio: $\nu_{112} = \nu_{113} = k_f \nu_{f12} + k_m \nu_m$	Poisson's Ratio: $\nu_{123} = \frac{E_m}{2G_{123}} - 1$	Ply thickness: $t_1 = [1/2][N_f d_f (\pi/k_f)^{1/2}]$ Inter Spacing: $\delta_s = \delta_1$

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The equations for relating ply elastic constants (Moduli and Poisson's ratios) are summarized in Table 3. Properties in the third direction are the same as those in the second because ply is transversely isotropic in the 2-3 planes. Therefore, a total of five independent elastic constants are required (E_{111} , E_{122} , G_{112} , G_{123} , and ν_{112}). In order to use the equations in Table 2, the fiber volume ratio (k_f), five fiber properties (E_{f11} , E_{f22} , G_{f12} , G_{f23} and ν_{f12}) and two matrix properties (E_m , and ν_m) are needed. The matrix shear modulus is related to E_m and ν_m by $G_m = E_m/2 (1 + \nu_m)$ since the matrix is assumed to be isotropic. The void effects are incorporated into these equations by using the fiber and matrix volume ratios (k_f and k_m) predicted by the appropriate equations in Table 2. The simple equations for predicting the ply thermal properties from constituent properties are summarized in Table-4. The thermal properties in this Table include heat capacity (C_1), heat conductivity (K_1) and thermal expansion coefficient (α_1). All these thermal properties are expressed in terms of the respective constituent properties, the fiber volume ratio (k_f), the matrix volume ratio (k_m), the void volume ratio (k_v) and the heat conductivity of the air (K_v). The thermal expansion coefficients are also related to ply properties (E_{111} and E_{122}). The simple micromechanics equations for determining ply hygral properties from constituent properties are summarized in Table 5. The ply hygral properties summarized include: diffusivity (D_1) and moisture expansion coefficients (β). To determine ply hygral properties summarized in Table 5, the respective properties of the matrix and the fiber volume ratio are needed. The longitudinal moisture expansion coefficient (β_{111}) depends also on the ply-longitudinal modulus (E_{111}) while the transverse (β_{122}) depends on the transverse modulus (E_{122}).

TABLE 4 : THERMAL PROPERTIES	TABLE 5 : HYGRAL PROPERTIES
Heat Capacity: $C_1 = (1/\rho_1)(C_f k_f \rho_f + C_m k_m \rho_m)$	Longitudinal Diffusivity: $D_{111} = (1 - k_f) D_m$
Longitudinal Conductivity: $k_{111} = k_f k_{f11} + k_m k_{m11}$	Transverse Diffusivity: $D_{122} = D_{133} = (1 - \sqrt{k_f}) D_m$
Transverse Conductivity: $k_{122} = (1 - \sqrt{k_f}) k_m + \frac{k_m \sqrt{k_f}}{(1 - \sqrt{k_f})(1 - k_m/k_f)} = k_{133}$	Transverse Moisture Expansion Coefficient: $\beta_{122} = \beta_{133} = \beta_m (1 - \sqrt{k_f}) [1 + \frac{E_m (1 - \sqrt{k_f}) \sqrt{k_f}}{\sqrt{k_f} E_{122} + (1 - \sqrt{k_f}) E_m}]$
Longitudinal Thermal Expansion Coefficient $\alpha_{111} = (k_f \alpha_{f11} E_{f11} + k_m \alpha_m E_m) / E_{111}$	Longitudinal Moisture Expansion Coefficient: $\beta_{111} = \beta_m (1 - k_f) E_m / E_{111}$
Transverse Thermal Expansion Coefficient: $\alpha_{122} = \alpha_{133} = \alpha_{f22} \sqrt{k_f} + (1 - \sqrt{k_f})(1 + k_f \nu_m E_{f11} / E_{111}) \alpha_m$	For Incompressible matrix: $\beta_{111} = 0$

The physical phenomenon of hygrothermal effect associated with polymer matrix composites was recognised during the mid 1970's. Combination of high temperature and high humidity environment causes a doubly deleterious effect on structural performance of composites. The two fold problem involves entrapment of moisture in the polymer matrix and attendant weight increase and more importantly swelling of matrix. Analysis of moisture absorption data for epoxy or matrix shows that the moisture concentration increases initially with time and approaches an equilibrium (saturation) level after several days or sometimes several months of exposure to humid environment.[5, 6, 7, 8, 9, 10, 11]. Epoxy resin absorbs moisture when exposed to humid atmosphere, initially by instantaneous surface absorption and subsequent diffusion through the interior. The absorbed water is not liquid, but exist in hydrogen bonded molecules or clusters within the polymer. Liquid water may however be transported by capillary action along cracks and in composites along fiber matrix interfaces and may appear at interior voids. The absorbed water softens epoxy resins, cause them to swell and lowers their Glass transition temperature [7,8]. In the classical Fickian linear diffusion model moisture flux J_x is assumed to be directly proportional to the concentration gradient as given in equation (1), as shown in figure 3 .

$$J_x = -D \frac{dM}{dX} \text{ (Fick's 1st law of diffusion) } \dots\dots (1)$$

$$\frac{dM}{dt} = D \frac{d^2 M}{dt^2} \text{ (Fick's 2nd law of diffusion) } \dots\dots(2)$$

$$M = \frac{W - W_a}{W_a} \times 100 \dots\dots\dots (3)$$

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$$\epsilon_{hygro.} = \frac{\Delta L}{L} = \beta \cdot \Delta m \quad \dots\dots\dots (4)$$

Where W is the weight of moist material and W_d is the weight of dry material. M_m is the maximum moisture content. Where M is the moisture concentration wt. percentage at (x,t) and 'D' is the coefficient of diffusion. Moisture absorption is a function of temperature and time. At higher temperature, rate of moisture absorption will be higher. It is established that ingestion of moisture varied linearly with the swelling reported as hygrothermal strain i.e. $\epsilon_{hygro.}$. Where Δm is the increase from zero moisture (dry condition) and β is the coefficient of moisture expansion. β along longitudinal and transverse direction is given below.

$$\beta_L = \frac{E_m \cdot V_m \cdot \beta_m}{E_m \cdot V_m + E_f \cdot V_f} \quad \dots\dots\dots (5)$$

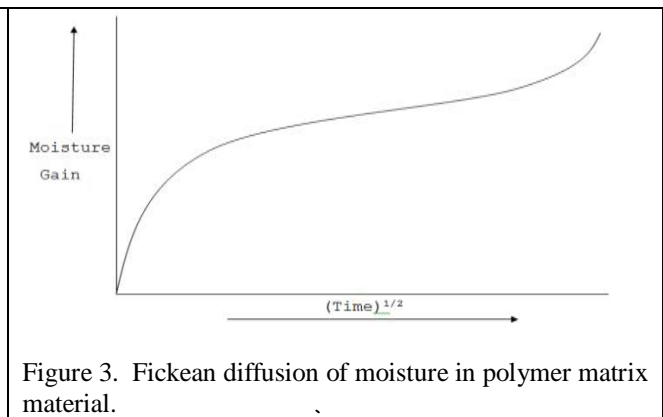
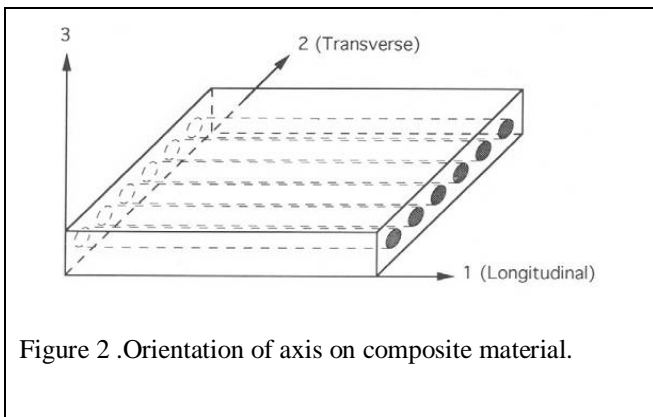
$$\beta_T = \beta_m V_m (1 + V_m) \quad \dots\dots\dots (6)$$

Due to elevated temperature, length of the bar will increase and thermal strain is given in equation no. 7 and the total strain due to hygro and thermal environment is given in equation no. 8.

$$\epsilon_{thermal} = \frac{\Delta L}{L} = \alpha \cdot \Delta T \quad \dots\dots\dots (7)$$

$$\epsilon = \epsilon_{hygro} + \epsilon_{thermal} \quad \dots\dots\dots (8)$$

here, ΔL = Change in length due to elevated temperature, ΔT = Change in temperature, L = Original Length.



Chamis et al. [5, 6, 7, 8, 9, 10, 11] proposed the following empirical equation for estimating the hygrothermal effect on the matrix properties. This can subsequently be used in modifying the matrix-dominated properties of a unidirectional lamina. The equations for predicting, hygrothermal degradation effects in composites using micromechanics are summarized in equation no. 9 and 10. The effects on the thermal properties are the reciprocal of those on the mechanical properties.. Effect on Mechanical and Thermal properties are given below respectively in equations no. 9 and 10 which are obtained by curve fitting experimental data

$$(P_{HT}) \frac{P_{HT}}{P_0} = \left[\frac{T_{GD} - T}{T_{GD} - T_0} \right] \quad \dots\dots\dots (9)$$

$$(P_{HT}), \frac{P_{HT}}{P_0} = \left[\frac{T_{GD} - T_0}{T_{GD} - T} \right] \quad \dots\dots\dots (10)$$

Here, P_{HT} = Matrix property at the use temperature T and moisture content M, P₀ =Matrix property at reference temperature. T_{GD} = Glass Transition temperature in the dry condition., T_{GW}=Glass Transition temperature in the wet

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condition with a moisture content M The Glass transition temperature in wet condition, T_{gw} is calculated using the following equation

$$T_{GW} = (0.005 \times M^2 - 0.1 \times M + 1) \times T_{GD} \quad \text{for } M < 10\% \quad \text{Or} \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} \dots\dots(11)$$

$$(T_{GW}) : T_{GW} = T + (T_{GD} - T_0) \left[\frac{F_{HT}}{F_D} \right]^2$$

Basically the moisture content in the material affects the glass transition temperature of the matrix. Time dependent Mechanical properties such as the tensile modulus and shear modulus may vary with temperature and moisture concentration, failure and strength characteristics, especially interfacial and matrix dominated ones, depends on temperature and humidity. The composite material undergoes reversible deformations related to thermal expansion and moisture expansion. Intra laminar and inter laminar stresses are developed as a result of the thermo elastic and hydro elastic in-homogeneity and anisotropy of the material. Hygrothermal is relating to a combination of moisture and heat, even under oily atmosphere and under salty water. The degradation of the mechanical, chemical, physical properties of polymeric composites, after exposure to a combination of moisture and temperature is referred to as hygrothermal ageing. Most composites materials are cured by application of heat. In other cases, when external heat is not applied, the curing process itself produces significant heat due to onset of exothermic reactions. Prior to curing, resin is in a viscous fluidic state and thus, composite constituents are reasonably free to move with respect to each other. However, once curing process is complete, the matrix gets solidified, and it no longer permits stress free motion of different constituent materials. However, at the time of curing, bulk temperature of composite is significantly high. Thus, the position of different composite constituents gets “locked-in” at an elevated temperature. As composite product cools down to room temperature, thermal stresses get generated due to differences in CTE of constituent materials of composite. Thus, almost all composite materials have a certain level of in situ thermal stresses owing their existence to the composite manufacturing process. Similar stresses also exist in composites with thermoplastic resins, as processing and solidification temperatures of these resins are significantly higher than composite use temperatures. Small to moderate concentrations of moisture (less than 1%) have no significant impact on material properties at room temperature. However, at elevated temperature, presence of moisture has a very significant adverse impact on shear and transverse strengths and moduli of composites. Glass fiber composites exhibit large strength reductions, especially if the matrix is thermoplastic or rubbery in nature. In contrast, glass fiber composites with regular thermoset resins (which tend to be brittle) suffer less degradation in their strengths due to exposure to elevated temperatures and humidity. Also, exposure to boiling water degrades several mechanical properties of glass composites with vinyl ester matrix. In general, fibre properties do not alter significantly due to enhanced moisture content and temperature. In contrast, matrix material properties are sensitive to these variables. Hence, those composite properties, which are strongly influenced by matrix properties, exhibit high sensitivity to hygrothermal effects. Specifically, these properties are transverse tensile and compressive modulus and strength, in plane shear modulus and strength, longitudinal compressive strength. Hygral, thermal and mechanical properties of unidirectional composites are fundamental to analysis/design of fiber composite structures. Another approach is the use of composite micromechanics to derive equations for predicting composite properties based on constituent (fiber and matrix) properties. Over the last twenty years, composite micromechanics have been used to derive equations for predicting selected composite properties. However, many of these equations are not of simple form and are not readily available since equations for different properties are scattered throughout the literature, referenced in [35] and [36]. In addition, recent developments on hygrothermal effects referenced in [37] provide simple equations for estimating moisture absorption, glass transition temperature of wet resins and hygrothermal degradation. Herein, a unified set of composite micromechanics equations is summarized and described. The set includes simple equations for predicting ply geometric, mechanical, thermal, and hygral properties using constituent material properties. In addition, the set includes simple equations for predicting the moisture absorption, the glass transition temperature of the wet resin and the degradation effects due to hygrothermal environments. The description consists of the significance of the participating variables in the equations. The equations for each subset geometry, mechanical properties, thermal, and moisture absorption and hygrothermal degradation effects are summarized in Tabular form. The micromechanics equations for estimating moisture in the resin and composite as a function of relative humidity ratio (RHR = 1.0 for 100 per cent relative humidity) are summarized. The

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equations in this figure are for the moisture in the matrix (M_m) and the moisture in the ply (M_l). To use these equations, the lineal moisture expansion coefficient of the matrix (β_m) and the saturation moisture of the matrix at 100 percent relative humidity are needed. If β_m is not known, it can be estimated from the equation in Table 5, by using the wet and dry density of the matrix. The saturation moisture $M_\infty = 7$ percent relative humidity for the particular resin is also needed. If it is not known, $M_\infty = 7$ percent by weight is a reasonable approximation. Moisture pickup in matrix: $M_m = M_\infty$ (RHR), Moisture pick up in composite: $M_l = M_m (3 \beta_m k_m + k_v) \rho_m / \rho_l$, Where; M_∞ =Matrix saturation moisture at 100% RH and room temperature. Some of the fiber and matrix properties are tabulated in the Table 6 and 7. With the help of these we will find out the composite properties and validate those composite material properties with the existing composite material.

TABLE 9 : CALCULATIONS OF CARBON (T300)/EPOXY COMPOSITE MATERIAL
USING MICROMECHANICS EQUATIONS UNDER NORMAL ENVIRONMENT

Partial Volume	$k_f + k_m + k_v = 1$	
Ply- Density	$\rho_l = k_f \rho_f + k_m \rho_m, \rho_l = 0.6 * 1.77 + 0.4 * 1.3 = 1.582 \text{ gm/cm}^3$	
Longitudinal Modulus	$E_{111} = k_f E_{f11} + k_m E_m,$	$E_{111} = 220 * 0.6 + 3.45 * 0.4 = 133.38 \text{ GPa}$
Transvers Modulus	$E_{122} = E_{133} = \frac{E_m}{(1 - E_m/E_{f22})(1 - \sqrt{k_f})}$	$E_{122} = E_{133} = \frac{3.45}{(1 - 3.45/14)(1 - \sqrt{0.6})} = 8.29 \text{ GPa}$
Shear Modulus	$G_{112} = G_{113} = \frac{G_m}{(1 - G_m/G_{f12})(1 - \sqrt{k_f})}$	$G_{112} = G_{113} = \frac{1.28}{(1 - 1.28/9)(1 - \sqrt{0.6})} = 3.81 \text{ GPa}$
Shear Modulus	$G_{123} = \frac{G_m}{(1 - G_m/G_{f23})(1 - \sqrt{k_f})}$	$G_{123} = \frac{1.28}{(1 - 1.28/4.6)(1 - \sqrt{0.6})} = 2.902 \text{ GPa}$
Poisson's Ratio	$\nu_{112} = \nu_{113} = k_f \nu_{f12} + k_m \nu_m,$	$\nu_{112} = \nu_{113} = 0.6 * 0.2 + 0.4 * 0.35 = 0.26$
Poisson's Ratio	$\nu_{123} = \frac{E_m}{2G_{123}} - 1$	$\nu_{123} = \frac{8.29}{2 * 2.902} - 1 = 0.428$

TABLE 10: CALCULATION OF CARBON (T300)/EPOXY COMPOSITE MATERIAL WITH THE HELP OF
COMPOSITE MICROMECHANICS UNDER HYGROTHERMAL ENVIRONMENT:

S.No.	Calculation of Carbon Epoxy composite T 300 material with the help of composite micromechanics under hydrothermal environment:	
1.	Moisture pickup in matrix:	$M_m = M_\infty$ (RHR) $\Rightarrow M_m = 2 * (0.8) = 1.6$
2.	Moisture pick up in composite: $M_l = M_m (3 \beta_m k_m + k_v) \rho_m / \rho_l$	$\Rightarrow M_l = 1.6 * (3 * 0.38 * 0.4 + 0) * 1.3 / 1.608 = 0.5898$
3.	Glass transition temperature of dry resin (T_{GD}) = 157°C	
4.	Glass transition temperature of wet resin (T_{GW}) = $(0.005 * M_m^2 - 0.1 * M_m + 1) * T_{GD} \Rightarrow T_{GW} = (0.005 * 0.5898^2 - 0.1 * 0.5898 + 1) * 157 = 148^\circ\text{C}$	
5.	The ration of degraded properties $\frac{PHTM}{P_0} \approx \sqrt{\frac{T_{GW} - T}{T_{GD} - T_0}}$	$\Rightarrow \frac{PHTM}{P_0} \approx \sqrt{\frac{148 - 113}{157 - 28}} = 0.5111$
6.	Ply Density: $\rho_l = k_f \rho_f + k_m \rho_m$	$\Rightarrow \rho_l = 0.6 * 1.77 + 0.4 * 1.3 * 1.05 = 1.608 \text{ gm/cm}^3$
7.	Longitudinal Modulus: $E_{111} = k_f E_{f11} + k_m E_m,$	$\Rightarrow E_{111} = 220 * 0.6 + 3.45 * 0.4 * 0.5886 = 132.235 \text{ GPa}$
8.	Transvers Modulus: $E_{122} = E_{133} = \frac{E_m}{(1 - E_m/E_{f22})(1 - \sqrt{k_f})}$	$\Rightarrow E_{122} = E_{133} = \frac{3.45 * 0.511}{(1 - 3.45 * 0.511 / 14)(1 - \sqrt{0.6})} =$

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	2.282GPa		
9.	Shear Modulus:	$G_{112} = G_{113} = \frac{E_m}{(1 - G_m/G_f)(1 - \sqrt{k_f})} \Rightarrow G_{112} = G_{113}$ $= \frac{1.28 * 0.5111}{(1 - 1.28 * 0.5111 / 9)(1 - \sqrt{0.6})} = 2.3224 \text{ GPa}$	
10.	Shear Modulus:	$G_{123} = \frac{E_m}{(1 - G_m/G_f)(1 - \sqrt{k_f})} \Rightarrow G_{123} = \frac{1.28 * 0.5111}{(1 - 1.28 * 0.5111 / 4.6)(1 - \sqrt{0.6})} = 1.949 \text{ GPa}$	
11.	Poisson's Ratio:	$v_{112} = v_{113} = k_f v_{f12} + k_m v_m \Rightarrow v_{112} = v_{113} = 0.6 * 0.2 + 0.4 * 0.35 * 0.5111 = 0.192$	
12.	Poisson's Ratio:	$v_{123} = \frac{E_m}{2G_{123}} - 1 \Rightarrow v_{123} = \frac{8.29 * 0.5111}{2 * 1.949} - 1 = 0.4$	

Similar calculation has been done for the two more composite materials i.e. Kelvar epoxy and Boron polyimide under normal as well as hydrothermal environment. Taking; Maximum temperature rise (T) = 113^oC, Maximum temperature rise (T₀) = 23^oC, Relative humidity ration (RHR) = 80%, Fibre volume ration (k_f) = 0.6, Matrix volume ration (k_m) = 0.4, Void volume ration (k_v) = 0.

TABLE 13: NEAT RESIN PROPERTIES α, β AND EQUILIBRIUM MOISTURE CONTENT

S. No.	Neat Resin System	Moisture Condition	Coefficient of Thermal Expansion (α) (10 ⁻⁶ /°C)	Coefficient Moisture Expansion (β) (10 ⁻³ /%M)	Equilibrium Moisture Content (%M)
1.	R914	Dry Wet	58.4 62.6	3.02	7.0
2.	3502	Dry Wet	50.5 55.5	2.70	5.0
3.	8551-7	Dry Wet	46.7 70.0	3.09	2.0

Depending upon individual values of α, β, Δm and ΔT different polymer materials behaves differently. Average material properties (α, β and equilibrium moisture content) of these materials under hydrothermal environment tested at room temperature is given in following Table-6 taken from reference [33] and [34].

TABLE14: PROPERTIES DEGRADATION OF CARBON EPOX (8551-7) COMPOSITE MATERIAL IN HYGROTHERMAL ENVIORN.

Properties of carbon Epoxy composite material	Normal Environ ment	Hygrotherml Environment (as per chamis equation)	Percentage variation (%)
Density(gm/cm3)	1.58	1.608	1.77
Longitudinal Young's Modulus(GPa)	133.38	132.705	0.5
Longitudinal Shear Modulus(MPa)	3.81	2.322	39

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TABLE15: PROPERTIES DEGRADATION OF KELVAR/EPOXY (3502) COMPOSITE MATERIAL

Properties of Kelvar Epoxy composite material	In Normal Environ.	In Hygrotherml Environ.	% variation
Density(gm/cm ³)	1.4	1.428	2.0
Longitudinal Young Modulus(GPa)	91.38	90.745	0.695
Transverse Young Modulus(GPa)	4	3.274	18.15

KINEMATIC VARIATIONS IN CAM AND FOLLOWER MECHANISM MADE COMPOSITE MATERIAL UNDER HYGROTHERMAL ENVIORNMENT

The Cam mechanism may be modeled as a three mass system (leading element, Cam and follower) with three degrees of freedom (displacement of the leading element, Cam and follower). Due to the complexity of such a model, usually the mechanism is divided into two systems: leading element, Camshaft, Cam system, and Cam-follower system which are considered as one Degree of Freedom (DOF) systems. When the Cam turns through one motion cycle, the follower executes a series of events consisting of rise, dwell and return. Rise is the motion of the follower that moves away from the Cam center, dwell is the motion during which the follower is at rest and return is the motion of the follower that moves towards the Cam center. The three common events of a follower's motion are designated in abbreviated form as follows: (i)Dwell-Rise-Dwell or Dwell-Return-Dwell (DRD): This is the most fundamental type of motion that has a dwell at the beginning and the end of the rise and return. (ii)Dwell-Rise-Return (DRR): There is no dwell between the rise and the return. (iii)Rise-Return (RR): In this case, there is no dwell. There are wide varieties of basic curves of DRD type that can be used as the follower's motion. Basic curves belong primarily to two classes: Simple algebraic polynomial curves; for example, constant velocity and higher degree polynomial curves; Trigonometric curves such as simple harmonic, Cycloidal and elliptical curves. The selection of the basic curve plays important role in designing a Cam-follower system. It is largely dependent on the performance requirement. The curve is used in the design of Cam as it decides the shape of the Cam. Through this shape Cam transmits the desired motion to its follower by direct contact. To make the jerk less follower smooth motion, the generating curve must be as smooth as possible.

The traditional Cam design process includes the specification of motion curves for the follower and the subsequent calculation of the Cam profile. Once the profile is generated, the radius of curvature, pressure angles, and other properties of the profile are checked for feasibility and the process is repeated until a feasible design is generated. Although there are standard motion curves such as 4-5-6-7 polynomial, they cannot always satisfy the actual needs. They are suitable for slow and medium speed of Cam machineries and have limitations when used in high speed machineries because jerk increases as the speed increases. To reduce these limitations, B-spline curve is used to design the Cam-follower system in this proposed research. In a Cam-follower mechanism, the load produced by inertia forces induces deflections and creates vibrations. These affect the operating life of the Cam. So the design of motion curves is used to minimize dynamic loading for high speed Cam mechanisms. It is well known that the velocity and acceleration curves are required to be continuous and to have the peak values as small as possible i.e. minimum jerk. The cam is assumed to rotate at a constant speed and the follower raises, dwells, returns to its original position and dwells again through specified angles of rotation of the cam, during each revolution of the cam. Various follower motion can be classified as (i) Uniform velocity(ii) Modified uniform velocity(iii) Uniform acceleration and deceleration(iii) Simple harmonic motion(iv)Cycloidal motion.

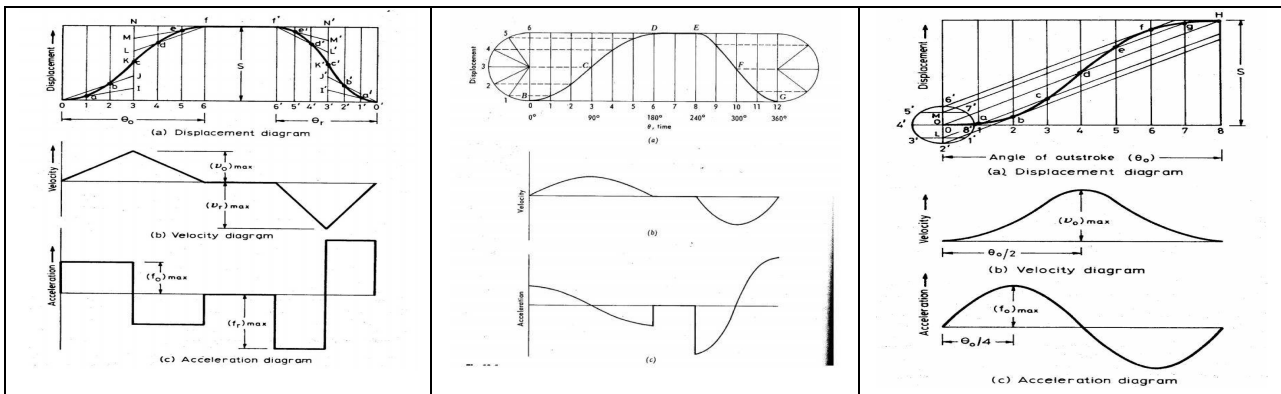
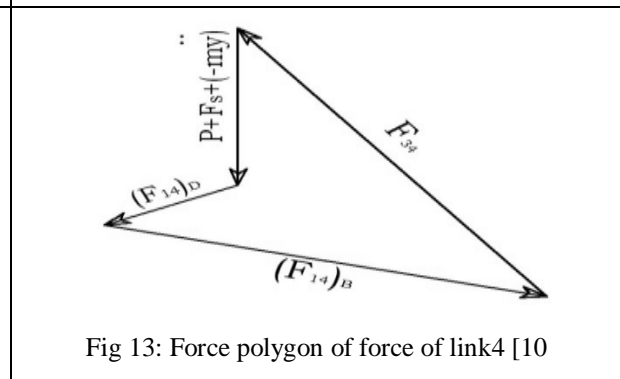
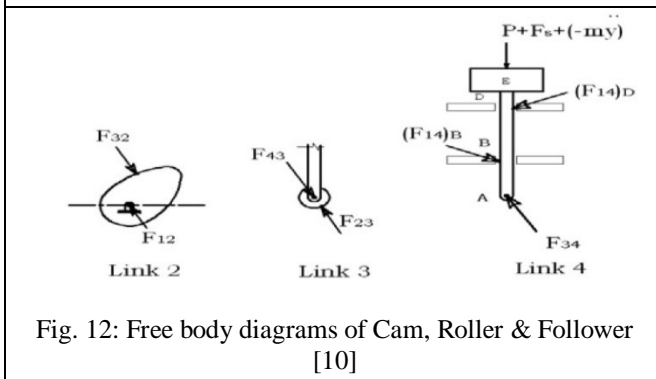
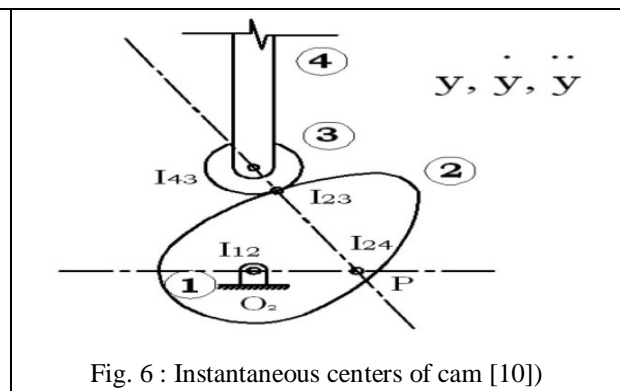
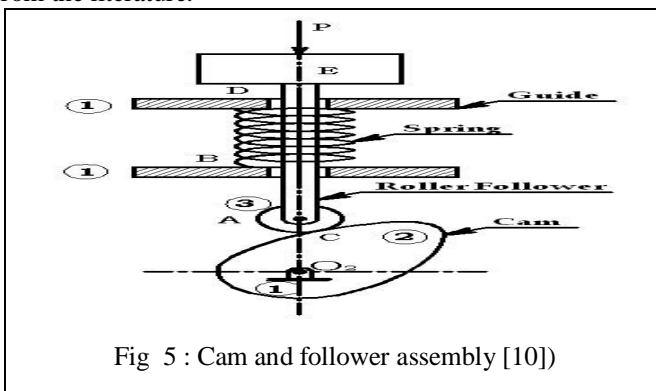


Figure 4 : follower motion with uniform acceleration and retardation , Simple Harmonic Motion and Cycloidal Motion [24].

Cams are commonly used in opening and closing of valves in internal combustion engines. Both the inlet and outlet valves are regulated using cam and follower. The study of cam and follower mechanism becomes important for desired and required performance of the engines. In this paper, complete kinematic and dynamic analysis of cam and follower mechanism is carried out using analytical method. The equations for governing motion of the follower have been taken from the literature.



The kinematic analysis of mechanism helps in answering many questions related to motion of the follower. In this present work displacement, velocity and acceleration values are calculated at each 15° rotation of cam using analytical relations. Fig. 4.6 shows cam follower assembly. The dynamic analysis includes the static and inertia force analysis of the follower. For normal working of mechanism, the resultant vertical force has to be in downward direction. If the

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instant force changes its direction, lifting of follower will take place and design will fail. In this paper kinematic parameters and forces are calculated analytically and critical angular speed of rotation is found for the design specification. The equations have been programmed for the computer solution for rotation of cam by an interval of 15° . Kinematic analysis involves the calculations of displacement, velocity and acceleration of the follower at different instant. Empirical relations are used for displacement. By differentiation we can get velocity and acceleration. Here, $k = \theta/\beta$, $h =$ Lift of the follower, $\theta =$ Angular displacement of the cam, $\beta =$ Angle of rise, $y =$ Vertical displacement of the follower.

TABLE 17: DISPLACEMENT, VELOCITY, ACCELERATION AND JERK FOR DIFFERENT TYPE OF CAM AND FOLLOWER MOTION [40, 41 ,42, 43]

Type of cam and Follower	Displacement	Velocity	Acceleration	Jerk
Cycloidal motion	$y = h[k - (1/2\pi) \sin(2\pi k)]$	$y' = 0.5 * \pi * h [\sin(\pi k)]$	$y'' = 0.5 * \pi^2 * [\cos(\pi k)]$	$y''' = -0.5 * \pi^3 * h [\sin(\pi k)]$
Simple Harmonic Motion	$y = 0.5 * h * [1 - \cos(\pi k)]$	$y' = \frac{\pi * h}{2 * \beta} \sin(\pi k)$	$y'' = \frac{\pi^2 * h}{2 * \beta^2} \cos(\pi k)$	$y''' = \frac{\pi^3 * h}{2 * \beta^3} \sin(\pi k)$
Constant Velocity Motion	$y = h * k$	$y' = \text{constant}$	$y'' = \text{zero}$	$y''' = \text{zero}$
Constant Acceleration and Retardation	$y = 2 * h * k^2$ for $\theta \leq (\beta/2)$ $y = h * [1 - 2 * \{1 - k^2\}]$ for $\theta \geq (\beta/2)$	$y' = 4 * h * k$ for $\theta \leq (\beta/2)$ $y' = 4 * h * k$ for $\theta \geq (\beta/2)$	$y'' = 4 * h$ for $\theta \leq (\beta/2)$ $y'' = 4 * h$ for $\theta \geq (\beta/2)$	$y''' = \text{zero}$ for $\theta \leq (\beta/2)$ $y''' = \text{zero}$ for $\theta \geq (\beta/2)$

Kinematic analysis of mechanism helps in determining the cam torque or torque delivered to the rotating cam. Using instantaneous centre of rotation of link 2 and link 4 we get torque delivered to the cam. Now, for the kinematic and dynamic calculation of cam and follower mechanism some inputs are required that are: **Inputs:** Follower displacement (h) = 1.5 inch, Angular rotation of cam (ω_2) = 62.83 rad/sec, Mass of the system in normal environment (m_d) = 1.6 kg, Angle of rise (β) = 75° , External load applied (P) = 100 N, Spring constant (k) = 1376.7 N/inch, Motion = Simple harmonic motion, Radius of the follower (r_f) = 0.6 inch, Base circle radius of cam (R_b) = 1.94 inch, Composite Material for the cam and follower = Carbon(T300)/ Epoxy(8551-7).

For Simple harmonic motion: Pitch circle radius (R_p): $R_p = (157 * h) / \beta$, Base circle radius of cam (R_b): $R_b = R_p - 2 * r_f$, Displacement (y): $y = 0.5 * h * [1 - \cos(\pi k)]$, Velocity (v): $v = 0.5 * \pi * h [\sin(\pi * k)]$, Acceleration (a): $a = 0.5 * \pi^2 * [\cos(\pi k)]$, Jerk (j): $j = -0.5 * \pi^3 * h [\sin(\pi * k)]$. Where: $k = \theta / \beta$. Hygrothermal expansion (ΔR), Thermal expansion, (ΔR_T) = $R_p * \alpha * \Delta T = 3.14 * 70 * 10^{-6} * 90 = 0.019782$, Hygral expansion (ΔR_H) = $R_p * \beta * \Delta m = 3.14 * 3.09 * 10^{-3} * 3 = 0.0291078$, Total Hygrothermal Expansion (ΔL), $\Delta R = \Delta R_T + \Delta R_H = 0.019782 + 0.0291078 = 0.04889$ inch, So new pitch circle radius under hygrothermal environment (R_p^1): $R_p^1 = R_p + \Delta R = 3.14 + 0.04889 = 3.189$ inch, And new follower displacement under hygrothermal environment (h^1): $R_p^1 = (157 * h^1) / \beta$, $3.189 = (157 * h^1) / \beta$, $h^1 = 1.523$ inch, Weight gain by the cam and follower system made by the carbon epoxy composite material: $\% M_m = (m_w - m_d) / m_d$, Where $m_w =$ mass of the system under hygrothermal environment $= [(m_w - 1.6) / 1.6] * 100$, Thus $m_w = 1.648$ kg. The results computed from the program developed for kinematic and dynamic analysis of the follower are given for each 15° rotation of cam. The results of kinematic analysis of the follower gives values of displacement, velocity and acceleration at different instants under normal and hygrothermal environment, which is shown in table below.

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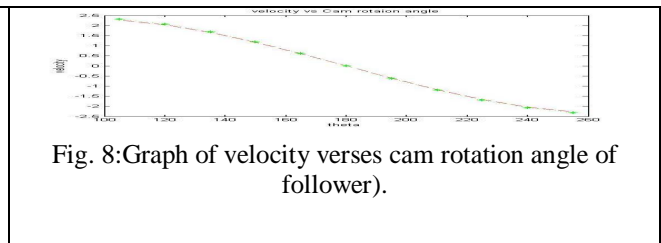
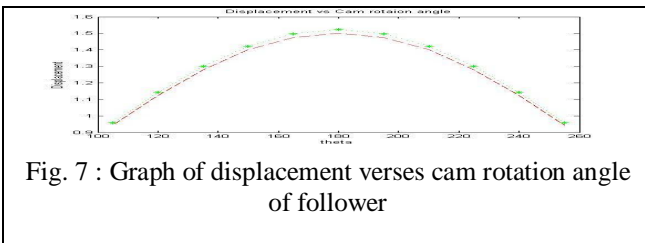
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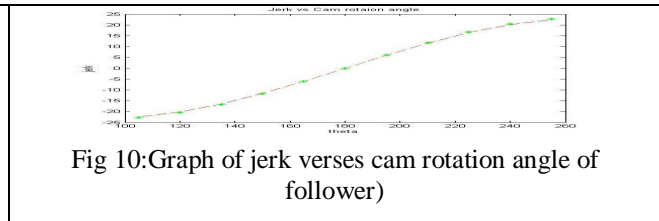
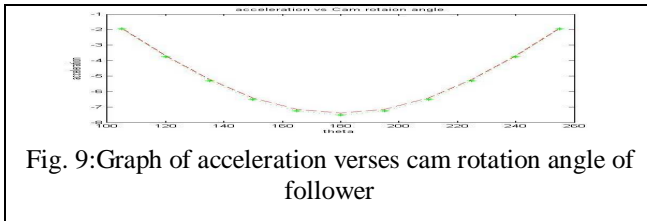
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TABLE 18: DISPLACEMENT, VELOCITY, ACCELERATION AND JERK UNDER NORMAL AND HYGROTHERMAL ENVIRONMENT.

Angle of Cam rotation in degree	Displacement of the follower In inch		Velocity of the follower In inch/sec		Acceleration of the follower In inch/sec ²		Jerk of the follower in inch/sec ³	
	Normal environ. [y]	Hygrothermal Environ. [y ¹]	Normal environ. [y']	Hygrothermal environ. [y' ¹]	Normal environ. [y'']	Hygrothermal environ. [y'' ¹]	Normal environ. [y''']	Hygrothermal environ. [y''' ¹]
105	0.9441	0.9585	2.2759	2.3108	-1.915	-1.945	-22.462	-22.806
120	1.125	1.1422	2.0405	2.0718	-3.701	-3.757	-20.139	-20.447
135	1.2803	1.2999	1.666	1.6916	-5.234	-5.314	-16.443	-16.695
150	1.3995	1.4209	1.178	1.1961	-6.410	-6.508	-11.627	-11.805
165	1.4744	1.497	0.6098	0.6191	-7.149	-7.259	-6.0187	-6.111
180	1.5	1.523	0	0	-7.402	-7.515	0	0
195	1.4744	1.497	-0.609	-0.6191	-7.149	-7.259	6.0187	6.111
210	1.3995	1.4209	-1.178	-1.1961	-6.410	-6.508	11.627	11.805
225	1.2803	1.2999	-1.666	-1.6916	-5.234	-5.314	16.443	16.695
240	1.125	1.1422	-2.0405	-2.0718	-3.701	-3.757	20.139	20.447
255	0.9441	0.9585	-2.2759	-2.318	-1.915	-1.945	22.462	22.806

The result from dynamic analysis gives the resultant vertical force on the follower and torque delivered to cam. Table: 5.7 shows Inertia Force, Spring Force, Resultant Force and torque according to cam rotation angle for simple harmonic motion. Kinematics variation of cam and follower made of Carbon Epoxy composite material under normal and hygrothermal environment: These graphs are generation by the coding in Matlab R2010a. These graphs are only for the cam rotation for 105⁰ to 255⁰. Although there will be no displacement in the follower from 0⁰ to 105⁰ and 255⁰ to 360⁰. These cases are dwell case of cam. So follower will rise during the rise periods of 105⁰ to 180⁰ and follower will down in return periods 180⁰ to 255⁰ of cam. The graphs are showing the result between the rise and return of the follower in the range of 105⁰ to 255⁰ rotation of cam. Kinematic analysis result of cam and follower made of Carbon Epoxy composite material under normal and hygrothermal environment are given below.





Cam simulator result ,Now, for the kinematic and dynamic calculation of cam and follower mechanism some inputs are required. After putting the inputs to the cam simulator it shows the shape of the cam follower and graphs of Displacement-Theta, Velocity-Theta, and Acceleration-Theta. So thesis result verifies the graphs with cam simulator’s graphs.

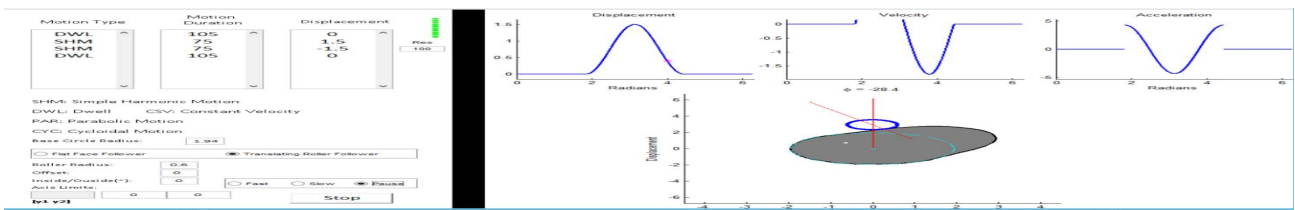


Fig 11: Result of cam simulator

VI. DYNAMIC VARIATIONS IN CAM AND FOLLOWER MECHANISM MADE OF COMPOSITE MATERIAL UNDER HYGROTHERMAL ENVIORNMENT

Now we have, $V_p = \dot{y} = \omega_2 \times O_2P$, Thus $O_2P = (\dot{y}/\omega_2)$, $T_2 = F_{32}^Y \times O_2P$ and $F_{32}^Y = P + F_s + (-m\ddot{y})$, Where, \dot{y} = Velocity of follower, \ddot{y} = Acceleration of the follower, ω_2 = Angular velocity of the cam, T_2 = Torque delivered to the cam, F_{32}^Y = Reaction of link 3 on link 2, m = Mass of the follower, F_s = spring force, P = External force. For finding F_{32} , dynamic analysis is done. Using the equations of displacement, values of all kinematic parameters are calculated with the help of computer program. The resultant force acting on the follower, link 4 consists of the following forces:-(i). Reaction due to link3 on link4, (F_{34}), (ii). Reactions at support due to link1 on link4 (F_{14})_B and (F_{14})_D,(iii). Inertia force due to mass of follower. ($-m \ddot{y}$),(iv). Spring force. (F_s), (v). Force due to load. (P).Dynamic analysis of follower gives resultant force acting on it in vertical direction which is directly related to the motion of follower. The negative sign of the resultant force ensures that the net downward force on the follower maintains its contact with the cam, through an idler roller. This remains so until it reaches a critical speed. Beyond the critical speed, the resultant force becomes positive and act in upward direction, which results in lifting of the follower, leaving its contact with the cam. Such situation is called jump of follower and the design fails to give desired performance. Force polygon gives the resultant force acting between the cam and the roller follower which will be helpful to find out the torque produced by the cam to displace the follower. Resultant force is the combination of inertia forces, spring force and the external force applied in the system.

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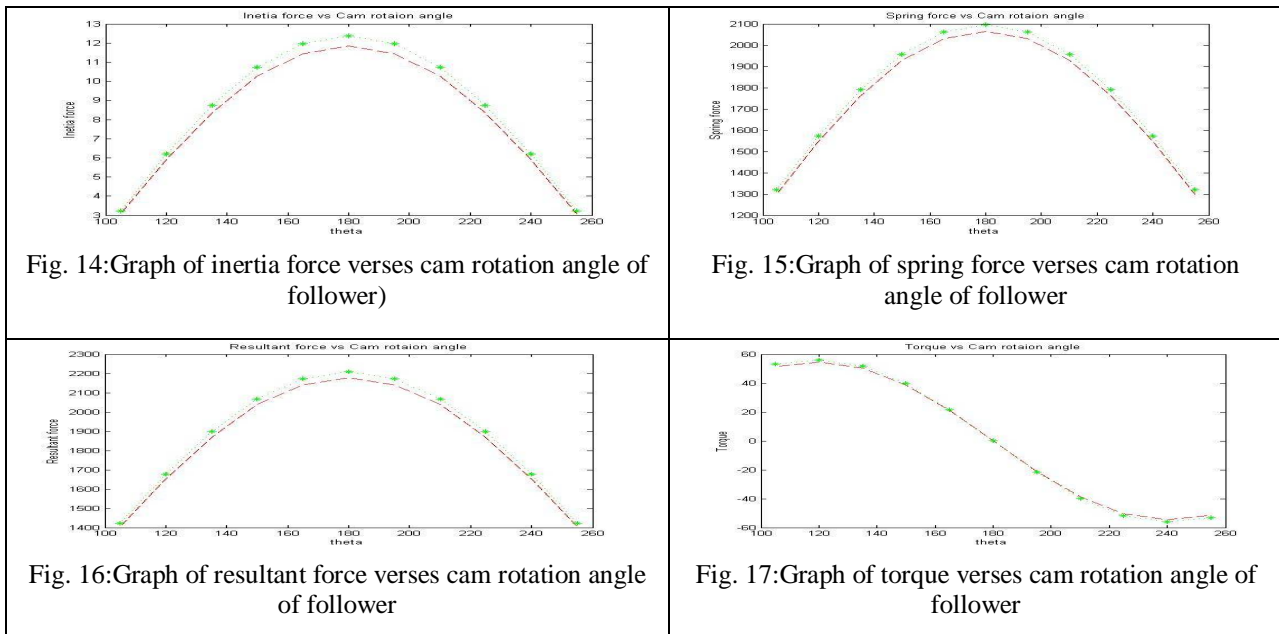
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TABLE 19 : Dynamic variation (inertia force, spring force, resultant force and torque of follower) of cam and follower made of carbon epoxy composite material under normal and hygrothermal environment:

Angle of rotation of cam in degree	Inertia force(F_i) Newton, $F_i = -m \cdot \ddot{y}$		Spring Force(F_s) Newton, $F_s = k \cdot y$		Resultant force(R) Newton, $R = P + F_i + F_s$		Torque(T) Newton-inch $T = R \cdot (\dot{y} / \omega_2)$	
	Normal enviro. [y]	Hygro-thermal [y ¹]	Normal enviro. [y]	Hygro-thermal environ. [y ¹]	Normal environ. [y]	Hygro-thermal environ. [y ¹]	Normal environ. [j]	Hygro-thermal environ. [j ¹]
105	3.0653	3.2057	1299.7	1319.6	1402.8	1422.9	51.4953	53.0329
120	5.9217	6.1929	1548.7	1572.5	1654.7	1678.7	54.4593	56.0969
135	8.3746	8.7581	1762.6	1789.6	1871.0	1898.4	50.2782	51.7970
150	10.256	10.726	1926.7	1956.2	2037.0	2067.0	38.7057	39.8782
165	11.439	11.963	2029.8	2060.9	2141.3	2173.0	21.0618	21.7008
180	11.843	12.385	2065.0	2096.7	2176.9	2209.1	0	0
195	11.439	11.963	2029.8	2060.9	2141.3	2173.0	-21.061	-21.700
210	10.256	10.726	1926.7	1956.2	2037.0	2067.0	-38.705	-39.878
225	8.3746	8.7581	1762.6	1789.6	1871.0	1898.4	-50.278	-51.797
240	5.9217	6.1929	1548.7	1572.5	1654.7	1678.7	-54.459	-56.097
255	3.0653	3.2057	1299.7	1319.6	1402.8	1422.9	-51.495	-53.033

Dynamic analysis results are given below



VII. CONCLUSIONS

A unified set of composite micromechanics equations of simple form is summarized and described. This unified set can be used to predict unidirectional composite (ply) geometric, mechanical, thermal and hygral properties using constituent material (fiber/matrix) properties. This unified set also includes approximate equations for predicting (1) moisture absorption; (2) glass transition temperature of wet resins; and (3) hygrothermal degradation effects. These equations demonstrate the interrelationship of the various factors (geometric to environmental) and help provide insight into composite behavior at the micro mechanical level. In kinematic analysis of cam and follower mechanism, it is observed that the displacement, velocity and acceleration changes because of variation in pitch circle radius of cam due to hygrothermal expansion. In dynamic analysis of Cam and follower mechanism under hygrothermal environment, it is observed that mass of Cam and follower increases thus inertia forces enhance which leads to enhancement in Resultant forces thus higher torque. Hygrothermal environment condition has a severe effect on composite material properties that are followings: Density(gm/cm^3) = 2.0% (Increased), Longitudinal Young's Modulus(GPa) = 0.695% (Decreased), Transverse Young's Modulus(GPa) = 34.0% (Decreased), Longitudinal Shear Modulus(MPa) = 39.0% (Decreased), Transverse Shear Modulus(MPa) = 32.8% (Decreased), Longitudinal Poisson's Ratio = 20.0% (Decreased), Transverse Poisson's Ratio=21.69%(Decreased). Tables show that the variation in properties of composite materials. Due to change in these properties the strength of composite material also degrades. Here, three neat epoxy resins were considered as material of links of four bar mechanism viz. R-914, 3502, and 8551-7. Results obtained for the three neat epoxy resins were compared. The maximum geometrical variations under hygrothermal environment were observed for R-914, as maximum moisture is absorbed by this epoxy resin so more swelling and more change in length of link thus higher structural and angular variations are observed. Due to absorption of moisture volume will enhance and density and mass will also increase thus mass moment of inertia of cam and follower also enhances Contact stresses can be finding under the hygrothermal environment and check the variation in contact stresses under hygrothermal environment. Modal analysis can be performed under hygrothermal environment of the cam and follower.

International Journal of Innovative Research in Science, Engineering and Technology

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