IMPACT OF NANOMATERIALS IN AIRFRAMES ON COMMERCIAL AVIATION

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ABSTRACT

The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) sponsors a research effort investigating carbon nanotube reinforced polymer (CNRP) composite materials in commercial aircraft, the performance of such aircraft, and their potential impact on the air traffic system. This paper discusses the overall goals of this research and highlights the methods for investigating nanomaterials, notional CNRP aircraft performance, and the potential impact of such a vehicle on airports and airspace.

In the last decade, nanotechnology concepts have motivated interdisciplinary science and engineering on the atomic and molecular scale, with a significant influence on materials research. Since Ijima's discovery of the carbon nanotube in 1991,[1] stronger than steel, lighter than aluminum materials with multifunctional capabilities have been realized in carbon nanotube technologies. Carbon nanotube enhanced materials especially fit the needs of the aerospace industry, where materials with high strength-to-weight ratios dominate designs.

INTRODUCTION

Aviation nanotechnology research at MITRE is inherently multidisciplinary, incorporating the expertise of several core aviation and nanotechnology disciplines such as molecular nanosystems, aircraft performance modeling and simulation, air traffic management operations and procedures, and aircraft economics and system efficiency. Integrating specific applications from each discipline, including carbon nanotube-polymer molecular mechanics modeling, analysis and flight simulation of aircraft performance, wake vortex analysis and modeling, airport and airspace capacity analysis, and aircraft efficiency analysis facilitates the accomplishment of the overall project goals.

The objective of this research is to assess the impact of carbon nanotube reinforced polymer composite airframes on aircraft performance and the National Airspace System (NAS). The specific research goals consist of CNRP composites mechanical property analysis, an investigation of the extent to which CNRP affects the weight of commercial aircraft, an analysis of subsequent performance improvements of notional CNRP-structured commercial aircraft, and an assessment of the impacts of improved performance on aircraft efficiency as well as airport and airspace capacity and throughput. Detailed results of this research are currently under validation; however, preliminary estimates suggest the possibility of promising CNRP material properties, broader, more cost-effective operating envelopes, and mitigated wake vortex circulation from CNRP-structured aircraft.

This paper highlights the methods and tools used in the research activities of MITRE's aviation nanotechnology research. A brief introduction to carbon nanotubes and CNRP is also presented. A general description of NASA Langley's Advanced Vortex Spacing System (AVOSS) tool is described as it relates to predicting wake vortex for a notional CNRP aircraft. MITRE's visualization tools as well as airport and airspace capacity models are also discussed.

CARBON NANOTUBE REINFORCED POLYMER

The Carbon Nanotube

The discovery of the carbon nanotube[1] holds spectacular potential for materials applications. This unique molecule is ultra-strong, super-light, and exhibits both metallic and semi-conducting properties. The chicken wire-like graphene carbon-carbon hexagonal lattice structure, seen in Figure 1, lends diamond scale strength and toughness to this new form of elemental carbon. The tubular structure also enables ballistic electron and phonon transport,[2] which gives the nanotube extraordinary current carrying and heat conducting capacity. Typical metals such as copper conduct approximately 2 million electrons per second through the wire's ~3 millimeter (0.12 inch) cross section. In comparison, single walled carbon nanotubes conduct nearly 2 trillion electrons per second through

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the ~3 nanometer (0.00000012 inch) nanotube molecule diameter.[3]

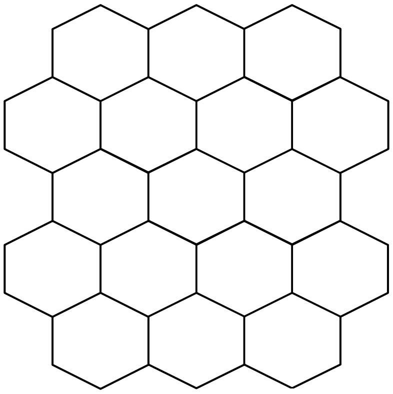

Figure 1. Graphene Carbon-Carbon Lattice Structure

Because of the high current carrying capacity of the carbon nanotube molecule, the recent primary market for nanotube composites focuses on conduction in polymers. The Zyvex Corporation[4] is currently researching this, as well as NASA Langley Research Center. NASA is studying the use of the conductive polymer to address static charge dissipation in space vehicles.[5] Previously limited to micron-scale nanotube lengths, research and development continues on carbon nanotubes as a reinforcing mechanism in composites as researchers manufacture nanotube fibers several centimeters in length.[6-9]

Carbon nanotubes form in extreme conditions through processes such as carbon vapor deposition, carbon arc discharge, and laser ablation.[10] They tend to form with multiple concentric walls, where the cross section appears much like a bull's eye, or in bundles of single walled tubes.

Pure single-walled nanotubes (SWNT) characteristically exhibit the highest toughness, or Young's modulus, peaking around 1.25 Tera Pascal, TPa, (181,300 thousand pounds per square inch, ksi).[2,11-13] This molecule is tougher than spider silk, whose Young's modulus nears 300 Mega Pascal, MPa (44 ksi).[14] Although both single and multi-walled nanotubes (MWNT) exhibit outstanding strength and modulus, pure SWNT prove exceptional reinforcing "fibers" for a carbon nanotube reinforced polymer composite. Some scientists claim the carbon nanotube to be "the strongest material that will ever be made."[15]

Carbon nanotubes form with various chiralities, or "twists" in the graphene lattice which define the tube structure. The angle of twist is directly related to the chiral vector, $\mathbf{C_h}$, which is defined by the vector addition of two normal vectors, $\mathbf{a_1}$ and $\mathbf{a_2}$, and their respective indices (m,n) as shown in the following equation:

$$\mathbf{C_h} = n\mathbf{a_1} + m\mathbf{a_2}$$

Figure 2 illustrates the chiral vector for an armchair nanotube, where $m = n = 2$. The name "armchair" originates from the geometry of the nanotube bonds around the tubes circumference.

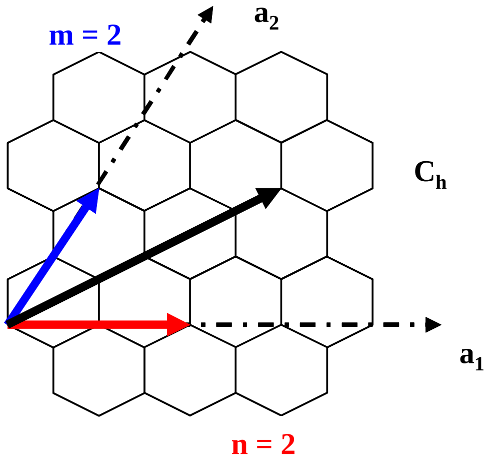

Figure 2. (2,2) Armchair Nanotube

The Young's modulus for a (10,10) armchair SWNT averages ~640 GigaPascal (GPa) (93,000 ksi) in both calculation[16] and measurement.[17] SWNT bundles exhibit tensile strengths on average from 15 to 52 GPa (23 to 75 ksi) and a corresponding tensile strain minimum of 5.3%, where the load is applied to the nanotubes at the perimeter of each bundle.[9,17,18] Multi-walled nanotubes range in tensile strength from 11 to 63 GPa (16 to 91 ksi) with a tensile strain at fracture of close to 12%.[19,20]

Carbon Nanotube Reinforced Polymer Composite

Classically, composites consist of a high-modulus fiber in a low-modulus matrix, where the fiber toughens and strengthens the material. Wood is a natural fiber-reinforced composite, where the cellulose serves as the fiber in a matrix of lignin and hemicellulose.[21] Because of their high modulus and strength, SWNT or MWNT serve as reinforcing fibers in CNRP. Due to their exceptional mechanical properties, armchair (10,10) SWNT serve as the reinforcing fiber in the CNRP property estimates in this research. In CNRP, polymers function as the matrix material; high density polyethelyne, both amorphous and crystalline[22] is the polymer used in the analysis of CNRP in this work.

MITRE tracks the emerging reality of carbon nanotube reinforced polymer composites. Ongoing research follows trends in experimental and theoretical findings on CNRP mechanical properties such as Young's modulus, tensile strength, and density. In parallel, MITRE explores its own theoretical analysis of these properties using the method of mixtures and molecular mechanics simulations in MacSPARTAN and mathematical analysis in Mathematica.

Several methods exist for calculating mechanical properties of composites, including the method of mixtures (MOM)[21,23] used as an initial analysis in this research to estimate the density, tensile strength, and Young's modulus of bi-directional CNRP. The aligned, uniformly dispersed fibers of a bi-directional composite falls under the category of an ideal uniformly dispersed aggregate composite commonly analyzed by MOM. MOM enables the analysis of materials on the macro-scale when given the bulk mechanical properties, including tensile strength, modulus, diffusivity, thermal conductivity, or electrical conductivity[21] of the composite's constituents. In this analysis, the density, tensile strength, and Young's modulus are known for the polymer, and the same properties are known of the single-walled carbon nanotube molecule.

The consideration of molecular interactions between the nanotube and the polymer are neglected in MOM, and the carbon nanotube's molecular mechanical properties are assumed to behave the same at the bulk, or macro-scale level. Micromechanical analysis methods and constitutive methods,[24-27] which equate the molecular potential energies in a molecular dynamics model to strain energies of bonded and non-bonded interactions from an equivalent-continuum model, both provide higher-fidelity estimates of CNRP because they include the molecular interactions neglected in MOM that alter the bulk behavior of the composite. Micromechanical and constitutive methods allow for appropriate consideration of the nano- and micro- scale material properties and material interactions critical to analyzing and predicting the behavior of CNRP composite material.

MITRE investigates CNRP with single walled carbon nanotubes oriented uni-directionally and bi-directionally (orthogonal) in high-density polyethylene, a thermoplastic at a range of nanotube volume fractions using the method of mixtures and molecular mechanics modeling. Bi-directional CNRP is analyzed as a laminate, where two uni-directional composite layers are orthogonally oriented. Using laminate theory, the mechanical properties of bi-directional CNRP composite are found. Details of these results are currently being validated, compared, and contrasted to experimental and theoretical findings in industry, academia, and government.

Experimental CNRP findings in the scientific community appear somewhat contradictory and exhibit slight improvement in the mechanical properties of current carbon fiber composites.[28-31] The problems root in the ability to uniformly disperse nanotubes throughout the matrix and in the purity of SWNT,[31] which tend to form in bundles making SWNT isolation a formidable challenge. As dispersion becomes more uniform and isolating SWNT from bundles does not affect their purity, experimental CNRP properties will reach closer to those predicted theoretically. In place of molecular dispersion, some investigators have been focusing on spinning the nanotube molecules into fibers, much as spiders spin silk, to weave fabrics used in composite laminate layers.[8,32,33] These issues are considered when analyzing internal theoretical findings and comparing them to experimental and theoretical findings in the literature.

Both experimental and theoretical findings for CNRP composite density depend on the volume fraction of nanotubes and the type of polymer used in the analysis. This research uses high-density polyethylene (HDPE) ($\rho = 955\ \text{kg/m}^3 = 59.6\ \text{lb/ft}^3$)[34] and a range of volume fractions of armchair (10,10) SWNT ($\rho = 1300\ \text{kg/m}^3 = 81\ \text{lb/ft}^3$)[35] in the CNRP composite mechanical analysis.

This research follows several phases. Phase I focuses on aircraft and airspace performance gains due to low density of the structural material presented. In this phase, current aircraft with aluminum structures are analyzed with CNRP structures and the resultant performance gains are applied to airport and airspace scenarios to project the potential impact of the material on the National Airspace System (NAS). Phase II considers the design capabilities lent to aircraft by the materials additional mechanical properties, especially Young's modulus and tensile strength. In this phase, an aircraft parametric study is performed, and the specific aircraft design benefits characteristic of this material are derived. Phase III considers the multifunctionality of CNRP composites. This paper describes the methods and tools used to complete Phase I.

WEIGHT ANALYSIS OF CNRP-STRUCTURED AIRCRAFT

Using CNRP in aircraft structures has several predictable impacts on aircraft design, the most obvious of which is significant airframe weight reduction stemming from CNRP's low density. To demonstrate this potential, four notional CNRP-structured present day commercial airframes are analyzed. The analysis includes aircraft from each wake vortex category:[36] the heavy Boeing 747-400, the large Airbus 320-200, the small Embraer 145, and an aircraft with unique wake turbulence characteristics, the Boeing 757-200. It is understood that constructing current aircraft with CNRP airframes is a highly unlikely future scenario; however, because future aircraft designs are still uncertain, looking at the impact CNRP has on today's aircraft provides insight into future aircraft performance and designs.

By replacing the volume of structural aluminum in each aircraft with an equivalent volume of CNRP, the empty weight for each notional airframe is found. In most cases, the structural aluminum is a weight percentage provided by the manufacturer. All other structural characteristics, including airfoil and fuselage geometry, remain as found in the original aircraft and as described by the manufacturer. For each aircraft, a common engine for that airframe is used. For example, in the Boeing 747-400, the analysis is performed with a Pratt & Whitney 4056 turbofan.

The CNRP mechanical property analysis includes a range of nanotube volume fractions in HDPE, up to the point of polymer saturation with SWNT. The airframe weight analysis reflects this consideration. Additionally, a range of up to four aircraft empty weights are considered. This provides a combination of airframe weight estimates per aircraft analyzed, with the conservative high empty weight low volume fraction option to the optimum low empty weight high volume fraction option.

Initial results show that some cases exhibit significant weight reductions in the airframe, and consequently fuel consumption experiences significant reduction. However, because in Phase I the airframe itself has not been altered, the fuel capacity remains as in the original aircraft. In light of this, the fuel consumption is analyzed as a part of the performance and economics benefits in the following section.

CNRP AIRCRAFT PERFORMANCE

Weight reduction directly affects aircraft performance, economics, and efficiency, even assuming no change in aircraft geometry. With changes in aircraft capability, more options exist for the aircraft at airports and in airspace, having indirect impacts on the capacity and throughput of the National Airspace System. These affects will become even more prominent and results more detailed with parametric aircraft sizing and performance studies in Phase II of this research.

The flight operating envelope both aluminum- and CNRP-structured are analyzed. The operating envelope provides several critical velocities over each aircraft's range of altitudes. The velocity profiles calculated include maximum and minimum, mach drag rise, stall, best range, best climb, and best angle of climb velocity. Using available information on aircraft-specific engines, the thrust available and thrust required are found. Estimates for required runway on takeoff and landing are also calculated. Aircraft performance analysis equations follow those in.[37-39] Performance data is then validated and reviewed for potential airport and airspace impacts.

Each aircraft is modeled in MITRE's flight simulator, enabling the flight test of aircraft not yet in existence. The simulator provides visual validation of broader operating envelopes enabled by nanomaterials. For Phase I, a CNRP-structured aircraft with no change fuselage or airfoil geometry, the flight simulation merely follows air carrier cruise charts for lower aircraft weight, commonly calculated by the aircraft's Flight Management System (FMS) to optimize the step cruise of the aircraft. The simulated CNRP-structured aircraft cruise profile is validated by integrating over air carrier cruise charts for the specified airframe weight. Further flight simulations performed in Phase II will illustrate the flight profiles of more probable aircraft designs with modified fuselage and airfoil geometry which best utilizes CNRP's mechanical properties. The resultant fuel savings and reduced fuel consumption potentially enables longer flights at the same fuel capacity and more cargo/passengers in place of the fuel load, among other benefits.

A lighter aircraft requires less lift to remain airborne and also produces less intense wake turbulence. Wake vortices, two counter-rotating tornado-like phenomena, occur as an inherent byproduct of lift.[40] Collaborations with NASA Langley Research Center led to the use of the AVOSS algorthim[41] and associated software for the prediction and analysis of wake vortex formation, transport, and decay in notional CNRP aircraft. Preliminary findings show reduction in wake vortex circulation and the potential safe reduction of in-trail aircraft spacing.[42] MITRE's portable aviation visualization environment illustrates the interpretation of AVOSS data (vortex decay and transport) for CNRP aircraft separations using 3-D visualization package customized for aviation systems applications.

AVOSS provides options for deducing aircraft separation matrices similar to that found in FAA O

7110.65 but which reflects safely reduced separations with CNRP aircraft. MITRE's Enhanced Airfield Capacity Model (EACM)[43] uses the reduced runway length requirement and separation matrix to evaluate potential capacity increases for airports currently burdened in today's system. Using a recently developed MITRE CAASD tool,[44] which lies midway between the detailed models like TAAM (Total Airport and Airspace Modeler) and the more abstract queueing models like DPAT (Detailed Policy Assessment Tool), further analysis of the benefits to airspace capacity are evaluated and quantified, taking into consideration aircraft performance and airport efficiency gains due to CNRP-structured aircraft.

If CNRP aircraft flew today, several impacts on the NAS would be feasible. Higher cruise altitudes mean that CNRP aircraft would provide more options for optimizing airspace. Airports would see the benefits of increased throughput, with aircraft turning off on earlier taxiways or land at smaller airports due to their reduced runway length requirements.

CONCLUDING REMARKS

MITRE continues to utilize internal modeling and simulation capabilities to identify, quantify, and analyze the impact of nanotechnology in aviation. Carbon nanotubes strength, toughness, and conductivity make them an excellent candidate as a reinforcing molecular fiber in a composite structure. With its potential high strength-to-weight ratio and multifunctionality, carbon nanotube reinforced polymer composites may provide a unique option to the aviation industry. At a very minimum, Phase I analysis shows lightweight CNRP affecting the design, flight performance, and efficiency of future aircraft. The parametric aircraft sizing study will include other CNRP mechanical properties in the analysis, potentially illustrating further benefits. These benefits necessarily reflect on the system in which the aircraft flies, increasing safety and capacity.

This work illustrates the potential impact of a revolutionary material made possible by aggressive nanotechnology research. It is highly unlikely that today's airframes will be built from CNRP with little to no change to their aerodynamics and structure. In the future, aircraft manufacturers armed with nanotechnology will learn from designs originating in airframes built for defense and intelligence purposes, which will utilize every advantage nanomaterials such as CNRP present, especially extraordinary strength and toughness as well as thermal and electrical conductivity. Nanomaterials and molecular electronics are the enabling technologies for morphing wings, infinitely redundant health monitoring systems, and perhaps structurally integrated avionics. This project stresses the importance of incorporating nanomaterials in the future vision of aviation technology, and exemplifies this importance with an exercise in how one advantage of nanomaterials might change today's aviation industry.

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