# Morphing skins

**C. Thill, J. Etches, I. Bond, K. Potter and P. Weaver**
Advanced Composites Centre for Innovation and Science (ACCIS)
Department of Aerospace Engineering, University of Bristol, UK

## ABSTRACT

A review of morphing concepts with a strong focus on morphing skins is presented. Morphing technology on aircraft has found increased interest over the last decade because it is likely to enhance performance and efficiency over a wider range of flight conditions. For example, a radical change in configuration, i.e. wing geometry in flight may improve overall flight performance when cruise and dash are important considerations. Although many morphing aircraft concepts have been elaborated only a few deal with the problems relating to a smooth and continuous cover that simultaneously deforms and carries loads. It is found that anisotropic and variable stiffness structures offer potential for shape change and small area increase on aircraft wings. Concepts herein focus on those structures where primary loads are transmitted in the spanwise direction and a morphing function is achieved via chordwise flexibility. To meet desirable shape changes, stiffnesses can either be tailored or actively controlled to guarantee flexibility in the chordwise (or spanwise) direction with tailored actuation forces. Hence, corrugated structures, segmented structures, reinforced elastomers or flexible matrix composite tubes embedded in a low modulus membrane are all possible structures for morphing skins. For large wing area changes a particularly attractive solution could adopt deployable structures as no internal stresses are generated when their surface area is increased.

## ABBREVIATIONS

| | |
|---|---|
| AAW | active aeroelastic wing |
| ABS | acrylonitrile butadiene styrene |
| AFRL | Air Force Research Laboratory |
| AFW | active flexible wing |
| Bi-STEM | bi-storable tubular extendible member |
| CFRP | carbon fibre reinforced plastic |
| CRG | Cornerstone Research Group |
| CTD | Composite Technology Development |
| CTM | collapsible tube mast |
| DARPA | Defense Advanced Research Projects Agency |
| DC | direct current |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt |
| EMC | elastic memory composite |
| EPNdB | effective perceived noise in decibels |
| FEA | finite element analysis |
| FMC | flexible matrix composite |
| LaRC | Langley Research Center |
| MAC | machine augmented composite |
| MACW | mission adaptive compliant wing |
| MAV | micro air vehicle |
| MAW | mission adaptive wing |
| MSMA | magnetic shape memory alloy |
| NASA | National Aeronautics and Space Administration |

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|---|---|
| NGC | Northrop Grumman Corporation |
| Nitinol | Nickel Titanium Naval Ordnance Laboratories |
| PAM | pneumatic artificial muscle |
| Prepreg | short form for ‘preimpregnated fibres’ |
| RF | radio frequency |
| SAMPSON | smart aircraft and marine project system demonstration |
| SMA | shape memory alloy |
| SMP | shape memory polymer |
| SPS | solar power satellite |
| TRIZ | theory of inventive problem solving |
| UAV | unmanned air vehicle |
| UCAV | unmanned combat air vehicle |
| USD | United States dollar |
| UV | ultraviolet |

## NOMENCLATURE

| | |
|---|---|
| $E_t$ | tensile elastic modulus |
| $T_g$ | glass transition temperature |
| $\varepsilon_{t,\max}$ | maximum tensile elastic strain |
| $\sigma_t^*$ | tensile strength |

## 1.0 INTRODUCTION AND DEFINITIONS

A major aim of any engineering discipline is to improve the efficiency of existing systems or to design new systems with greater efficiency than their predecessors. In aerospace engineering, this means optimising the aerodynamic, thermodynamic and structural layout of an air vehicle. One way of achieving this is by using the concept of morphing. Morphology, as a science, is defined in the *Oxford English Dictionary* as the study or classification of a shape, form, external structure or arrangement(1). In the field of engineering the word morphing is used when referring to continuous shape change i.e. no discrete parts are moved relative to each other but one entity deforms upon actuation. For example, on an aircraft wing this could mean that a hinged aileron and/or flap would be replaced by a structure that can transform its surface area and camber without opening gaps in and between itself and the main wing, or leading to sudden changes in cross-section which could result in significant aerodynamic losses, excessive noise and vibration in the airframe.(2)

A morphing skin can be envisaged as an aerodynamic fairing to cover an underlying morphing structure. A requirement for use in an aerospace application is that it must be able to change shape in at least one of two ways: change in surface area (e.g. flaps, slats on an aircraft wing) and changes in camber (e.g. aileron, flaps, slats, winglet on an aircraft wing or variable pitch propeller)(2). This shape change can be instigated either by external or integrated actuators which would make the skin self-actuating or active and potentially 'smart'. An active structure can be defined as possessing an ability to change shape whilst maintaining a continuous form, whereas a passive structure, such as a hinged aileron, has discrete components which move relative to each other. A smart structure is able to sense external stimuli (pressure, velocity, density or temperature change), process the information and respond in a controlled manner, in real-time. Overall, sensing, actuation and control are embedded in a single multifunctional ‘smart’ structure. Smart materials encompass a broad range of components that can respond mechanically (e.g. shorten, elongate, flex) to a variety of stimuli including electromagnetic fields, pressure, temperature and/or light.(3, 4) Note that it is often not obvious how to differentiate between the material and structural levels of any given system due to the hierarchical nature and multi-functionality of the components involved.

This work shows that the importance of a compliant and stiff morphing skin has been recognised but not many satisfactory solutions have yet been proposed. Hence, this paper reviews the concepts that offer potential solutions. First, it seeks to clarify the benefits for morphing and outline the problems involved. Then inspirational concepts found in nature, as well as a historical overview on previous morphing studies, establish a background for evaluating the current state-of-the-art in morphing technologies. This main section is divided into four parts. The first three show how large wing surface area changes, or wing shape changes and small wing area changes can be achieved. This division is necessary since the applications and requirements differ greatly. Besides, these three parts focus on those wing structures where primary loads are transmitted in the spanwise direction and a morphing function is achieved in the chordwise direction. The fourth part deals with integral morphing concepts that combine structure, actuation and skin.

## 2.0 ADVANTAGES FOR USING MORPHING WINGS

Sanders *et al*(5,6) state that the aerodynamic performance of an aircraft is optimised for a specific flight condition, e.g. cruise for long range commercial passenger aircrafts or high speed short range flight for fighter aircraft. This means that away from this design point in the aircraft’s flight envelope the aerodynamic performance will decrease. Hence, by being able to change the aircraft's configuration e.g. wing surface area, the optimal flight regime can be expanded which is shown theoretically to work by Joshi *et al*(7) and Bowman *et al*(8).

Most aircraft today, especially large passenger airliners, use hinged devices that augment lift during slow flight especially take-off and landing. These devices are called high-lift systems. Although the current high-lift systems perform well, there is always the desire to improve efficiency. A further reduction in drag and noise could be achieved by eliminating open gaps during deployment and operation. A further reduction in complexity could also decrease mass and cost.(9) Bauer *et al*(10) describe the process as: ‘the key objective in all design approaches to variable camber wing technology is to achieve a maximum aerodynamic advantage with minimum penalties due to additional weight, increased maintenance expense and reduced reliability’. Wlezien *et al*(11) state that half the mass and cost of a transport aircraft wing are due to the complexity of the high-lift system which could potentially be replaced by lighter and simpler morphing systems. Roth *et al*(12, 13) applied a genetic algorithm to analyse optimal wing geometry change in flight via morphing. They found that in their case the morphing wing aircraft had nearly 8% lower take-off gross weight compared to a fixed-geometry wing aircraft and had lower engine thrust requirements. Spillman(14) showed that the use of variable gapless wing camber can reduce drag, mass and costs for a transport aircraft. These cost reductions mainly arise from the reduction in fuel burn and hence reduction in direct operating costs. This is of immense economic interest to today’s aircraft operators who struggle to cope with the ever increasing fuel prices. Furthermore, as described by Bein *et al*(15), the strong growth of air travel puts a huge strain on the environment due to the emission of pollutant gases such as $CO_2$ and $NO_x$ by the aircraft engines. If the aircraft of tomorrow were to be made more efficient and environmentally friendly by implementing morphing technology, significant benefits could be realised.

Not only aerodynamic performance but also aeroelastic and control of a morphing aircraft can be improved as described by Kudva(16), Bartley-Cho *et al*(17) and Gern *et al*(18, 19). This results in an enlarged flight envelope and increased manoeuvrability which is of paramount importance for fighter aircraft. Spillman(14) even believes that variable camber could be used for direct lift control since by changing the camber of the wing at constant angle of attack and flight speed the spanwise lift distribution is altered. This would make pilot initiated response more rapid. Note that control of spanwise lift distribution also means control of wing bending and twisting moments.

Wlezien *et al*(11), Noor *et al*(3, 20), Bein *et al*(15), Kudva(16), and Bartley-Cho *et al*(17) give examples of smart controls used in conjunction with morphing technology. Hence no additional input from a pilot is required which reduces workload and allows fully automated and autonomous flight. Concepts that are mentioned include active aerodynamics (e.g. transonic shock control), active noise control, active aeroelastic control, airframe health monitoring and active shape control.

Rodriguez(21) gives a further reason to consider the adoption of morphing by citing the considerable economic benefits derived from operating a fleet of one type of morphing aircraft which can fulfil a variety of mission objectives compared to a fleet of different types of aircraft, each specialised for one type of mission. Although both fleets can achieve the same mission objectives, reduced maintenance and support requirements as well as operational flexibility will keep costs lower in a single type fleet.

To summarise, the University of Bristol morphing wing project(22) states that reasons for applying morphing technologies can be divided into four categories: "1. improve aircraft performance to expand its flight envelope; 2. replace conventional control surfaces for flight control to improve performance and stealth; 3. reduce drag to improve range and; 4. reduce vibration or control flutter" to improve comfort, safety and reduce fatigue.

## 3.0 BIOMIMETICS

Many engineering concepts have been copied from nature. Rao(23) gives examples of famous landmarks which have been designed on the basis of concepts found in nature; such examples include the Crystal Palace in London and the Eiffel Tower in Paris. Ball(24) shows how lessons can be learnt from nature by engineering. Most of the time nature does not employ exotic materials, nor extreme energies or high pressures but rather uses 'budget science' involving simple but clever ideas. Such an illustration is given by John *et al*(25), who states that nearly all load bearing structures in nature are fibrous which means that they are good in tension but poor in compression. There is a similar problem for man made composite materials. Nature has four solutions: pre-stress fibres, introduce high volumes of mineral phases (matrix), heavily cross-link the fibres to introduce lateral stability or change fibre orientation so that compressive loads do not act along fibres. Ball(24) also mentions the Russian engineer Genrich Altshuller who said "In nature there are lots of hidden patents" and it is just a question of finding and making use of them. This is one reason why Altshuller came up with his 'Theory of Inventive Problem Solving' (TRIZ, Russian acronym)(26,27).

The study of biological mechanisms and their application to science and engineering is called biomimetics or bionics. It is the act of imitating (mimicking) nature. According to Menon *et al*(28) biomimetics may be defined as the practice of reverse engineering ideas and concepts from nature and implementing them in a field of technology. Trask *et al*(29) do so by reviewing and classifying biomimetic approaches that could advance the field of self-healing polymer composites further.

Lakes(30) explains how the understanding of hierarchical structures can be used to improve mechanical properties such as strength and toughness of materials. Natural and synthetic hierarchical structures contain structural elements which themselves have a structure. An example of a natural hierarchical structure is mammalian bone which is made up of large hollow fibres composed of lamellae and pores. The lamellae are built of collagen fibres which are fibrous structural proteins. These contain collagen fibrils which consist of collagen molecules. Each level is responsible for a specific property, e.g. stiffness comes from collagen fibres. This shows that intentionally designing structures with different hierarchies results in materials with physical properties that are tailored for specific applications.

Famous aviation pioneers such as Otto Lilienthal observed the flight of birds and transferred their findings to the design of gliders. Blondeau and Pines(31,32) describe how birds, such as falcons, are able to loiter on-station in a high aspect-ratio wing configuration using air currents and thermals to circle at relatively high altitude until they detect prey. They are then able to morph their wings into a strike configuration to swoop down on an unsuspecting victim. Bechert *et al*(33) describe winglet designs for aircraft wings that are similar to wing tip feathers that help to reduce drag for slow predatory land birds with low aspect ratio wings. Although at present these aircraft winglet designs are rigid, birds are able to change the position of their feathers according to flight conditions. If this were possible for an aircraft wing significant benefits could arise, thus technologies for morphing winglets and wings are currently being pursued.(2,4)

Since this work is concerned with the development of a morphing aircraft skin it is worth first considering the skin of humans and animals. Generally, skin properties, such as thickness, strain and strength vary over the body of a living organism to cater for the necessary functions it needs to fulfil. These are protection, facilitating sensory reception, contribution to locomotion and osmoregulation of temperature. The skin consists of a multilayered epidermis and the dermis. The thickness of the dermis, which accounts for the skin's durable construction, is mainly determined by the content of collagen fibres(34).

When studying systems such as human skin or the membranes of insect wings it is interesting to note that under loading, work has to be done to strain the material. Contrary to what would be expected for minimal energy input, it is quite common for skin or membranes to wrinkle under load(35). Both of those characteristics indicate that nature does employ systems that rely on mechanical characteristics conventionally considered unsuitable or impractical for many engineering applications. However, Menon *et al*(28) believe that it is not the aim of designers to fully replicate biological ideas but rather to abstract the biological principles by which organisms function and survive. It should be borne in mind that for most biological systems simple and elegant solutions are employed in preference to complex and sophisticated systems. They also state that the most sophisticated engineering systems are often lacking in robustness and adaptability while simple natural organisms excel in terms of adaptability to their environment, actuation flexibility and sensory robustness. Biomimetics applied to engineering promises the prospect of greater miniaturisation, integration and packaging efficiency which biological systems generally exhibit. In terms of design philosophy, a functional unit should be treated in a concurrent and multidisciplinary way similar to the holistic design of natural systems.

There are many more examples of interesting concepts in nature that could be mimicked for morphing skin applications. Parallels to natural phenomena will be highlighted as engineering ideas are presented.

## 4.0 HISTORIC REVIEW OF MORPHING AIRCRAFT AND WING TECHNOLOGIES

Although morphing technologies are relatively new as research areas in aerospace, the design of changing wing planforms is as old as motorised flight itself. The pioneers of flight, Orville and Wilbur Wright, were the first to fly a powered heavier-than-air flying machine on 17 December 1903. This machine used flexible wings with pulleys and cables that twisted the wingtips. Back then such an approach was known as wing warping, but it is nowadays referred to wing morphing(4).

The first US patent for a variable camber wing was issued in 1916(36) and many more followed. Several designs were published and even test flights were made with variable camber wings, telescopic wings and variable incidence wings. However, no morphing ideas were taken to a production stage(37). One possible reason was that the implementation of relatively stiff metallic wing designs meant that higher loads resulting from increased flying speeds and aircraft masses could be endured(4). The post-WW2 pursuit of supersonic flight saw the recurrence of morphing wing ideas, for example, variation of wing sweep on ground by the German Messerschmidtt P-1101 and in flight by the Bell X-5 in 1951. This dynamic feature allows an aircraft to fly more efficiently at both sub- and supersonic speeds. Many swing wing concepts followed including the MiG-23 in 1967, Grumman F-14 Tomcat in 1970 and the Rockwell B-1B Lancer in 1983. One of the major problems tackled and overcome by designers was the change in position of the centre of gravity of an aircraft between one configuration and the other(37).

Other morphing concepts, such as change in dihedral, moving wing tips and nose drooping (Concorde) have been designed and implemented. Furthermore, engine morphing is commonplace in terms of altering engine outlet nozzle position and geometry to achieve thrust vectoring on the Harrier, Eurofighter and Joint Strike Fighter; or the rotation of the entire engine as in the V-22 Osprey. It is worth noting that a form of morphing in the form of wing area and camber change is present on most aircraft today in form of mechanically operated slats, flaps, spoilers and control surfaces(37).

While the previous concepts were based on entirely mechanical actuation, there has also been intermittent interest in inflatable wing designs in the 1930s and 1950s. One example is Goodyear Aerospace's GA-33 Inflatoplane prototype which was designed to be dropped by container behind enemy lines as a means of rescuing downed pilots. It could be inflated within five minutes. After testing and evaluation the projected terminated in 1973. Other inflatable unmanned air vehicles have been designed and built by ILC Dover(38), in particular, wing and fin components were fabricated using gas-retaining bladders(39, 40).

However, the morphing interests of today's researchers goes far beyond moving one solid wing element to a different angle or location with respect to another. The modern technology of morphing involves a seamless, aerodynamically efficient aircraft capable of radical shape change. Lightweight, actively controlled systems of sensors (nerves), actuators (muscles) and structures (skin, tendons and bones) that mimic the ability of natural organisms to adapt to widely changing environments and threats are being developed(41, 42).

In line with this ideology, several morphing research programmes have been conducted since 1979. The Mission Adaptive Wing (MAW) research programme had the aim of changing the wing cross-sectional shape in flight. It was managed by the US Air Force Research Laboratory at Wright-Patterson and the flight tests were performed by the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center. Six wing leading edge (three on each wing) and two trailing edge segments (one on each wing) employed flexible, smooth upper surfaces made out of flexible fibre-glass and actuated by hydraulic actuators which were used to vary the wing camber. These hingeless and gapless segments used overlapping and sliding panels on the lower aerofoil surface to allow chord changes with camber variations. This system was installed on an F-111 aircraft and made 59 flights from 1985 through to 1988 with satisfactory results. Unfortunately, increases in weight, complexity, volume and mechanical performance significantly offset the aerodynamic benefits and limited further development(37,42-46).

Two further programmes followed that did not have morphing as a specific objective, however, they showed that wing flexibility could provide weight savings and improved aerodynamic performance. The Active Flexible Wing (AFW) programme by NASA and Rockwell International used flexible wings and no horizontal tail on an aircraft model and demonstrated in two different wind-tunnel tests (first in 1986-1987; second in 1989-1991) the proof-of-concept and aeroelastic control via active digital control technology. Multiple hydraulically powered leading and trailing edge control surfaces were used in various combinations to achieve a variety of manoeuvres, demonstrating single/multi-mode flutter suppression, load alleviation and load control(47).

The Active Aeroelastic Wing (AAW) research programme led by US Air Force Research Laboratory (AFRL) Wright-Patterson Air Force Base, NASA Dryden Flight Research Center and Boeing Phantom Works started in the mid-1990s and used wing flexibility as a benefit to increase control power, reduce drag, manoeuvre loads and mass, and enlarge the design envelope. The flight test bed was a modified F/A-18 with new wing panels made of thinner composite skins with a honeycomb substructure(48,49).

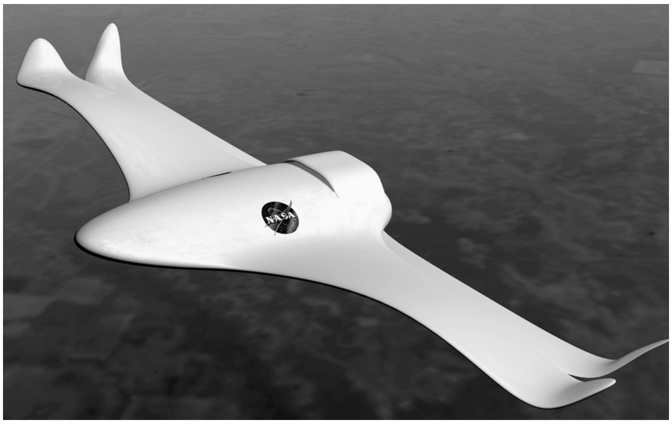

Figure 1. NASA's morphing aircraft(57).

In the late 1990s, a six year programme led by the NASA Langley Research Center (LaRC), entitled NASA's Morphing Project, started and was tasked with coordinating research efforts by governmental and academic institutions to foster the development of morphing technologies. It focused on adaptive structural morphing, micro-aero adaptive control and biologically-inspired flight systems. Some of the projects described in this review were a part of this effort.(11,50,51)

During the same period, the US Defense Advanced Research Projects Agency (DARPA)(52) together with AFRL, LaRC and Northrop Grumman Corporation (NGC) ran a two phase (January 1995-November 2001) Smart Wing programme. The overall objective was to develop novel, smart materials based control surfaces that would provide improved aerodynamic, aeroelastic, and other system level benefits to military aircraft. Gapless, hingeless leading and trailing edge control surfaces were tested on a 30% scale full span wind tunnel model of an unmanned combat air vehicle (UCAV)(16,17,53).

At the Deutsches Zentrum für Luft- und Raumfahrt (DLR; German Aerospace Centre)(54) researchers are investigating variable camber wings i.e. flexible trailing edges and local spoiler bumps. The latter is used to reduce shock effects and hence the wave drag increase over a wing for transonic and supersonic flight regimes(55).

In 2001, NASA released an artist's impression of how it envisages a morphing aircraft by 2030 (Fig. 1). The wings are able to sweep back and change shape for high speed drag reduction and low sonic boom. The engine inlets and nozzles are also capable of morphing. Small jets of air and feather-like control surfaces provide additional control forces for extreme manoeuvres and added safety.(4,56)

Since April 2002, DARPA's Morphing Aircraft Structures (MAS) programme has the stated aim to design, build and test air vehicles that radically change shape in flight. As part of this three phase programme, several innovative aircraft and material designs have appeared over the last few years. Cornerstone Research Group (CRG)(58) has developed a reinforced (nearly any fibre type can be used) shape memory polymer (see Section 6.3.1) wing skin that can soften and hence change shape within seconds of heating. FlexSys(59) has developed a smooth, hinge-free wing whose trailing and leading edges change camber on demand to adapt to different flight conditions (see Section 6.4.5).

Lockheed Martin Skunk Works(60) is focusing on a folding wing concept i.e. out-of-plane morphing, and wants to achieve x2·8 increase in wing surface area. It will be applied to a small UAV for US Air Force missions and is also known under the name of Z-wing morphing concept (Fig. 2). Bye and Clure(61) describe the research

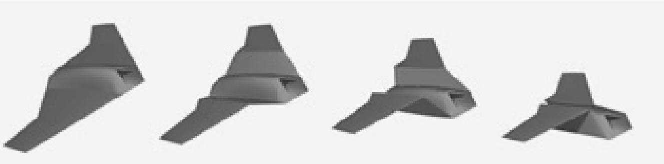

Figure 2. Lockheed Martin’s Z-wing morphing concept(36).

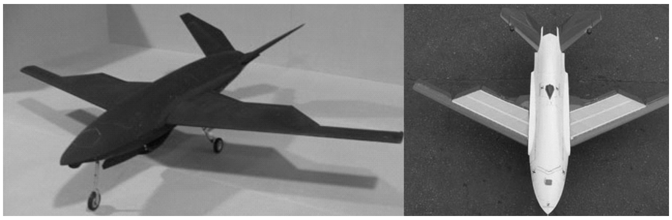

Figure 3. NextGen’s Batwing morphing concept(64).

that has been taking place on the Z-wing. Seamless skins are used in the folding regions. Initially shape memory polymers made by CRG were used however problems with the electrical resistive heating system lead to the selection of a fabric reinforced silicone based material. It was used as an elastomeric sock and a new infusion process was invented to manufacture this skin. A new electrical resistive heating system has apparently successfully been developed since but no details are given.

Love *et al*(62) explain how the thermopolymer smart actuator (TPA) for the leading edge of the Z-wing was selected however no details are given of how it works. Love *et al*(63) describe the wind tunnel tests on a half model of the Z-wing that uses the reinforced elastomer skins over the hinges with a vacuum assist stability system to prevent the skin from flapping. Wind tunnel tests showed that the main problem with the elastomeric skin is its non-linear behaviour due to creep when actuated. In the un-folded position the strain in the skin is due to the vacuum while in the folded position the strain in the material comes predominately from the tension due to hinge rotation.

Hypercomp and NextGen Aeronautics(64) derived a sliding wing concept, i.e. in-plane morphing, also called Batwing (Fig. 3); they use a Firebee drone as their design platform. NextGen tested a 45kg remote controlled model in August 2006 (outside the MAS programme) that can change sweep from 15° to 35° and wing area by 40% in five to ten seconds. It has a silicone elastomeric skin with an underlying ribbon structure to improve out-of-plane stiffness that can stretch up to 100% and a light-weight, kinematic, moving wing substructure which is actuated by single electric motor and remotely controlled. This structure can withstand air loads of around 19,150Pa(8,64-66).

Raytheon has looked at telescopic wings to be used on a US Navy Tomahawk cruise missile fuselage, but this design was dropped at the start of Phase II. In the final phase of the study (ending April 2007) NextGen and Lockheed Martin were to air test their respective models (in January 2007 and February 2007 respectively).(67)

Engine component morphing using smart materials such as shape memory alloys is also a current research topic of great interest. In the late 1990s, the Smart Aircraft and Marine Project System Demonstration programme, funded by DARPA, was investigating the possibility of changing engine aircraft inlet through capture area and internal duct shape variations. Two separate wind tunnel tests were carried out on a full-scale F-15 fighter engine inlet that validated control and structural changes of tactical aircraft inlet geometry and their respective internal flows. Shape memory alloys (see Section 6.3.1) were used as part of the novel actuation(68).

Currently, engine manufacturers are looking at using shape memory alloys to reduce engine noise. Serrations around the edge of the outlet nozzle at the rear of the engine reduce noise during take off by as much as 2-3EPNdB (effective perceived noise in decibels). However, it is undesirable to have them deployed during the entire flight because they disturb the airflow, creating drag and leading to a thrust loss of 0·25%. Thus, making these serrations out of a material that can change configuration would be beneficial. A mechanical mechanism cannot be used as it would be heavy and expensive, however, shape memory alloys (see Section 6.3.1) appear ideal(69, 70). Turner *et al*(69, 71) fabricated active shape memory alloy hybrid composites to replace the static chevrons on a jet engine outlet nozzle. Although performance was somewhat less than required, the concept was proven to be feasible.

A recent paper by Rodriguez(21) reviews current morphing projects including many projects carried out in academic institutions. The morphing aircraft project research group at the University of Bristol (UK)(22) is currently working on adaptive winglets, aeroelastic tailoring, multi-stable structures and truss-type structures. The goal of the Cornell University (NY, USA)(72) morphing team is to create an aircraft capable of macro-scale structural shape changes in order to meet multiple performance requirements or to enhance existing flight characteristics. To this end they are developing unmanned air vehicles (UAVs) capable of long loiter flight that may morph their geometries to high speed/high manoeuvrability configurations when attack or evasion manoeuvres are desired. At the Virginia Polytechnic Institute and State University (VA, USA)(73) an aircraft model, called Morpheus, has been designed and tested in a wind tunnel with the following objectives;

- to model quasi-steady aerodynamic behaviour of an aircraft with large planform changes and transient aerodynamic behaviour of high-rate planform changes,
- to optimise studies in achieving efficient flight configurations, and
- to evaluate how planform manoeuvring affects the flight control and to simulate gimballed flight controls of a morphing aircraft.

Research at the University of Florida (FL, USA)(74) is being conducted into using small and micro air vehicles (MAVs). The aim of the research group is to investigate issues related to control of a morphing system. Specifically, the studies of dynamic effects related to morphing i.e. modelling the time-varying dynamics during morphing, designing non-linear controllers to utilise morphing and constructing experimental test beds to demonstrate morphing.

## 5.0 SYNOPSIS OF CURRENT AIRCRAFT SKIN MATERIALS, HIGH-LIFT SYSTEMS AND ACTUATORS

### 5.1 Aircraft wing skin materials

Historically, the wing skin on early aircraft was fabric but with increasing flight speeds and hence aerodynamic loads, stiffer and more robust materials were needed. The majority of aircraft today use stiffened metallic (typically aluminium alloy) panels as an outer skin, although high specific strength and stiffness fibre reinforced polymer composites in the form of glass or carbon fibre/epoxies are increasingly being employed. The stiffeners are usually Z or T-shaped. The panels are supported by ribs in the chordwise direction and by spars in the spanwise direction. Propellers or rotor blades often include a sandwich structure with a honeycomb core and metallic or composite faces. While most of the axial and bending loads are counteracted by the stringers, ribs and spars, the skin needs to withstand a combination of tensile, compression and shear forces (semi-monocoque structures i.e. stressed skin concept) and needs to be able to distribute the diffuse aerodynamic pressure loads to the underlying structure. This highlights the difficulties inherent in replacing the current stiff and strong solutions with a more flexible approach(75,76).

### 5.2 High-lift systems and actuators

Rudolph(9) gives a good review of conventional high-lift systems and actuators on current commercial subsonic airliners. These systems can be divided into two categories: leading and trailing edge devices. Krueger flaps and slats are included in the first category while the second includes simple flaps, slotted flaps and Fowler flaps. All of those moving elements are supported by hinges, linkages and tracks. Broadly speaking there are two ways of actuating high-lift systems. Each support or panel (leading or trailing edge device) is actuated either individually by one or more linear hydraulic actuators or the high-lift systems are geared together and powered by a centrally located power drive unit. These systems use screw jacks, rotary hinges, rotary actuators, or rack and pinion drives for the mechanisms. It is considered to be the safest approach to guard against asymmetric and passive failures.

The complexity of these systems peaked in the early 1970s with the introduction of triple slotted, trailing-edge flaps on the Boeing 727, 737 and 747. After that, simpler systems were the preferred solution. They have a reduced mass, increase the lift over drag ratio due to a minimised drag when the devices are deployed, reduce noise and complexity which decreases manufacturing, spare parts and maintenance costs.(9)

In the last few years there has been an increasing interest and movement towards a more electric and ultimately an all electric aircraft. According to Cloyd(77) current hybrid mechanical, hydraulic, pneumatic, electrical and sometimes ‘fueldraulic’ aircraft non-propulsive power systems, that provide motive force for all onboard functions, are still a major factor in aircraft maintenance down-times and failures. He states that a more electric aircraft may dramatically reduce or eliminate (in the case of all electric) the need for centralised aircraft hydraulic power systems to be replaced by an electrically-based power system with greatly improved reliability, maintainability, and supportability as well as the potential for significant performance improvements in terms of weight, volume and system complexity.

Finally, current high-lift systems are passive devices whereas morphing technology could potentially make structures smart and adaptive and lead to reduced weight, volume, costs, noise and drag.

## 6.0 REVIEW OF MORPHING SKIN TECHNOLOGIES AND CONCEPTS

This section considers the materials, structures and concepts that are or could potentially be used for morphing aircraft skins. It describes materials/structures that allow large increases in surface area, materials/structures that have the ability to change shape with/without change in area and finally it mentions concepts that cover integration of sub-structure, skin and actuation.

### 6.1 Change in surface area

#### *6.1.1 Stretchable structures*

#### *6.1.1.1 Elastomers*

Although there are many morphing programmes underway, not many consider the need for a flexible but at the same time a load-bearing skin. Many papers(16,78,79) mention elastomers as being a promising solution for morphing skins. As an example, in the DARPA Smart Wing programme, a high strain-to-failure silicone skin was used(16). Elastomers (or rubbers) are a class of polymer with a low density of cross-links(80). Hence they have the ability to undergo large elastic deformations without permanent changes in shape. However, the few cross-links give them a memory effect so that they return to their original shape on unloading(79).

The low tensile modulus of elastomers (~0·5 to 50MPa) makes them easily deformable up to 1,000% (elongation at break) of their original length. At the same time the load required is relatively low; tensile strength can have values up to around 50MPa(80). Since the stress-strain curve of elastomers is non-linear its modulus of elasticity varies with strain, and strain rate and temperature. Below the glass transition temperature ($T_g$) polymers behave like glass and are brittle, above $T_g$ they are in a rubbery state. Hence the $T_g$ for useful elastomers to be used as stretchable morphing skins must be well below their operation temperature range. A further property exhibited in general by polymers is viscoelasticity which means that when subjected to a load the strain does not occur instantly i.e. the strain is time dependent.(80)

While these properties potentially make good flexible skins they are unsuitable for carrying loads which means that it would be difficult to design elastomeric skins that can sustain and transfer aerodynamic loads to the underlying structure(79). At the same time, working against the strain of the material should be avoided as much as possible since it is likely that it will induce fatigue problems as well as requiring excessive actuation power to hold the deformed skin in place.

Kikuta(81) is one of the few investigators that experimentally tested a few thermoplastic polyurethanes, co-polyesters and woven materials that are commercially available to investigate the materials' viability as morphing skins. He first explicitly outlines the requirements for a morphing skin of an aircraft wing:

- elastic/flexible in chordwise direction to allow low force actuation,
- stiff in spanwise direction to withstand aerodynamic and inertial loads,
- toughness,
- abrasion and chemical resistant,
- resistant to different weather conditions,
- high strain capability,
- high strain recovery rate,
- environmental longevity and fatigue resistance.

Then uniaxial tensile, biaxial tensile and pressure deflection tests were made and the results for the different materials were compared. According to the author’s results none of the selected materials satisfy all of the previously mentioned requirements. A material that was able to strain and recover well was not able to carry a high load and vice versa. The best polymer tested was found to be Tecoflex® 80A (thermoplastic polyurethane). A suggestion was made to combine a woven material like Spandura® (woven material) with a polyurethane like Tecoflex® 80A, that way the high strength required would be achieved by the fibres and the elasticity by the polymer.

#### *6.1.1.2 Auxetic materials*

A material that offers some potential for morphing use is a negative Poisson's ratio or auxetic material. These auxetic materials behave in a counter-intuitive manner since they become narrower when compressed and wider when elongated, due to their negative Poisson’s ratio. They can be foams, ceramics, composites or polymers and their unique property is achieved by a mechanism on the micro-scale. Auxetic materials consist of many hinge-like cells joined together. These cells have re-entrant geometry, so under extensive load the sides expand outwards producing an overall negative Poisson’s ratio effect (Fig. 4)(82,83).

Auxetic effects occur naturally in cow teat skin and cat skin. The auxetic behaviour was first reported in 1944 and applications of the auxetic effect in graphite cores in nuclear reactors has been studied since the 1950s(83). Grima *et al*(84) explain that auxetic foams can be produced from commercially available conventional foams by a

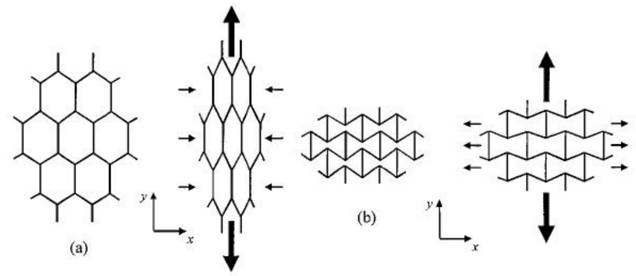

Figure 4. (a) Positive Poisson's ratio honeycomb and (b) auxetic honeycomb [83].

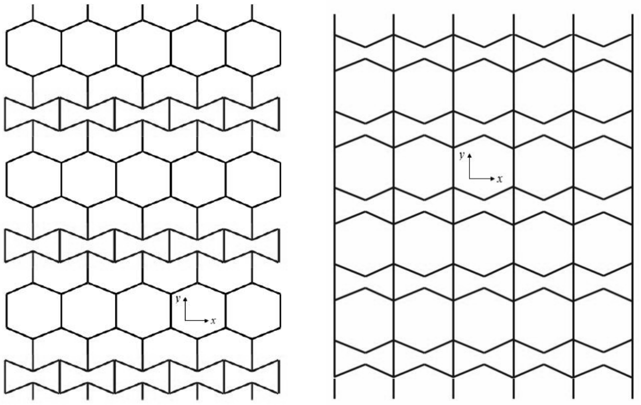

Figure 5. Hybrid (left) and accordion (right) cellular structures[88].

process involving volumetric compression, heating beyond the polymer's softening temperature and then cooling whilst remaining under compression.

Other interesting properties of auxetic materials are a high energy absorption, fracture toughness and resistance to indentation[82,85]. Exploiting such properties in auxetic reinforcements and/or matrices can lead to composite materials with minimal fibre pull-out failure i.e. failure of the matrix/fibre interface. Alderson *et al*[85] manufactured and tested two different forms of auxetic composite. Firstly, they used commercially available IM7/5882 unidirectional carbon epoxy preimpregnated fibres (prepreg) and due to the stacking sequence achieved an overall negative Poisson effect. Secondly, they used auxetic polypropylene fibres in an epoxy (Araldite®) non-auxetic matrix. Improved static indentation, low velocity impact damage and fibre pull-out resistance were shown during the experiments.

Research on a morphing aerofoil concept using a hexagonal chiral honeycomb structure (a cellular network featuring a negative Poisson effect) was conducted by Bornengo *et al*[86]. Finite element analysis (FEA) of a chiral honeycomb made from acrylonitrile butadiene styrene (ABS) plastic and used as concept for a F1 car wing box predicted a trailing edge deflection of 5mm due to the pressure distribution of the air flow. Wei and Edwards[87] looked at ways of making composite materials with auxetic inclusions in order to improve the low modulus of elasticity in auxetic materials.

Olympio and Gandhi[88] suggest using zero-Poisson's ratio cellular structures as morphing skins. They present an analytical model and a FE model that shows that by using hybrid (negative and positive Poisson's ratio materials) and accordion cellular honeycomb cores (Fig. 5) the Poisson's ratio is zero and hence would be ideal for morphing. Additionally these honeycombs give low in-plane and high out-of-plane stiffness.

Auxetic polymer foams appear to offer some potential for use as a 'gap filling' material in a morphing application. Due to their low modulus they can be easily deformed whilst simultaneously expanding when elongated. An example would be to use such materials between a hinged aileron and the main wing of an aircraft to maintain a smooth aerodynamic profile and minimise drag.

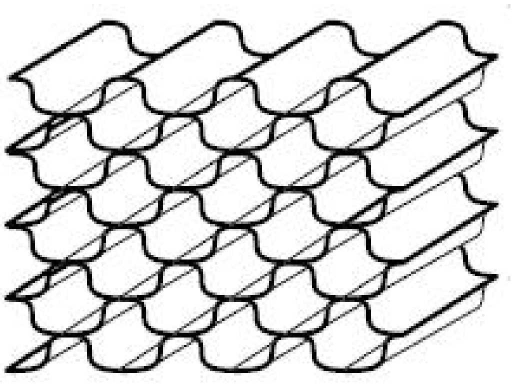

Figure 6. Schematic of Flex-Core® by Hexcel[89].

Although not auxetic, there are cellular structures that can be formed into small radii curvatures without deformation of the cell walls, loss of mechanical properties or experiencing anticlastic behaviour. Hexcel[89] produces metallic and non-metallic cores, called Flex-Core®, (Fig. 6) as an alternative to the standard hexagonal cell honeycomb to be used for radomes, ducts, leading edges of wings and stabilisers. This kind of cellular material as support structure covered with a thin skin could present a potential morphing skin solution.

### *6.1.2 Deployable structures*

Deployable structures allow big surface area changes which are desirable during change from high to low speed flight configuration e.g. trailing edge flap deployment during landing. There are five different classes of deployable structures: rollable, collapsible, foldable, inflatable and overlapping/stacked/nested structures.

### *6.1.2.1 Rollable and collapsible structures*

Many rollable structures mimic nature such as the coiling/uncoiling proboscis e.g. the tubular feeding and sucking organ of a butterfly (Fig. 7)[90]. Typical everyday examples are roller blinds or garage doors. Such ideas find many applications in space vehicles. Seboldt *et al*[91] describe the European sail tower solar power satellite (SPS) concept. This structure is designed to collect solar energy in space, transform it into microwave energy, send it to earth where it is collected by rectennas (antennas + electric rectifiers; a special type of antenna that is used to directly convert microwave energy into DC electricity) and fed to the power distribution grid. In order to transport the entire module into space it needs to be packed in a small volume and then deployed. To meet this requirement, large ultra-lightweight structures called Gossamer space structures are needed. The sail tower SPS consists of four deployable carbon fibre reinforced plastic (CFRP) booms and four triangular solar sails. The booms combine high specific strength and stiffness and can be packaged in a very small volume. They consist of two laminated sheets which are bonded at the edges to form a tubular shape. These can be pressed flat around a central hub for storage and uncoil from central hub during deployment. This design was developed by DLR and Invent GmbH[92] and a successful ground deployment of a model under simulated zero-g (no gravity) conditions was carried out at DLR in Cologne, Germany in December 1999. Numerical and experimental results from the analysis of those booms are given by Sickinger[93].

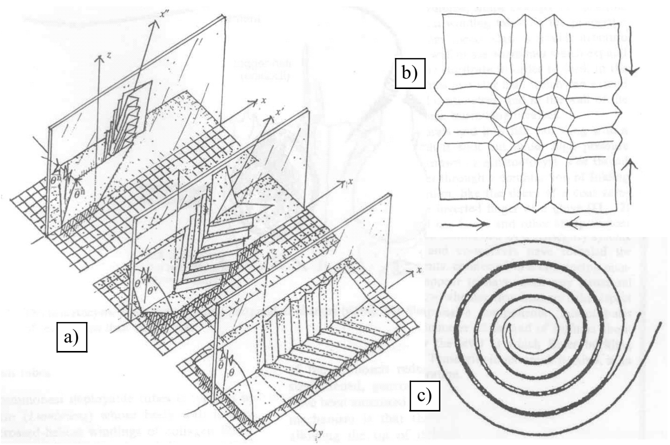

Figure 7. (a) Geometry of expanding leaf, (b) expanding poppy petal, (c) proboscis of butterfly(90).

Unckenbold *et al*(94) reviews the current state of the art in deployable (rollable and collapsible) structures for space applications. Apart from the sail tower SPS concept, two other deployable mechanisms are described. Firstly, the Bi-STEM (bi-storable tubular extendible member) used in the Hubble telescope which is made from stainless steel or beryllium copper(95) and was developed by Astro Aerospace(96), an affiliate of Northrop Grumman Space Technology. Secondly, the collapsible tube mast (CTM) developed by Sener in Spain(97) which can be made from metal or CRFP. Both of them have sheets of material that are curled into tubular cross-sections when deployed (two sheets for the BI-STEM for additional strength) but can be flattened and stored on a roller (two rollers for the BI-STEM). A further Gossamer structure is the AstroMast, again developed by Astro Aerospace, which has been used in many space missions. It comes in different designs depending on the specific application. The self-deployable AstroMast can be stowed within 2% of its deployed length and deploys using its own stored strain energy, similar to a recovering compressed spring. Unckenbold(94) compares the properties of the sail tower SPS concept, CTM and AstroMast. He concludes that existing boom deployment concepts can only deploy one boom at a time which restricts them in their abilities to withstand axial loads during the initial deployment sequence and to further tension a flexible membrane during a mission. In contrast the sail tower SPS concept deployment module can uncoil four booms simultaneously which gives it a higher bending stiffness.

Although these structures are very useful in space applications, there are limits to what they can deliver in a high load environment such as an aircraft wing. The absence of gravitational loading means low structural loads which makes it easy to design lightweight unsupported booms that deploy over several metres.

### *6.1.2.2 Foldable structures*

Vincent(90) and De Focatiis and Guest(98) give many examples of folding structures in nature e.g. folding of poppy petals, tree leaves and insect wings (Fig. 7). Practical applications in aerospace are easy to find: packaging of parachute and deploying of solar sails(91). However, to implement such ideas in a wing as a means of increasing surface area seems somewhat more complicated since no smooth surface is guaranteed during deployment. Nevertheless, there are and have been designs of aircraft wings with a folding skin made of fabric, elastomers elastomeric polymers or shape memory polymers (see Section 6.3.1)(31,37,99).

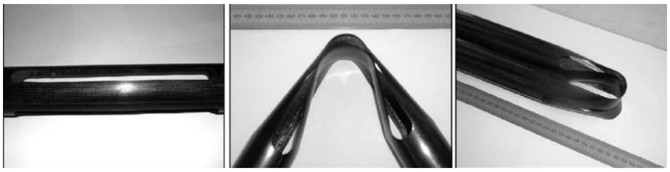

Figure 8. Deployable CFRP boom hinge (unfolded (left), folded 110° (middle) and folded 180° (right)(102).

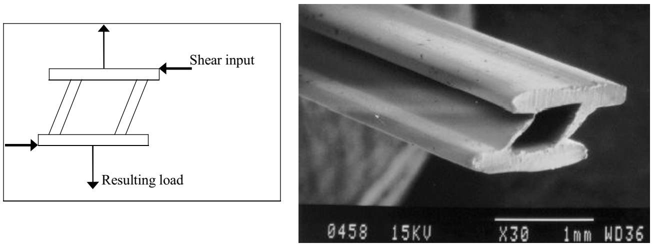

Figure 9. Schematic of a stress conversion machine (left) and scanning electron micrograph of an extruded stress conversion machine (right)(103).

The manufacturing process of honeycomb consists of placing strips of adhesive on thin sheets of material (e.g. aluminium) in a staggered pattern. Then the sheets with the adhesive are stacked together and cured. Once cured, the blocks are cut to the desired thickness, and pulled apart or expanded to form honeycomb(100,101). Before this final process the blocks of material allow large elastic deformations at low Poisson's ratios before the thin sheets are permanently deformed to shape honeycomb. This essentially is a foldable structure that allows changes in surface area.

Yee & Pellegrino(102) manufactured and tested self-deployable CFRP booms by cutting three slots in thin walled tubes. This allows bending (folding) the booms while forming an elastic hinge that will deploy the booms under its own energy (Fig. 8). Experimental tests showed that the maximum strains for bending tests on the booms made from woven carbon/epoxy prepreg were 2·8% for one ply and 1·9-2·2% for two ply specimen in the direction of the fibres.

Hawkins *et al*(103) present the concept of machine-augmented composites (MACs). The fibres in a composite are replaced by small machines, called stress conversion machines, that are simple structures that transform the input forces by virtue of their geometry (Fig. 9). They are four bar linkage type stress-conversion machines that convert shear forces into tensile/compressive forces and vice versa. This means that when a shear force is applied to the machine the inclined walls change their angle causing tensile/compressive forces on any neighbouring material. It also works the other way such that when the machine is compressed between its top and bottom surface it creates a shear force. Hence this can be classed as an additional function given to a composite. MAC machines can be extruded in a continuous manner of about 150m long and 1mm wide. Combined with the fact that they can be made out of nylon, results in very low manufacturing costs, i.e. 'pennies per foot' according to Hawkins *et al*. Some of those MACs were manufactured by laying extruded machines side by side and adhesively bonding them to a polyester fibre cloth which represented one ply of machines. These can then be stacked to form a laminate. The wall angle was 60° and different cross-section lengths of 1mm, 1cm and 1·5cm for the machines were used. The experimental results showed that shear-to-compressive displacement is approximately one to one and that compression-to-shear conversion is purely a function of the geometry of the machines and not of the machine/matrix volume ratio or the size of the machine. This idea could potentially be used to achieve area changes (not increases) for morphing wings or thickness changes for morphing aerofoils by using the MACs as spars.

#### 6.1.2.3 *Inflatable structures*

Cadogan *et al*(39,40) state that the maturation of materials used in inflatable structures such as space suits and Mars landing craft impact attenuation airbags has led to an improved understanding of high strength fibres and laminates that can be used in high performance inflatable wings. Fabrics with high strength to weight ratios and durability such as woven Kevlar®, VectranTM (high strength liquid crystal polymer) and PBO (poly-p-phenylenebenzobisoxazole, rigid-rod isotropic crystal polymer) have enabled the design of inflatable wings that possess a high packing efficiency. Small UAVs which can be packed into a tight volume to facilitate human transport and easy logistics are of particular interest for military applications. These kinds of vehicles could be gun launched from a safe distance, would inflate their wings in mid air and drop their payload at the destination or survey the target region. It is even conceptually possible to construct a system with retractable inflatable wings i.e. vehicles that can increase/decrease the inflated section of their wings. Generally, the irregular surface of inflated wings is a problem because a smooth continuous shape is important for good aerodynamic performance and hence low fuel consumption. However, for low Reynolds numbers (<500,000) it was found during testing that no extra skin was needed to improve the surface texture of an inflatable wing as the bumpy surface geometry had a positive effect on the aerodynamics.

Cadogan *et al*(40) present various concepts to actuate an inflatable wing. For example, a piezoelectric actuator attached under the inflated wing skin can move the trailing edge to give satisfactory aerodynamic performance. In Cadogan *et al*(39), the concept of rigidising is introduced since un-reinforced inflated wings often lack the necessary stiffness and are vulnerable to puncture and leakage. Rigidisation converts the initially inflated flexible structure into a rigid composite. The wing is made from a reinforcement fabric which is impregnated with an uncured polymer that chemically cures when exposed to ultra-violet (UV) light to form a composite structure.

Unckenbold *et al*(94) also review several inflatable structures developed by European company Contraves and by US companies LaGarde and ILC Dover for space applications. For mission durations of several years the inflatable structures will need to be rigidised in space for similar reasons as outlined by Cadogan *et al*(39).

Mollerick(104) gives a general review of inflatable structures for space applications. They offer the potential to reduce spacecraft/instrument mass, cost, volume, complexity and increase deployment reliability. These improvements combined with current budget limitations for space missions means that inflatable structures are an enabling or enhancing technology for numerous 21st century space missions. One of the possible techniques for the inflation process uses a pressure source, e.g. nitrogen, reinforced Kapton (polyimide film) and aluminium foil which serve as the inflatable tubes, and valving for sequencing the controlled pressurising process. Mollerick makes an important remark concerning past space applications which had simple shapes, no tight requirements on surface shape and size, were not used in functional elements, did not require the structural, thermal or other subsystem performance, and deployment dynamics and shape control was not a concern. Although discussing space applications this is even more relevant to aircraft applications where loads are higher and aerodynamic shape control is vital.

#### 6.1.2.4 *Overlapping/stacked/nested structures*

Good examples are the telescopic booms designed by Blondeau and Pines(31,32) to test a pneumatic actuated morphing wing in a wind tunnel or the early telescopic wing designs described by Jha and Kudva(37). These telescopic wings consisted of several chord-wise overlapping wing sections that extend from each side of the wing tips. However, the nested booms used by Blondeau and Pines only give large changes in length. They do not give a surface area increase thus a morphing skin is still required. Again, various space applications such as telescopes (e.g. Hubble) can be readily found and research to develop lightweight space telescopes is under way(105). Terry Weisshaar, manager of DARPA's MAS programme, reveals in an interview by Marks(106) that Raytheon(107) is currently looking at telescopic wings and Weiss(4) states that telescopic wings may be in the skies by 2020-2030.

## 6.2 Change in shape due to stiffness tailoring

This concludes the review of deployable structures that are most practical when used to achieve large increases in surface area. The other change necessary for morphing wings is the modification of shape. For an aerofoil section this typically is the change in camber. There are principally two ways of achieving this. The first one is by specifically designing the material so that the material strength and stiffness properties are optimised in different directions.

Ursache *et al*(108) present the optimisation and numerical analysis of structures (rods) that operate in the post-buckling regime used for altering the geometric shape of an aerofoil. The advantage is that modest applied force changes can result in large deformations. While this paper focuses on the optimisation of the morphing structural aspect, Pastor *et al*(45) and Reich *et al*(109) employ topology optimisation to determine the distribution of material properties needed for a morphing skin that can endure an in-plane transformation while minimising out-of-plane displacement. Although Pastor *et al* use the Veriflex SMP as an example for a skin material, the analysis remains very general. The following examples are more specific in terms of materials and applications.

### 6.2.1 *Extreme anisotropic material*

In order to change the form of a structure with minimal actuation force it needs to be relatively soft in the direction the structure will be deformed in. This is where stiffness tailoring comes in useful i.e. designing the structure in such a way that low stiffness is present in the planes where deformation occurs and high stiffness is present in the planes where loads need to be reacted against. A morphing aerofoil that is supposed to change camber needs to be stiff in the spanwise direction to counteract aerodynamic and inertial loads and be flexible in the chordwise direction. Materials that exhibit such a radical variation in stiffness for two orthogonally opposed directions are called (extreme) orthotropic structures(78,110). Orthotropy is as many other concepts not a man-made idea. Veronda *et al*(111) state for example that cat skin is orthotropic since its planar properties differ from its thickness properties.

Potter and Wisnom's(110) aim was to design and manufacture composite components with minimal torsional rigidity but with high bending stiffness for which a potential application would be a bearingless rotor hub for a heavy helicopter. They present an alternative to designing components with complex cross-sectional geometries that increase torsional rigidity but are difficult to manufacture. These extreme anisotropic specimens were made from a low modulus matrix reinforced with pre-cured fibrous composites in a conventional epoxy matrix. The specimens were tested in torsion, bending and compression. Results showed that for a polyurethane matrix a torsional-flexural-tensile modulus ratio of 1:239:923 can be achieved.

Peel *et al*(112) described the manufacturing process of composite prepreg plies using an elastomer matrix such as urethane or silicone with glass or cotton fibres. The fibres were wound onto a rectangular aluminium mandrel with a release agent using a filament winder. Then the elastomer resin was applied and a peel ply was wrapped around to protect the second layer sticking to the first. A primer was used in certain cases to improve bonding between fibres and resin. This procedure was repeated 4-5 times. A bleeder cloth and a vacuum bag was wrapped around and the entire mandrel was put in the autoclave.

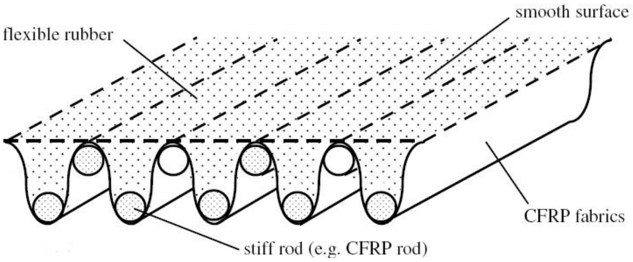

Figure 10. Reinforced corrugated structure with elastomeric surface(78).

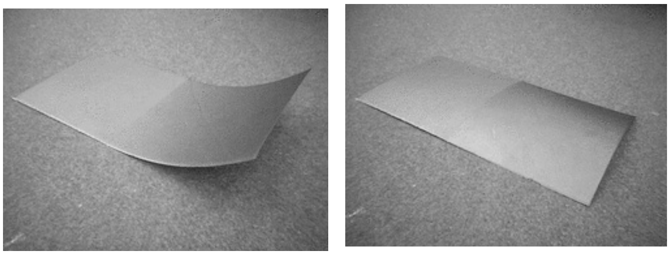

Figure 11. A four ply bi-stable composite plate(22).

After curing the prepregs could be cut of the mandrel and used as plies for laminates using liquid elastomer as adhesive between them. Some experimental test results were presented: the maximum tensile stress was 6MPa at 75% strain for the urethane/glass 45° prepreg and 2MPa at 100% strain for the silicone/cotton 60° prepreg. This could be a way of manufacturing reinforced elastomeric laminates that have orthotropic properties. Similarly Murray *et al*(113) present results from simple analytical and experimental analysis on reinforced elastomeric skin called flexible matrix composite membrane. They suggest using this composite as skins for one-dimensional wing morphing i.e. chord/camber or span morphing.

Yokozeki *et al*(78) demonstrated the use of corrugated composite sheets as a candidate material for flexible wing skins (Fig. 10). The corrugated samples are tested in four different tests to assess their mechanical properties. These tests are longitudinal and transverse (relative to the corrugation direction) tensile and bending tests. A simple analytical model, based on a sinusoidal cross-section of the corrugation, is used to calculate the longitudinal and transverse Young's modulus as well as the longitudinal and transverse flexural modulus of the corrugated structure. Experimental and analytical results confirmed the orthotropic behaviour of corrugated structures. Further improvements to the stiffness in the longitudinal direction and the creation of a smooth aerodynamic surface were attempted by modifications. Yokozeki *et al* installed stiff rods (e.g. CFRP rod) and one-sided filling (e.g. flexible rubber). It was found that flexible rubber decreased the specific stiffness and it was suggested to use thin film instead of rubber. Furthermore stiff rods are an effective method of increasing stiffness in the longitudinal direction without a loss of flexibility in the transverse direction.

Although Yokozeki *et al* tried to come up with a smooth aerodynamic surface, as mentioned earlier a non-smooth surface at low Reynolds numbers can be beneficial. Tamai *et al*(114) carried out experimental tests on a smooth aerofoil, flat plate and corrugated plate (dragonfly profile) at low Reynolds number (34,000 i.e. MAV operating regime). It was found that the corrugated plate delayed flow separation up to an angle-of-attack of 12·5°, however when flow separated the separation wake was higher than for a smooth aerofoil and flat plate at the same angle-of-attack.

Butler(115) picks up Yokozeki *et al*'s idea by manufacturing and testing corrugated composite laminate specimen made from Kevlar/914 prepreg. Analytical and FE analysis complemented the experimental analysis. A longitudinal-to-transverse elastic modulus ratio of over 8,000 was observed and it was even further increased by inserting carbon fibre rods along the corrugation direction. A morphing trailing edge demonstrator was built from a Kevlar/914 corrugated laminate that could be actuated manually. Inviscid aerodynamic analysis using XFOIL was carried out and showed that a higher lift coefficient could be achieved with a morphing trailing edge than a hinged flap.

### 6.2.2 Multi-stable composites

Multi-stable structures have similarities with the mechanism used to fold and unfold insect wings which uses elastic spring elements and bi-stable states(35), e.g. the rapid movement (about 100ms; considered to be one of the fastest movements in the plant kingdom) of the Venus flytrap due to an elastic leaf (bi-stable state).(116)

The multi-stability of composites, a property usually considered unfavourable, could potentially be used for morphing skin applications (Fig. 11). Multi-stability of thin laminates is due to residual stresses forming during the cure cycle of a non-symmetric lay-up or due to Gaussian curvature effects. Generally bi-stable composites exhibit large deformations but only require low actuation forces. This makes them in the current form difficult to use as morphing skins since aerodynamic loads may be greater than the forces needed to snap the laminates from one stable configuration to the other. However there are still a lot of interactions not clearly understood; such as how different parameters (fibre angle, lay-up sequence, ply geometry) affect multi-stability and how they interlink. When these questions are solved multi-stable laminates might present them-selves as a viable option for morphing skins. More detailed explanations of bi-stable composites, the parameters affecting them and the modelling techniques used so far are given by Hyer(117-119), Dano and Hyer(120,121), Kebadze *et al*(122), Hufenbach *et al*(123) and Iqbal and Pellegrino(124). The research on multi-stable composite and its applications at the University of Bristol (UK) is documented for example in Weaver(125) who mentioned the use of snap-through buckling as a deployment mechanism in anisotropic composite structures and in references(126-130).

Norman *et al*(131) manufactured multi-stable corrugated panels made from copper-beryllium alloy via cold working. Bi-stable panels consisted of corrugated state and a coiled state parallel to the corrugations that occurs when the corrugations are pressed flat the panel. Tri-stable panels have two states where the panel is twisted along an axis not aligned with the corrugations in two different directions and a coiled state like the bi-stable panels. Applications could include flexible display screens or rollable keyboards, or adaptive wings/skin panels for UAVs and spacecrafts. Although these panels have been manufactured in metal there should be no reason why similar multi-stable composite corrugated panels could not be made. Furthermore this work is interesting since it combines anisotropy and multi-stability.

### 6.2.3 Segmented structures

Typical examples of segmented structures found in nature are fish skins. Ramrakhyani *et al*(132) explain that due to the multiple discrete elements, called scales, which slide relative to each other, the structure can deform (Fig. 12). This arrangement provides a high local lateral stiffness i.e. on their on own the scales are fairly stiff and hence can transmit the loads via myotomes (muscles) to the underlying structure (vertebral structure) while overall the structure can deform. However a significant aerodynamic concern is the non-continuous profile where the scales overlap. Analysis of fish scales showed that different layers in the skin have different properties and hence roles similar to human skin. A more detailed description of the morphology and functions of fish scales can be found in Varma(133), Long *et al*(134) and Bechert *et al*(135).

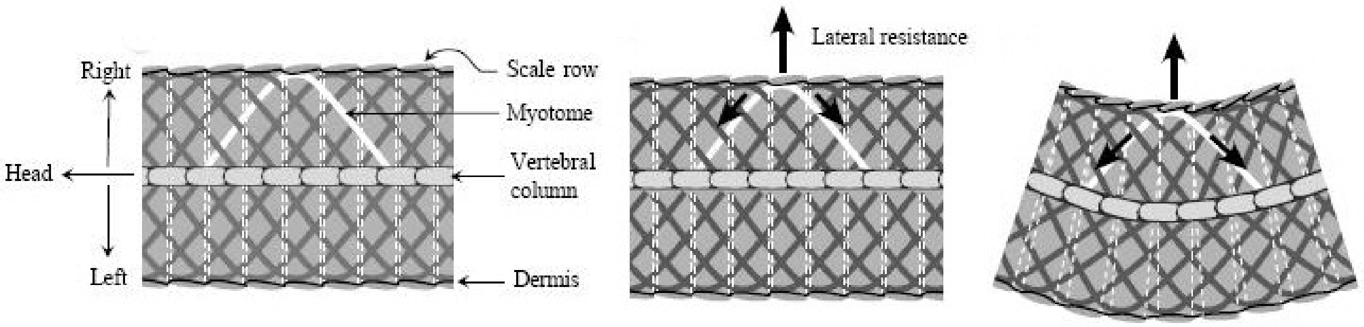

Figure 12. Function model of fish scales(134).

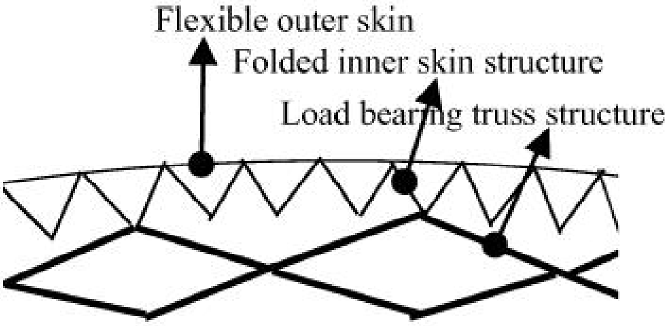

Figure 13. Folded inner skins(132).

Garner *et al*(136) and Rediniotis *et al*(137) have designed and tested an underwater highly maneuverable biomimetic vehicle. The design is based on the swimming techniques and anatomic structure of fish, primarily on the undulatory body motions which is possible due to the vertebrae structure of the backbone and the segmented skin.

#### 6.2.4 Folded inner skins

Ramrakhyani *et al*(132) suggest the use of folded inner skins (Fig 13), that provide lateral support to very flexible outer skins e.g. elastomers, as a potential morphing skin solution. The folded inner skins would expand and contract with the main-load bearing substructure. Although this seems like a viable concept it is difficult to imagine how this would help with the actual problem that aircraft skins need to be able withstand loads applied perpendicular to their surface.

#### 6.2.5 Multilayered skins

Ramrakhyani *et al*(132) also mention using a multilayered skin (Fig. 14) that consists of multiple thin layers of conventional material (e.g. metal or composite) that are not bonded together. In this configuration transverse shear stresses are not transmitted from one layer to another which reduces bending stiffness compared to a monolithic skin — in effect the through-thickness shear modulus is very low. This allows large bending curvatures to develop but the skin can withstand the same tensile loads as a monolithic structure of the same thickness. This means that the multilayered skin lends itself to be used for an aileron skin for example since curvature changes are possible at low actuation forces. However more support is probably needed for the multilayered skin along its length compared to a monolithic skin due to the reduced bending stiffness. Furthermore for practical solutions totally uncoupled layers are not feasible hence layers would need to be clamped together without restricting them to slide relative to each other.

Gordon and Clark(138) present an analytical model (simple beam theory) and a few experimental results of a beam, consisting of different layers, loaded with a concentrated load at its free end. By either bonding or un-bonding the layers and by varying the thickness and material of the layers a stiffness variation can be achieved. It is shown that a reduction of an order of magnitude in beam stiffness was achieved when the layers were de-bonded compared to a monolithic beam.

Figure 14. Multilayered skin(132).

### 6.3 Change in shape due to stiffness change

As previously discussed, there are generally two ways of achieving change in form with relative ease; the first one being explained in Section 6.2 'Change in shape due to stiffness tailoring', the second one deals with designing materials with the ability to change stiffness.

#### 6.3.1 Shape memory materials

##### 6.3.1.1 Shape memory alloys

Shape memory materials have been the focus of many researchers only recently although the one-way shape memory effect was first observed by Chang and Read in 1951 for a gold-cadmium alloy. In 1963 Buehler *et al* developed the SME of an equiatomic nickel-titanium alloy, commercialised under the trade name Nitinol an acronym for Nickel Titanium Naval Ordnance Laboratories(139,140).

The one-way SME for an alloy is defined as a change in shape of the material due to a change in temperature which is called a thermally induced shape-memory effect. The shape memory alloy (SMA) is cooled from its austenite phase (possible temperature range 52°C to 77°C) to its twinned martensite phase (possible temperature range –20°C to 35°C); note that there is no change in shape during this phase transformation process. In this latter phase it has low stiffness and can be deformed easily. Hence when a load is applied the SMA can be changed in shape to a deformed temporary martensite phase. When heated above its austenite finish temperature it will return to its original shape in the austenite phase (Fig. 15). Typically a recovery of the memorised shape for deformations of up to 8% plastic strain and a two- to fourfold increase in Young's Modulus can be observed. This is called one-way SME. The shape that a SMA memorises can be assigned or reassigned through an annealing process (heating above 500°C). More recent research has

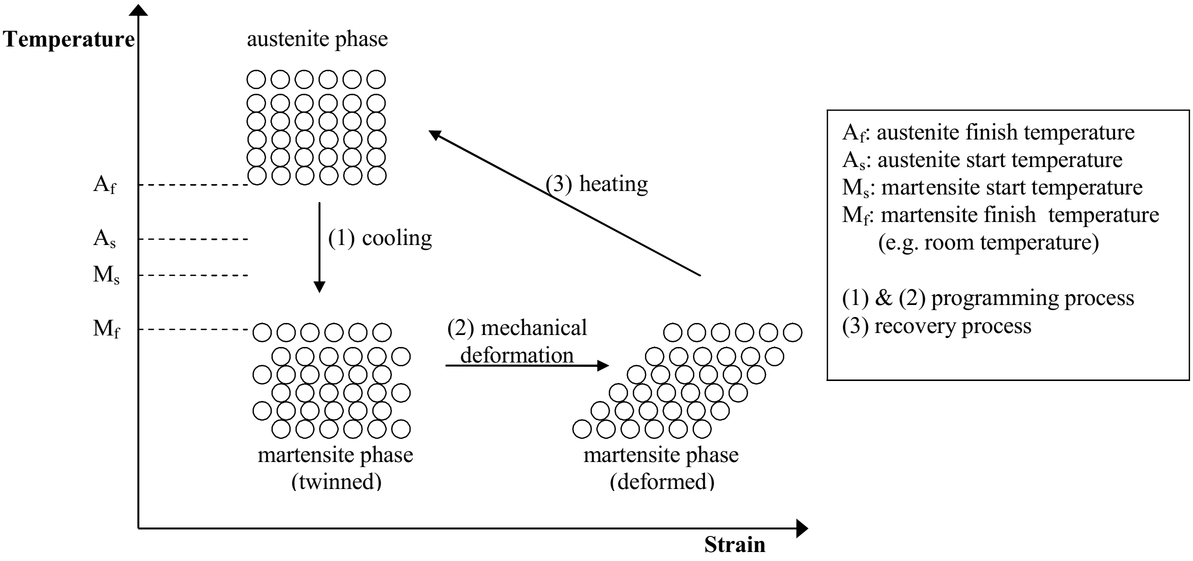

Figure 15. Temperature-strain diagram of one-way SMA material.

shown that the two-way SME can be achieved after certain thermal training which involves repeating the one-way SME cycle several times. This means that the SMA can switch between two configurations when heated and cooled. There is a third effect that SMAs encounter which is called pseudoelasticity. Pseudoelasticity or superelasticity is the effect of shifting of the transformation temperatures and, in some cases, to partial or even total formation of martensite of SMAs in the austenite phase when subjected to stress at constant high temperatures. This implies that, in general, transformation temperatures of a given alloy increase with increasing applied stress. A final general point to make about SMAs is the presence of temperature hysteresis which means that the change from martensite to austenite during heating occurs at a higher temperature than the change from austenite to martensite during cooling(137,140-143).

Some researchers have embedded SMA actuators in laminates to obtain self-actuating structures. So for example, Zheng *et al*(144) embedded prestrained SMA TiNiCu wires into a glass/epoxy and a Kevlar®/epoxy prepreg. Simpson *et al*(139) integrated SMA wires in the zero degree direction of quasi-isotropic laminates manufactured from E-glass/Fiberite 934 to control structural and acoustic response of aircraft fuselages. Balta *et al*(141) sandwiched prestrained NiTiCu SMA wires and fibre Bragg grating (FBG) sensors in the middle of a unidirectional (UD) prepreg Kevlar® laminate producing a hybrid composite. The SMA wires were used as actuators and the FBG in an optical fibre as sensors to measure strain in the composite during production and activation. Dano and Hyer(145) attached SMA wires to a bi-stable composite plate to initiate snap-through phenomena. The wires could not be directly surface mounted but rather attached to supports in order to have a larger moment arm. Barrett and Gross(146) embedded SMA wires in a very-low-modulus silicone matrix (no additional reinforcements were used).

SMA actuators have also been used in proof of concepts such as presented by Garner *et al*(136) and Rediniotis *et al*(137). These actuators are one-way SMA wires that are combined in an antagonistic way such that some contract and others expand. The wires are heated and cooled through a gas medium. Pitt *et al*(68) show how SMA wires have been used as actuators to change aircraft engine inlet area using electrical resistive heating to make the SMA extend and contract. Hargreaves(70) describes how SMAs might be used in the future as serrations, that can move in and out of the flow, around the edge at the back of the engine to reduce engine noise during take off. Kapps(82) reviews SMA actuators for space applications such as release mechanisms and shuttle wing trailing edge camber manipulation by SMA wires. The most relevant application of SMA actuators in the morphing field is the actively cooled SMA actuated leading edge of the DARPA Smart Wing. However it failed to make the final down-selection due to the low actuation rate of the SMA actuators(16).

### *6.3.1.2 Shape memory polymers*

The second shape memory material which will be presented in this review is the shape memory polymer (SMP). It works in a very similar way to one-way SMAs. By heating the SMP above its transition temperature which can be a glass transition or a melting temperature it becomes soft and can be deformed by application of a load. When the polymer is cooled in this new shape and the load is removed, the polymer will assume this new (temporary) shape. This concludes the programming process. If the polymer is heated back above the transition temperature the polymer will return to its permanent or memorised shape; this is called the recovery process. In theory this process can be repeated indefinitely. The first few cycles of programming and recovery can differ from each other. The stress-strain-temperature curves become more similar with increasing number of cycles. The SME for polymer results form a combination of the polymer structure and the polymer morphology together with the applied processing and programming technology. The shape memory behaviour can be observed for several polymers that may differ significantly in their chemical composition. Since the 1960s heat-shrinkable materials, e.g. polyethylene (PE) which is a covalently cross-linked thermoplastic, are made and have an analogy with the thermally induced SME. Today more and more reports about polymers with an SME can be found in the literature under the generic term of SMPs.

SMPs can be elongated up to 1100%(140) and their mechanical properties can be varied over a wide range. Potential applications include: self-repairing auto bodies, kitchen utensils, switches, sensors, intelligent packing, tools and medical applications. However, not many applications have been implemented to date since only a few SMPs have been investigated and even less are available on the market. Other stimuli than heat transfer through hot

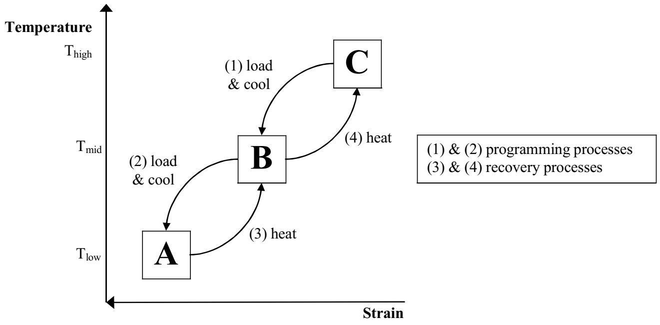

Figure 16. Temperature-strain diagram of triple-shape SMP.

exhaust gases or electrical resistive heating such as UV light of different wavelength, electromagnetic fields and two-way SME are being investigated.(99,140,147)

In fact, very recently Bellin *et al*(148) describe how different kinds of SMPs can be programmed to memorise two shapes so that a material can switch from one shape A, to a shape B and to a shape C as it is heated from $T_{low}$ to $T_{mid}$ to $T_{high}$ (Fig. 16). During the programming process a polymer in shape C at its highest transition temperature $T_{high}$ is deformed to shape B and cooled to its middle transition temperature $T_{mid}$. Then it is deformed to a shape A and cooled to its lowest transition temperature $T_{low}$. The SMP can return to shapes B and C when heated to $T_{mid}$ and $T_{high}$ in turn. Although this is still no two-way SME these triple-shape SMPs feature more attractive properties than the standard one-way SMPs.

Perkins *et al*(99, 149) give an overview of research carried out at a US company called Cornerstone Research Group (CRG)(58) whose aim is to come up with a wing that can increase its lift by 80% and that can morph between different configurations within 1 second. Many years of research have resulted in the production of three main products based on a fully-cured thermoset SMP that can change shape due to a thermo-molecular relaxation rather than a thermally-induced crystalline phase transformation as with SMA (both processes were explained earlier). The first product is Veriflex® which is the styrene based SMP it self (Fig. 17). It was used as a skin material for a morphing aerofoil section. Experiments showed though that its cycles to failure were too low and it was too brittle in the hardened state to withstand the expected vibration loads which implies that performance modifications are required for Veriflex® to perform optimally for this application. The second is Veritex™ (Fig. 18) which is a composite that can be fabricated with nearly any fibre type and with Veriflex® as the matrix resin. These composites can be easily deformed above the transition temperature and show high strength and stiffness at lower temperatures. And finally CRG's third product is a low-density foam based on Veriflex® called Verilyte™ (Fig. 18). It could be used as core material in a sandwich structure that can be reshaped when soft at high temperature and carry out structural functions at low temperature. The method used by the manufacturer to heat the SMP is electrical resistive heating using nichrome wires.

Belfourd and Tsang(151) carried out mechanical tests such as tensile, flexural, hardness and shape memory property tests on SMPs. They used the Veriflex® SMP resin. Resin transfer moulding


Original
Stowed Shape
1st Recovery Snapshot
2nd Recovery Snapshot
Fully Recovered

Figure 17. Veriflex® honeycomb structure self-recovering under an IR heat lamp(99).

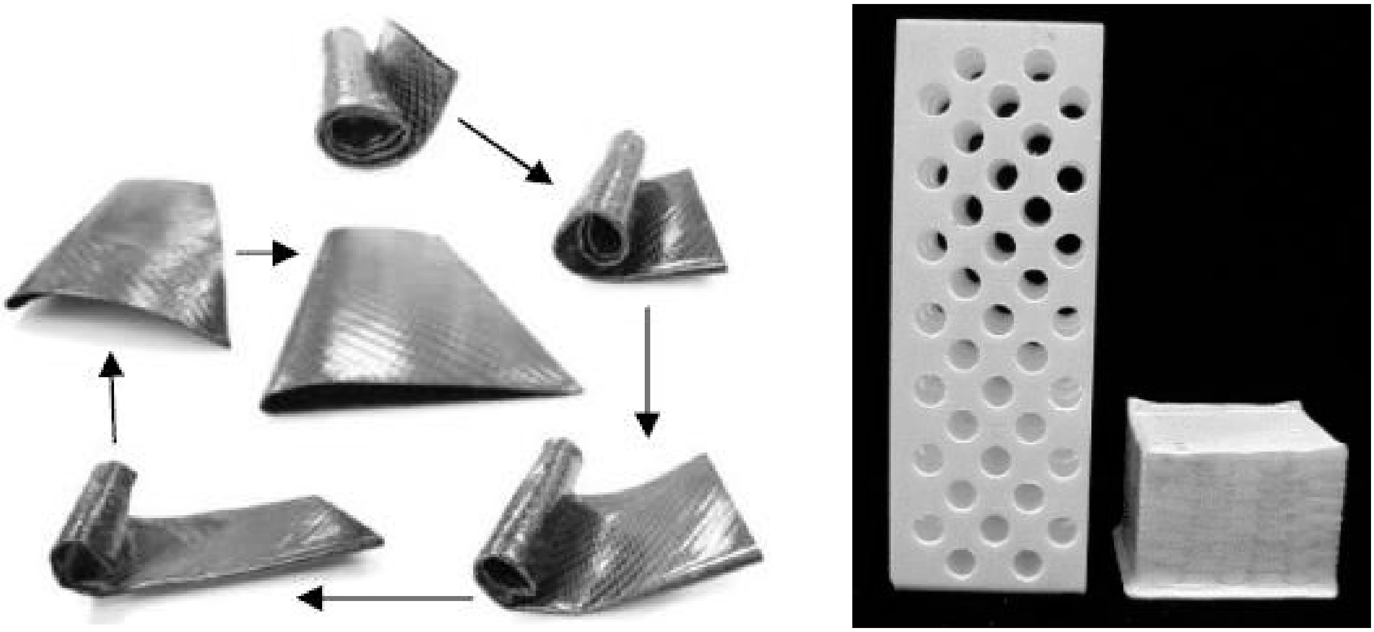

Figure 18. Veritex™ aerofoil self-recovering from rolled state (left) and Verilyte™ (right)(99, 150).

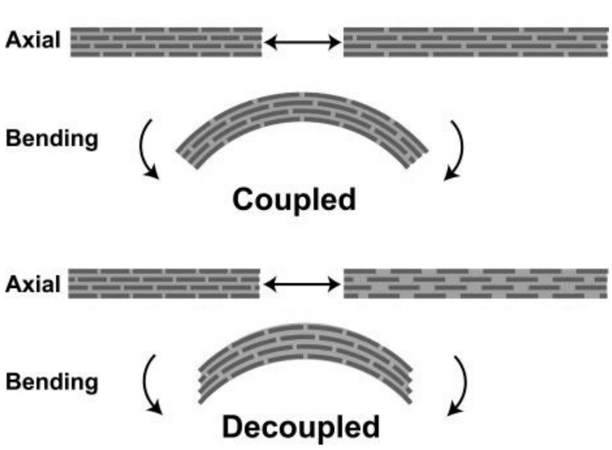

Figure 19. High stiffness (top) and low stiffness (bottom) structure(153).

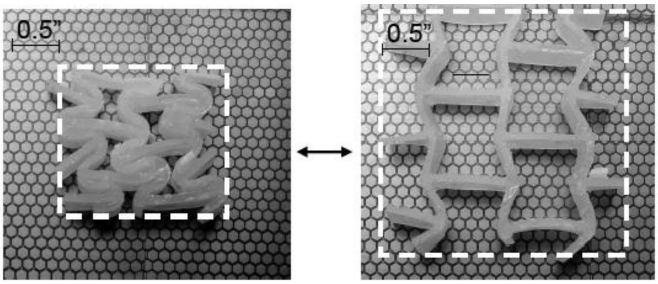

Figure 20. Auxetic cellular material(152).

(RTM), open poured mould and closed poured mould were the manufacturing techniques used to process the Veriflex®. The latter with the appropriate de-gassing process and release agents proved to be the best one in terms of ease of use and sample quality. They also tried to improve the stiffness of the SMPs by reinforcing them with nano-alumina particles. This resulted in improved mechanical properties and the particles effect on shape memory properties was barely noticeable which can be considered as a positive fact.

Keihl *et al*(79) believe that SMPs are an attractive and promising solution for morphing skins since the multiple stable state abilities of SMPs allow them to easily change shape and once cooled to resist appreciable loads. They did shear tests on various (no specification on type) SMPs below and above their transition temperature. As expected the SMP properties were found to be time and temperature dependent. Furthermore the force and power needed to actuate SMPs were rate dependent. Keihl *et al* say that current SMPs need less actuation power when the morphing takes place slowly.

McKnight and Henry(152, 153) use SMPs to achieve variable stiffness materials for reconfigurable structures. In their first paper they design a laminate with constant and variable stiffness elements. “The function of the constant stiffness elements is to carry the structural loads while the function of the variable stiffness element is to provide variable connectivity between the constant stiffness elements. In the structural mode, the variable stiffness elements rigidly connect the stiff elements which creates high stiffness (similar to traditional structural composites). In the morphing mode, the variable stiffness material becomes soft leaving the stiff elements effectively disconnected.” In this mode large axial, shear and bending deformations can be achieved (Fig. 19). They used high yield spring steel for the stiff elements and a thin film polyurethane SMP (produced by Mitsubishi Heavy Industries., Diaplex 5510(154)) for the variable stiffness elements to manufacture their samples. The key design variables were length and thickness of stiff elements, spacing of elements, thickness of variable stiffness elements, fraction of stiff elements within segmented layer and volume fraction of stiff elements.

From experimental tests they found that large differences in upper and lower stiffness can be achieved by varying the geometry and operating temperature and they noted that it is important to understand the relationship between the geometry and the elastic properties. In applications where structural rigidity is required during transformation a large stiffness reduction may not be desirable. However, for space missions where gravity is absent a large stiffness change will enable the use of smaller actuation and power systems.

In their second paper Henry and McKnight(152) showed similar disadvantages of SMPs as in their first paper(153). They can be deformed to a high strain level but have a very weak recovery force which implies that they are not good actuators. Often stiffening elements (reinforcements) are needed to improve the SMP’s stiffness but then its maximum strain reduces to 10%. So large strains (>20%) are only practically achievable with polymers but they cannot be used as structural materials because of their low stiffness, poor toughness, durability and temperature sensitivity. Hence they conclude that current available materials are unsuitable for large strain structural reconfigurations. They suggest an alternative route to achieve large strain and stiffness materials using variable stiffness and cellular architecture structures. FEA and experimental results are presented for two positive and two negative Poisson’s ratio cellular material types made from Veriflex® SMPs with and without carbon reinforcements. Results show that area increases of 130% can be achieved due to the cellular structure (Fig. 20), the stiffness decreases by a factor of 450 when the temperature changes from room to transition temperature and strains of up to 8·5% for SMPs with carbon reinforcements at high temperature are possible.

They also realised that large positive Poisson’s ratio material plates give anticlastic shapes and negative Poisson’s ratio material plates induce synclastic behaviour when bent out of plane. “This type of behaviour could be extremely useful in cases where large out-of-plane deformation and smooth concave shells are desired, such as for radio frequency (RF) reflectors in antennas and mirror reflector surfaces.”

### 6.3.1.3 *Elastic memory composites*

Tupper *et al*(155) present elastic memory composite (EMC) materials which are traditional fibre reinforced composites with a polymer resin that exhibits shape memory properties. This idea is in fact identical to the variable stiffness structures by McKnight and Henry(152, 153) or the Veritex™ by CRG(58). Tupper says that these materials are still in the early stages of development and require further development before they are ready for applications. However their initial experimental results agree well with their micro-structural models. Several components and structures, including a mini beam and an open grid tube for deployable space structures, were fabricated using EMC materials.

Lake & Campbell(156) list current available Tembo® SMP resins made by the US company Composite Technology Development (CTD)(157). They explain how to design and manufacture EMCs using Tembo® resins, give details about how to avoid material fibre failure i.e. micro-fibre-buckling, the deployment time needed and the energy analysis, and finally they mention that an efficient heating system design is a critical aspect for the correct and in time property changes of the SMP. During experimental testing they found out that generally the bending response of EMCs is nonlinear. There seems to be a variety of components that can be readily made from EMC materials: small mechanisms: e.g. hinges, release devices and large structural members, e.g. booms and panels.

Abrahamson *et al*(158) show experimentally that one of the Tembo® SMPs, CTD-DP5.1, can be used according to a new thermo-mechanical cycle where the SMP is not heated above its $T_g$

when a load is applied. This results in a permanent strain slightly less than the induced strain. The viscoelastic model presented results that agreed well with measurements. This new cycle has fewer steps involved and hence takes less time however higher deformation forces are presumably required.

Arzberger *et al*(159) are more concerned with the application side of the Tembo® EMCs. An important advantage of Tembo® is that it is a thermoset resin whereas nearly all past SMP focussed on thermoplastics, however most structural-grade composite components for aerospace applications incorporate thermoset resins due to better mechanical performance and environmental durability. Reinforcements can include carbon, glass, aramid and/or nano-reinforcements. In general EMCs are well suited for deployable space applications. Other possible applications include EMC hinges for deployable structures on spacecrafts (e.g. International Space Station) or satellites, EMC booms to deploy solar arrays, optic systems and antennas. Arzberger *et al* state that future developments at CTD will include Tembo® polymer nano-composites, Tembo® SMP foams and Tembo® EMCs for biomedical applications, e.g. biodegradable stent.

Hulse *et al*(160) show via tensile and compressive experimental tests that EMCs made from Tembo® reinforced with carbon fibres exhibit a non-linear stress-strain behaviour i.e. elastic modulus increases with strain. This is predominately due to carbon-fibre nonlinearity effects while process induced wavy-fibre effects play a relatively minor role. Finally they present a model including both effects and reasonable results were obtained compared to the experimental data.

#### *6.3.1.4 Shape memory textiles*

Shape memory textiles or cloth are an exciting innovation and are expected to receive much attention from researchers. This, at least, can be concluded from selected university websites around the world e.g. Hong Kong Polytechnic University(161) or Georgia Tech(162) where is drawn upon the experience from the shape memory polymers.(163,164)

#### *6.3.1.5 Magnetic shape memory materials*

As previously discussed in Section 6.3.1 under 'Shape memory polymers', other stimuli than electrical resistive heating are being investigated to trigger the transition from a stiff to a soft SMA or SMP. One such mechanism is the magnetic field. Tellinen *et al*(165), Sozinov *et al*(166) and Suorsa *et al*(167) introduce the SME for alloys, specifically for NiMnGa alloys that can be used as linear, bending or twisting motion actuators and achieve strains of 10%. Most of them are pre-stressed by springs to make use of the reversible magnetic-field-induced strain. However magnetic shape memory alloys (MSMAs) can be used as sensors, since their surrounding magnetic field alters when subjected to a mechanical input(168). Discrete MSMA actuators on their own might not be of much interest for morphing skin solutions, however embedded in a matrix they could perform the duties of an actuating element in a smart material that can change shape(169, 170).

The magnetically induced SME for polymers is presented by Mohr *et al*(171). They incorporated magnetic nano-particles having an iron(III) oxide core in silica matrix in thermoplastic SMP. By inductive heating the SMP in an alternating magnetic field the shape memory effect of the composites was triggered and the magnetic SME was successfully demonstrated in these magnetic SMPs. "The mechanisms of heat generation are hysteresis loss and/or related processes that are a direct result of superparamagnetism" (form of magnetism which occurs only in the presence of an externally applied magnetic field below the Curie/Neel temperature(172)). It was found that neither the glass transition nor the melting temperature are affected by the incorporation of nano-particles. In addition magnetically and thermally induced shape recovery results were comparable. Experimental tests on three samples with different nano-particles weight percentages allowed the determination of the mechanical properties. The Young's modulus was determined to be 130-150MPa, the maximum elongation at break 660% at room temperature and the Young's modulus was lowered by 70-75% at a temperature of 55°C. According to Mohr *et al*, potential applications for magnetically induced SMPs include smart implants and controlled medical instruments.

From the previous sections on shape memory materials, it is possible to summarise that only the SMAs and SMPs are currently at a level ready to be considered in morphing skin concepts. The one-way SMAs and SMPs could be used where changes in modulus are required although one could argue that this could also be achieved with conventional thermoplastics. The novel property of Veriflex® and Tembo® is that they are based on thermoset resins whereas previous polymers with a SME, i.e. heat shrinkable material were made from thermoplastics. This means that these new SMPs are a mixture between thermoplastics in terms of modulus change and elastomers in terms of recovering to a memorised shape but can take on a structural role as can thermosets. The two-way SMAs could be used as actuators in an on-off mode i.e. two fixed positions.(79, 140) Table 1 gives an overview of properties from the literature of the SMPs mentioned.

### *6.3.2 Flexible matrix composites*

Flexible matrix composite (FMC) actuators were only introduced recently however pneumatic artificial muscle (PAM) actuators have been around for a lot longer. They are also known under the name of pneumatic muscle actuator, fluid actuator, fluid-driven tension actuator, axially contractible actuator and tension actuator. PAMs were introduced by a Russian inventor named Garasiev in the 1930s but due to the restricted material technology at the time, they were of limited use. Only in the 1950s J.L. McKibben developed a pneumatic actuator as an orthotic appliance for polio patients, since then often referred to as a McKibben actuator. It is powered by compressed gas and is made from an inflatable inner bladder sheathed with a double helical weave which contracts lengthwise when expanded radially. Typical materials used for the membrane are latex or silicone rubber while nylon is normally used for the fibres. PAMs recently found application in factory floor automation due to their relative low weight in assembly as compared with their electric and hydraulic counterparts and their high power and force-to-weight ratios. Even a legged robot, called LUCY, actuated by PAMs has been developed. Two antagonistically coupled PAMs were implemented to power each rotative joint. This is novel since most of the legged robots nowadays use electrical drives with torque densities too low to actuate the legs and hence requiring gearboxes to deliver the required torque at low rotation speeds, thereby making the joint stiff and losing joint compliance. Another advantage of a PAM actuator is that it operates by means of over-pressure as compared to under-pressure operated bellows; and usually over-pressure is easier to achieve than under-pressure.(174-179)

Analytical and numerical models have been presented in the literature as well as experimental results to show the general working principles of PAMs(175,177,180,181). The most interesting report was by Devereux and Tyler(182) who showed how PAMs could be used for morphing applications. They focused their project on carrying out experimental tests on two PAM specimen of different length and consequently mass. Test scenarios included constant length, force and pressure tests. It was found that the most efficient range in terms of work done for a PAM to work as an actuator is at moderate pressures and high loads. As stated before it was shown that PAM actuators have a very high force to weight ratio compared to other existing actuators; e.g. 9,000N/kg for a PAM actuator compared to 900N/kg for an electric motor. Their restriction is that they are able to generate high forces with small displacements or low forces with large displacements. The most common failure at testing was seal and membrane burst failure. They also built a variable thickness

**Table 1**
**Properties for Veriflex®, Tembo® DP5.1 and Diaplex 5510**

| SMP type | $T_g$ | below $T_g$ | | | above $T_g$ | | |
|---|---|---|---|---|---|---|---|
| | | $E_t$ | $\sigma_t$* | $\varepsilon_{t,\ max}$ | $E_t$ | $\sigma_t$* | $\varepsilon_{t,\ max}$ |
| Veriflex® (styrene based thermoset) CRG | 62°C(58) | 1·2GPa(58) | 23·0MPa(58) | 7%(151) | 0·07MPa at 25%/<br>0·30MPa at 200% strain(81) | N/A | 200%(58, 81) |
| Tembo® DP5.1 (epoxy based thermoset) CTD | 71°C(158) | 470 MPa at low strain/<br>3·7MPa at high strain(158) | N/A | N/A | 5·4MPa(158) | N/A | N/A |
| Diaplex (polyurethane) 5510 Mitsubishi Heavy Industries | 55°C(173) | 500MPa at 5% strain(173) | 40MPa(173) | 200%(173) | 40MPa at 5% strain(173) | 10MPa(173) | 200%(173) |

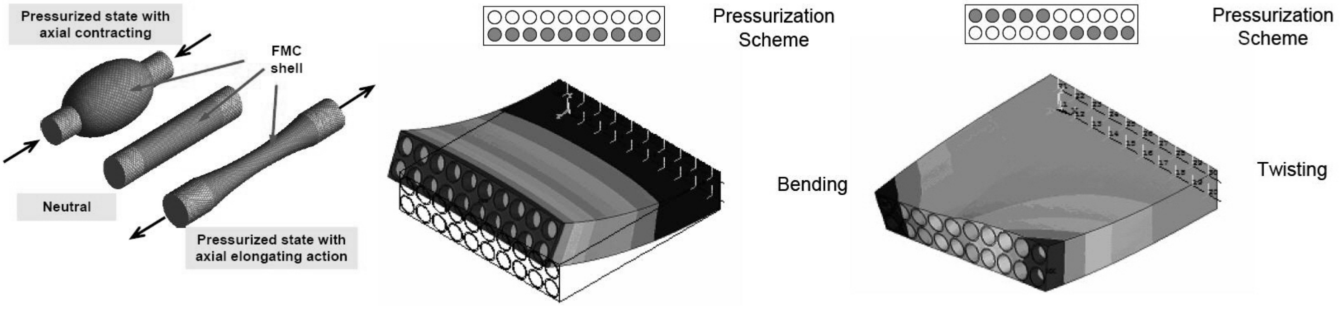

Figure 21. FMC actuators(186) and pressurisation scheme of FMC actuators in an elastomer matrix(188).

aerofoil section actuated by a PAM as a demonstrator.

FMC actuators can be used to achieve stiffness and shape changes from a structure. The concept is to embed several braided composite tubes, FMC tubes, into an elastomeric matrix making a multi-cellular FMC adaptive structure. The FMC tubes contract or expand depending on their initial fibre angle and actuator membrane anisotropy when pressurised with a fluid (Fig. 21). The adaptive structure changes stiffness and shape (stretch, contract, bend, twist) depending on the pressure in the FMC tubes and the pressurisation scheme (Fig. 21). The FMC tubes themselves are manufactured by filament winding carbon fibre in a polyurethane matrix. It is a bio-inspired actuation system e.g. fibrillar network in plant cell walls or nastic movements of plants. Many plants angle their stems so that their leaves face light sources and that their flower petals open. They do this by changing the osmotic or turgor pressure in their specialised motor cells. This is called nastic motion of plants(183). Fibres in FMC actuators can be orientated at any angle whereas PAM actuators are generally restricted to fibre angles above 15°. Hence FMC actuators can be designed to twist or provide greater axial force than a PAM actuator.(184-189)

In the papers by Shan *et al*(188,189) an analytical model is presented that is validated by experimental data. The results show that the modulus of a single FMC tube is a function of the fibre braid angle and that the demarcation angle between contraction and extension angle increases with the moduli ratio $E_1/E_2$ and converges to around 55° when $E_1/E_2 > 100$. With the help of the model a single FMC tube is analysed in a free strain state (i.e. displacement but no external resisting force) to determine displacement and a blocked stress state (i.e. no displacement but force) to measure actuation force. This is done for different internal pressures and applied loads. Other results show that using an incompressible fluid as pressurising medium increases the axial stiffness of the actuator; and under a constant volume condition the contraction type actuator is significantly stiffer in the axial direction and shows a much smaller shape change compared to the constant pressure condition.

Philen *et al*(186) make it clear using analytical and FE models how the pressure change inside FMC tubes can change the stiffness of multi-cellular FMC adaptive plate. The plate is modelled as a beam with a uniform transversely distributed load applied to the top surface. For the particular tube analysed a reduction of 3·7 in the maximum transverse displacement is achieved by closing the valves to the tube i.e. pressurising the tube compared to the open valve scenario. Furthermore, they discuss the impact of optimum fibre angle for maximum stiffness ratio for open/closed valve solution and the effect of fluid bulk modulus on stiffness ratio for open/closed valve solution. Tailoring the fibres (orientation, number of layers, material) and matrix material can lead to FMC tubes with a high degree of anisotropy but with improved performance. Finally, Philen *et al* added a thin skin with fibres orientated at ±45° to the sides of the beam to find that the ratio of maximum transverse displacement for the open/closed valve scenario increased from 3·7 to 5. This ratio has in fact a constant value of five for any multi-cellular FMC adaptive beam of width longer than about 1cm.

More recently Philen *et al*(190) expanded the FMC FE model that considers the tube's radial compliance and thin inner liner made of silicone to prevent fluid losses at high pressures. They also manufactured several FMC tubes and one multi FMC tube structure from carbon fibres/silicone matrix using a filament winder. Experiments were carried out on the specimen and it was found that further improvements needed to be made to the FE model. In a further paper

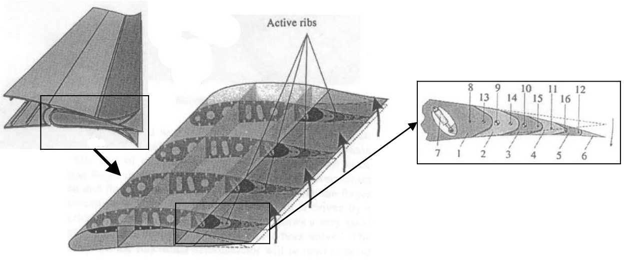

Figure 22. Finger concept(55).

Philen *et al*(191) integrate the FMC tube with an electro-osmotic pump to mimic nastic plant movement. The applied voltage through a charged porous membrane of the FMC tube is adjusted and hence the internal pressure of the actuator is controlled. They present an integrated electro-osmotic actuating and FMC structural model.

Shan *et al*(188,189) suggest that FMCs embedded in a matrix are a promising material in applications where large structural deformations are needed such as in robots, morphing aerospace and marine structures. Shan(187) describes in his PhD thesis how FMC tubes could be used as driveshafts for helicopter tail rotors since they need to be flexible in length i.e. flexurally soft because the tail boom moves a lot during flight due to loads and vibrations, but stiff in torsion to transmit the torque. A possible way of combining variable and tailored stiffness structures would be to integrate FMC tubes into the troughs of corrugated panels. This way the stiffness along the corrugation could be controlled.

## 6.4 Morphing concepts

So far two different aspects have been considered for morphing skins: how to change/increase surface area mainly by deployable structures and how to change shape via stiffness tailoring, variable stiffness materials or possibly smart materials. Now this review shall look at some morphing concepts that combine structure, actuation and skin.

### *6.4.1 Finger concept*

Monner *et al*(55) used a finger concept in order to obtain a variable camber trailing edge for a civil airliner wing. A metallic but flexible skin is used to achieve an aerodynamic profile. The inflexible ribs at the trailing edge were replaced with a few plate like elements, fingers, that were joined together and could rotate relative to each other (Fig. 22). Although each element had a high stiffness the combined structure was flexible and allowed chordwise and spanwise differential variable camber when actuated by electrical motors. The technology was implemented in a 3·2 × 0·9 × 0·6m (span × chord × thickness) demonstrator model to show that it works. The elements were made out of metal and CFRP. Unfortunately, not enough details were given about the skin material and how it performed to judge the viability of this concept.

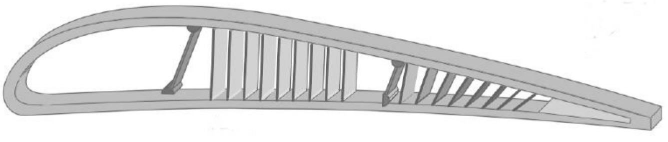

Figure 23. Belt rib concept(193).

### *6.4.2 Belt rib concept*

At DLR a wing aerofoil has been developed where the ribs have been removed and the number of spars increased. The orientation, i.e. angle, of the spars makes camber change possible due to the low stiffness. The skin of the aerofoil, which defines the shape, is essentially like a belt and the spars like spokes or ribs, hence the name belt-rib concept (Fig. 23). A 1:2 model (500mm wide) was manufactured based on the A340 outboard flap and it was made from carbon fibre/epoxy resin composite with metallic hinges for the rib/belt connections. The concept could be actuated in the future with integrated solid-state actuators such as piezoceramic or SMA actuators. Test results showed a maximum deflection of 5° and an experimentally measured maximum strain of 0·099%. Stiffness requirements were also satisfied through experimental tests. Although increased chordwise flexibility is demonstrated compared with a standard aerofoil design, values for actuation loads or long term performance of the belt (fatigue) are not stated.(192,193)

### *6.4.3 Sliding rib concept/crossbar concept*

The shape memory products introduced earlier are used as materials for morphing aerofoil demonstrators by CRG. The company looked at a sliding rod, a sliding rib and a cross-bar concept for the underlying load bearing structure (Fig. 24). The sliding rib concept was found to be the most structurally reliable and therefore selected. It consists of flat ribs of which some can extend outwards in-plane between others that are fixed and hence act as support. The Veriflex® SMP with embedded nichrome wires for electrical resistive heating was planned to be used as skin material. The

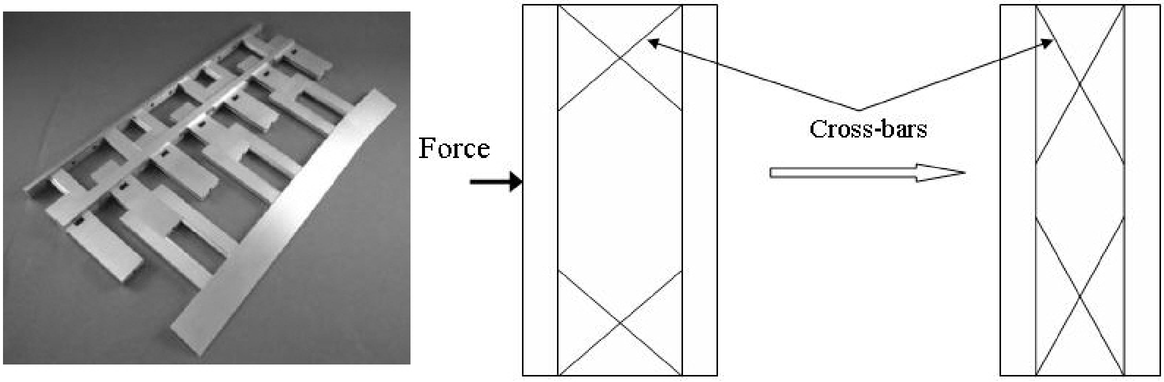

Figure 24. Sliding rib concept (left) and schematic of cross-bar concept (right)(149,150).

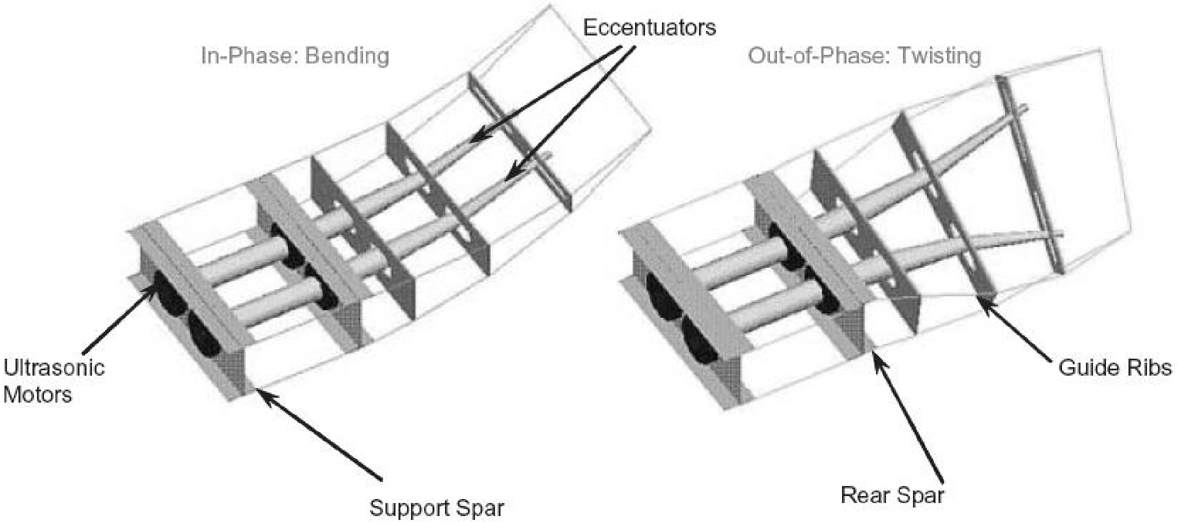

Figure 25. Eccentuator(16).

substructure activation was attained via small DC motors however piezoelectric inchworm motors are believed to present the long term solution. As mentioned earlier the brittleness and the low cycle life enforce improvements to the SMP. Veritex$^{TM}$, the reinforced Veriflex® by CRG, might be the answer however no published work is available yet.(99,149,150)

### 6.4.4 Eccentuator

Kudva(16) presents a concept using an eccentuator integrated into a flexible control surface to morph an aerofoil trailing edge. The eccentuator is essentially a bent rod that transforms rotary motion at one end into vertical force and displacement at the other end (Fig. 25). In the Smart Wing programme it was actuated by an ultrasonic piezoelectric motor(17). The trailing edge of the model wing tested in the wind tunnel was split into ten segments with each driven by one eccentuator and one ultrasonic electric motor. This combination represented the actuation system whereas the segments themselves were made from a flexible honeycomb core covered with a silicone skin and the tips were made from aluminium. Wind tunnel tests were made at Mach 0·8 and dynamic pressures of up to 14,400Pa on a 2·8m span, 2·5m long and 273kg heavy model. Over 70 different trailing edge shapes were demonstrated with deflection rates of 80°/s and maximum deflections of 20°. Although the experimental test results showed higher coefficient of lift values for this smart wing compared to a conventional wing at the same angle of attack other skin designs need to be investigated such as foam cores, coreless semi-rigid skin that may be superior to the honeycomb core/silicone skin design. Similar to other work, no detailed specifications are given for the skin material and performance.

### 6.4.5 Compliant structure

Compliant structures could be said to be inspired from insect wings. They consist of tough flexible membranes acting as the primary aerodynamic structure and supported by a network of fairly rigid longitudinal or radiating tubular hollow veins and containing a fluid which serves to prevent the wing material from becoming brittle. The insect wings are similar to a sail which is of not much use, when not supported, and unless guided by a mast and ropes, it would flutter uselessly like a flag. The veins are like the mast and the flexible membranes are like the sail. The strength and stiffness of an insect wing can be increased in three different ways: vein enlargement, thickening and fusion of neighbouring veins into a single strong tube; increased relief (corrugation/dips); membrane thickening. All three ways increase the second moment of area and hence the stiffness of the wing. A wing with longitudinal veins that are strongly cross-linked is particularly resistant to bending (in any plane) and stiff in torsion.(194-197)

Ramrakhyani *et al*(132) consider cellular trusses (also called compliant structures, tensegrity structures or variable geometry trusses) made from octahedral unit cells that could be used as structures for morphing applications. Some of the trusses are replaced by cables or tendons, possibly SMA wires, making it possible to change the shape of the unit cell by lengthening or shortening the cables. A numerical model was made where multiple cells were implemented in a wing and the relation between the strain in the trusses and the truss angle, and between strength and weight were analysed. Results showed that other cell geometries need to be investigated to increase area change and that a tendon actuated wing has a similar mass than a conventional wing for the same design requirements but allows larger deflections. Ramrakhyani *et al* state that aeroelastic effects might be possible to address with active controls. Four skin solutions were suggested which were described earlier: high strain-capable materials, folded inner skins, multilayered skins and segmented skins.

Wiggins *et al*(2) also looked at tensegrity structures to design a wing that can change its spanwise camber elliptically i.e. droop the wing tip. They present kinematic, aerodynamic and structural analysis. Baker *et al*(198) analysed the truss concept which they describe as “the creation of an active, pin jointed, truss structure by the substitution of bar members with linear actuators.” It is a very efficient way of using a structure since the bars that resist deformation are removed and the remaining ones should be orientated in the externally applied load directions. Some truss structures are based on the ancient weaving pattern of Kagome (Japanese) baskets. Kagome trusses are special because they are statically indeterminate and are effectively isotropic (and stiff) in-plane(199). The use of a flexible skin design is briefly mentioned, suggestions are segmented skin e.g. fish scales or spring-steel honeycomb mesh covered with a layer of silicone.

Trease and Kota(200) and Lu and Kota(201) describe the methods used (including genetic algorithms based on survival of the fittest) to optimise structural and actuation geometry simultaneously in a smart structure. They base their analysis on compliant structures in nature and try to find the optimum position to embed actuators and sensors in a compliant structure. While the practical aspects are neglected in this paper, Kota *et al*(43) and Weiss(202) illustrate how the compliant

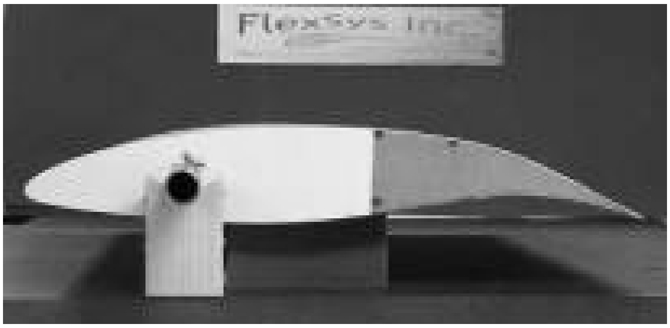

Figure 26. FlexSys MACW, picture of 10° deflected trailing edge(59).

Figure 27. FlexSys MACW installed on White Knight for flight tests(59).

structure concept is used by FlexSys. Their research targeted minimising the force required to morph surfaces during flight while maintaining maximum stiffness to withstand the external loads. The company designed and manufactured an aerofoil section, the Mission Adaptive Compliant Wing (MACW) (Fig. 26) which can change camber through a morphing leading (by 6°) and trailing edge (by +/–10°). It has an internal compliant structure and a flexible overlapping skin, and it was first tested structurally and in a wind tunnel(59). Flight tests followed from October to December 2006 when the MACW with a morphing trailing edge only was attached to the White Knight, a jet aircraft designed by Scaled Composites and best known as the aircraft that launched SpaceShipOne into space in 2004 (Fig. 27). The MACW was made from aluminium, however, making it from composite could lead to a weight saving of 20-30%(203). Hetrick *et al*(203) say that performance improvements were shown by one study (not referenced) of the MACW flap compared to a conventional wing. The flight test results are presented in their paper and they conclude that the MACW minimises flow separation and airfoil/wing drag; drag results agree reasonably well with predicted values; and, flow was laminar over 60% chord on the upper surface. They also predict that a 15% or more fuel saving could be made with a MACW which could result in millions of USD savings per year when applied to the entire US aircraft fleet. Unfortunately no aerodynamic experimental data comparison was made (e.g. lift and drag coefficient) to a conventional flap tested in the same conditions which would give direct results of improvement or degradation.

## 7.0 CONCLUSIONS

This review has introduced morphing skins as an emerging aerospace technology that needs to be addressed thoroughly if morphing aircraft are to be successful. Many papers reviewed in this paper indicate that there are likely aerodynamic, performance and operational benefits from morphing technology. The challenges are the diverse requirements for a morphing skin of an aircraft wing, which are well outlined by Kikuta(81), that need to be met.

This study showed that the concepts, materials or structures found in the literature do not fulfil all these characteristics. The biggest current design problem seems to be to combine properties like flexibility and stiffness into one structure. In fact, Section 6 showed that the level of maturity for morphing skins is low and the existing concepts are very early in their development. This implies that for most of the concepts issues such as operation in demanding environments, fatigue and chemical resistance have, so far, largely been ignored. However, there are quite a few principles available, especially in nature, that can be used as a starting point.

For example, to achieve large area increases a deployable structure such as a 'roller blind' concept appears promising. For shape changes or small area increases anisotropic or variable stiffness structures offer the potential to combine compliance and stiffness. Following both naturally inspired and conventional design practice, concepts should be as simple as possible while design methods should be sufficiently flexible to expand the envelope and seek a step-change in technology. A morphing skin is likely to be a hierarchical or heterogeneous structure and not a homogeneous material. Hence, it is possible to conclude that one focus of research into morphing skin materials can be on designing new composite materials including an internal structure that allows significant elastic deformations due to built-in geometric features (e.g. corrugations), or mechanisms (e.g. re-entrant designs) integrated within a low modulus elastomer.

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## REFERENCES

1. *Oxford English Dictionary*, 2007, http://dictionary.oed.com, Oxford University Press.
2. WIGGINS, L.D., STUBBS, M.D., JOHNSTON, C.O., ROBERTSHAW, H.H., REINHOLTZ, C.F. and INMAN, D.J. A design and analysis of a morphing hyper-elliptic cambered span (HECS) wing, 2004, American Institute of Aeronautics and Astronautics, USA.
3. NOOR, A.K., VENNERI, S.L., PAUL, D.B. and HOPKINS, M.A. Structures technology for future aerospace systems, *Computers and Structures*, 2000, **74**, (5), pp 507-519.
4. WEISS, P. Wings of change — Shape-shifting aircraft may ply future skyways, *Science News,* 2003, pp 359-367.
5. SANDERS, B., EASTEP, F.E. and FORSTER, E. Aerodynamic and aeroelastic characteristics of wings with conformal control surfaces for morphing aircraft, *J Aircr,* 2003, **40,** (1), pp 94-99.
6. SANDERS, B., JOO, J.J. and REICH. G.W. Conceptual skin design for morphing aircraft, 2005, 16th International Conference on Adaptive Structures and Technologies (ICAST), Paris, France.
7. JOSHI, S.P., TIDWELL, Z., CROSSLEY, W.A. and RAMAKRISHNAN. S. Comparison of morphing wing strategies based upon aircraft performance impacts, 2004, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Palm Springs, CA, USA.
8. BOWMAN, J., SANDERS, B., CANNON, B., KUDVA, J., JOSHI, S. and WEISSHAAR, T. Development of next generation morphing aircraft structures, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.
9. RUDOLPH, P.K.C. High-lift systems on commercial subsonic airliners, 1996, NASA Ames Research Center, Moffet Field, CA, USA.

10. BAUER, C., MARTIN, W., SIEGLING, H.-F. and SCHUERMANN, H. New structural approach to variable camber wing technology of transport aircraft, 1998, American Institute Aeronautics and Astronautics.
11. WLEZIEN, R.W., HORNER, G.C., MCGOWAN, A.R., PADULA, S.L., SCOTT, M.A., SILCOX, R.J. and SIMPSON. J.O. The aircraft morphing program. 1998, International Society for Optical Engineering.
12. ROTH, B.D. and CROSSLEY, W.A. Applications of optimization techniques in the conceptual design of morphing aircraft, 2003, Third Annual Aviation Technology, Integration, and Operations (ATIO), Denver, CO, USA.
13. ROTH, B., PETERS, C. and CROSSLEY, W.A. Aircraft sizing with morphing as an independent variable: motivation, strategies and investigations, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.
14. SPILLMAN, J.J. The use of variable camber to reduce drag, weight and costs of transport aircraft, *Aeronaut J*, 1992, **96,** (951), pp 1-9.
15. BEIN, T., HANSELKA, H. and BREITBACH, E. Adaptive spoiler to control the transonic shock, *Smart Mat and Struc,* 2000, **9,** (2), pp 141-148.
16. KUDVA, J.N. Overview of the DARPA smart wing project, *J Intell Mat Sys and Struc,* 2004, **15,** (4), pp 261-267.
17. BARTLEY-CHO, J.D., WANG, D.P., MARTIN, C.A., KUDVA, J.N. and WEST, M.N. Development of high-rate, adaptive trailing edge control surface for the smart wing phase 2 wind tunnel model, *J Intell Mat Sys and Struc,* 2004, **15,** (4), pp 279-291.
18. GERN, F.H., INMAN, D.J. and KAPANIA, R.K. Structural and aeroelastic modeling of general planform wings with morphing airfoils, *AIAA J*, 2002, **40,** (4), pp 628-637.
19. Gern, F.H., INMAN, D.J. and KAPANIA, R.K. Computation of actuation power requirements for smart wings with morphing airfoils, *AIAA J,* 2005, **43,** (12), pp 2481-2486.
20. NOOR, A.K., SPEARING, S.M., ADAMS, W.W. and VENNERI, S.L. Frontiers of the material world, *Aerospace America,* 1998, **36,** (4), pp 24-31.
21. RODRIGUEZ, A.R. Morphing aircraft technology survey, 2007, 45th AIAA Aerospace Sciences Meeting and Exhibition, Reno, NV, USA.
22. The design of morphing aircraft, 2007, Aerospace Department, University of Bristol, http://www.aer.bris.ac.uk/research/morphing/morph-main.html.
23. RAO, P.R. Biomimetics, *Sadhana — Academy Proceedings in Engineering Sciences,* 2003, **28,** (3-4), pp 657-676.
24. BALL, P. Life's lessons in design, *Nature,* 2001, **409,** (6818), pp 413-416.
25. JOHN, G., CLEMENTS-CROOME, D. and JERONIMIDIS, G. Sustainable building solutions: a review of lessons from the natural world, *Building and Environment,* 2005, **40,** (3), pp 319-328.
26. DEW, J. TRIZ: a creative breeze for quality professionals (inventive problem solving theory), *Quality Progress,* 2006, **39,** (1), pp 44-51.
27. SAMPSON, B. Inspired by nature, *Professional Engineering*, 2006, **19,** (18), pp 39-40.
28. MENON, C., AYRE, M. and ELLERY, A. Biomimetics — a new approach to space system design, *ESA Bulletin*, 2006, **125**, pp 20-26, European Space Agency.
29. TRASK, R.S., WILLIAMS, H.R. and BOND, I.P. Self-healing polymer composites: mimicking nature to enhance performance, *Bioinspiration & Biomimetics*, 2007, **2**, (1), pp 1-9.
30. LAKES, R. Materials with structural hierarchy, *Nature,* 1993, **361,** (6412), pp 511-515.
31. BLONDEAU, J. and PINES, D.J. Wind tunnel testing of a morphing aspect ratio wing using an pneumatic telescopic spar, 2003, Second AIAA 'Unmanned Unlimited' Systems, Technologies, and Operations-Aerospace, Land, and Sea Conference and Workshop & Exhibition, San Diego, CA, USA.
32. BLONDEAU, J. and PINES, D.J. Pneumatic morphing aspect ratio wing, 2004, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, CA, USA.
33. BECHERT, D.W., BRUSE, M., HAGE, W. and MEYER, R. Fluid mechanics of biological surfaces and their technological application, *Naturwissenschaften,* 2000, **87,** (4), pp 157-171.
34. GREVEN, H., ZANGER, K. and SCHWINGER, G. Mechanical-properties of the skin of Xenopus-Laevis (Anura, Amphibia), *J Morphology,* 1995, **224**, (1), pp 15-22.
35. BRACKENBURY, J.H. Wing folding and free-flight kinematics in Coleoptera (Insecta) — a comparative-study, *J Zoology*, 1994, **232,** pp 253-283.
36. TOENSMEIER, P.A., Radical departure, *Av Week and Space Tech*, 2005, **162,** (21), pp 72-73.
37. JHA, A.K. and KUDVA, J.N. Morphing aircraft concepts, classifications, and challenges, 2004, Smart structures and materials and nondestructive evaluation for health monitoring and diagnostics conference, San Diego, CA, USA.
38. ILC Dover, Frederica, DE, USA, http://www.ilcdover.com.
39. CADOGAN, D., SMITH, T., LEE, R., SCARBOROUGH, S. and GRAZIOSI, D. Inflatable and rigidizable wing components for unmanned aerial vehicles, 2003, American Institute Aeronautics and Astronautics, Norfolk, VA, USA.
40. CADOGAN, D., SMITH, T., UHELSKY, F. and MACKUSICK, M. Morphing inflatable wing development for compact package unmanned aerial vehicles, 2004, American Institute Aeronautics and Astronautics, Reston.
41. WILSON, J.R. Morphing UAVs change the shape of warfare, *Aerospace America,* 2004, **42,** (2), pp 28-29.
42. BONNEMA, K.L. and SMITH, S.B. AFTI/F-111 mission adaptive wing flight research program, 1988, Fourth AIAA Flight Test Conference, San Diego, CA, USA.
43. KOTA, S., HETRICK, J.A. and OSBORN, R.F. Adaptive structures: moving into the mainstream, *Aerospace America,* 2006, **44,** (9), pp 16-18.
44. DECAMP, R.W. and HARDY, R. Mission adaptive wing research programme, *Aircraft Engineering,* 1981, **53,** (1), pp 10-11.
45. PASTOR, C., JOO, J.J., SANDERS, B. and MCCARTY, R. Kinematically designed flexible skins for morphing aircraft, 2006, ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, USA.
46. DECAMP, R.W. and HARDY, R. Mission adaptive wing advanced research concepts, 1984, AIAA (CP 849), **2088**, New York, NY, USA.
47. PERRY, B., COLE, S.R. and MILLER, G.D. Summary of an active flexible wing program, *J Aircr*, 1995, **32,** (1), pp 10-15.
48. PENDLETON, E.W., BESSETTE, D., FIELD, P.B., MILLER, G.D. and GRIFFIN, K.E. Active aeroelastic wing flight research program: technical program and model analytical development, *J Aircr*, 2000, **37,** (4), pp 554-561.
49. PENDLETON, E., FLICK, P., PAUL, D., VORACEK, D., REICHENBACH, E. and GRIFFIN, K. The X-53 a summary of the active aeroelastic wing flight research program, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.
50. MCGOWAN, A.-M.R., COX, D.E., LAZOS, B.S., WASZAK, M.R., RANEY, D.L., SIOCHI, E.J. and PAO, S.P. Biologically-inspired technologies, NASA's Morphing Project, 2003, International Society for Optical Engineering.
51. MCGOWAN, A.-M.R., WASHBURN, A.E., HORTA, L.G., BRYANT, R.G. COX, D.E., SIOCHI, E.J., PADULA, S.L. and HOLLOWAY, N.M. Recent results from NASA's Morphing Project, 2002, International Society for Optical Engineering.
52. http://www.darpa.mil, 2007, Defense Advanced Research Projects Agency (DARPA), Arlington, VA, USA.
53. FLORANCE, J.P., BURNER, A.W., FLEMING, G.A., HUNTER, C.A., GRAVES, S.S. and MARTIN, C.A. Contributions of the NASA Langley research center to the DARPA/AFRL/NASA/Northrop Grumman smart wing program, 2003, Norfolk, VA, USA.
54. http://www.dlr.de, 2007, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany.
55. MONNER, H.P., BREITBACH, E., BEIN, T. and HANSELKA, H. Design aspects of the adaptive wing — the elastic trailing edge and the local spoiler bump, *Aeronaut J,* 2000, **104,** (1032), pp 89-95.
56. The morphing aircraft, The Dryden X-Press, NASA, http://www.dfrc.nasa.gov/Newsroom/X-Press/stories/043001/new_morph.html, 2007.
57. http://www.nasa.gov, 2007, NASA.
58. http://www.crgrp.net, 2007, Cornerstone Research Group.
59. http://www.flxsys.com, 2007, FlexSys.
60. http://www.lockheedmartin.com/skunkworks, 2007, Lockheed Martin Skunk Works.
61. BYE, D.R. and MCCLURE, P.D. Design of a morphing vehicle, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.
62. LOVE, M.H., ZINK, P.S., STROUD, R.L., BYE, D.R. and CHASE, C. Impact of actuation concepts on morphing aircraft structures, 2004, American Institute Aeronautics and Astronautics.
63. LOVE, M.H., ZINK, P.S., STROUD, R.L., BYE, D.R., RIZK, S. and WHITE, D. Demonstration of morphing technology through ground and wind tunnel tests, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.

64. http://www.nextgenaero.com, 2007, NextGen Aeronautics.
65. FLANAGAN, J.S., STRUTZENBERG, R.C., MYERS, R.B. and RODRIAN, J.E. Development and flight testing of a morphing aircraft, the NextGen MFX-1, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.
66. ANDERSEN, G.R., COWAN, D.L. and PIATAK, D.J. Aeroelastic modeling, analysis and testing of a morphing wing structure, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.
67. LAWLOR, M. The shape of wings to come, *Signal Magazine*, 2006, AFCEA.
68. PITT, D.M., DUNNE, J.P. and WHITE, E.V. Design and test of a SMA powered adaptive aircraft inlet internal wall, 2002, 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, CO, USA.
69. TURNER, T.L., BUEHRLE, R.D. CANO, R.J. and FLEMING, G.A. Design, fabrication, and testing of SMA enabled adaptive chevrons for jet noise reduction, 2004, Smart Structures and Materials conference, San Diego, CA, USA.
70. HARGREAVES, B. Material benefits, *Professional Engineering,* 2006, **19,** (21), pp 22-23.
71. TURNER, T.L., LACH, C.L. and CANO, R.J. Fabrication and characterization of SMA hybrid composites, 2001, SPIE-International Society for Optical Engineering.
72. Cornell morphing aircraft project, http://morphing.mae.cornell.edu/index.htm, 2007, Mechanical & Aerospace Engineering Department, Cornell University.
73. http://www.cimss.vt.edu, 2007, Centre for Intelligent Material Systems and Structures (CIMSS), Virginia Polytechnic Institute and State University.
74. http://128.227.42.147/morph/index.html, 2007, Center for Morphing Control, Department of Mechanical and Aerospace Engineering, University of Florida.
75. MEGSON, T.H.G. *Aircraft Structures for Engineering Students*, 1999, Third edition, Arnold, London, UK.
76. TIMOSHENKO, S. and WOINOWSKY-KRIEGER, S. *Theory of Plates and Shells,* 1959, Second edition, McGraw-Hill Book Company, New York, USA.
77. CLOYD, J.S. Status of the United States Air Force's more electric aircraft initiative, *IEEE Aerospace and Electronic Systems Magazine,* 1998, **13,** (4) pp 17-22.
78. YOKOZEKI, T., TAKEDA, S.-I., OGASAWARA, T. and ISHIKAWA, T. Mechanical properties of corrugated composites for candidate materials of flexible wing structures, Composites Part A: *Applied Science and Manufacturing*, 2006, **37**, (10), pp 1578-1586.
79. KEIHL, M.M., BORTOLIN, R.S., SANDERS, B., JOSHI, S. and TIDWELL, Z. Mechanical properties of shape memory polymers for morphing aircraft applications, 2005, International Society for Optical Engineering.
80. CALLISTER, W.D.J. *Materials Science and Engineering: An Introduction,* 2006, Seventh edition, Wiley.
81. KIKUTA, M.T. Mechanical properties of candidate materials for morphing wings, 2003, p 123, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University.
82. KAPPS, M. Smart-material mechanisms as actuation alternatives for aerospace robotics and automation, 2006, International Space Development Conference, Los Angeles, CA, USA.
83. EVANS, K.E. and ALDERSON, A. Auxetic materials: functional materials and structures from lateral thinking, *Advanced Materials,* 2000, **12,** (9) pp 617-628.
84. GRIMA, J.N., GATT, R., RAVIRALA, N., ALDERSON, A. and EVANS, K.E. Negative Poisson's ratios in cellular foam materials, *Materials Science and Engineering A*, 2006, **423,** (1-2), pp 214-218.
85. ALDERSON, K.L., SIMKINS, V.R., COENEN, V.L., DAVIES, P.J., ALDERSON, A. and EVANS, K.E. *How to Make Auxetic Fibre Reinforced Composites*, 2005, Wiley-VCH, Poznan-Bedlewo, Poland.
86. BORNENGO, D., SCARPA, F. and REMILLAT, C. Evaluation of hexagonal chiral structure for morphine airfoil concept, *J Aero Eng,* 2005, **219,** (3), pp 185-192, Proceedings of the Institution of Mechanical Engineers, Part G.
87. WEI, G. and EDWARDS, S.F. Auxeticity windows for composites, *Physica A*, 1998, **258,** (1-2), pp 5-10.
88. OLYMPIO, K.R. and GANDHI, F. Zero-$\nu$ cellular honeycomb flexible skins for one-dimensional wing morphing, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA.
89. http://www.hexcel.com, 2007, Hexcel, Dublin, CA, USA.
90. VINCENT, J.F.V. Deployable structures in nature: potential for biomimicking, *J Mech Eng Sci,* 2000, **214,** (1), pp 1-10, Proceedings of the Institution of Mechanical Engineers Part C.
91. SEBOLDT, W., KLIMKE, M., LEIPOLD, M., and HANOWSKI, N. European sail tower SPS concept, *Acta Astronautica,* 2001, **48,** (5-12), pp 785-792.
92. http://www.invent-gmbh.de, 2007, Invent, Braunschweig, Germany.
93. SICKINGER, C., HERBECK, L. and BREITBACH, E. Structural engineering on deployable CFRP booms for a solar propelled sailcraft, *Acta Astronautica,* 2006, **58,** (4), pp 185-196.
94. UNCKENBOLD, W.F., EIDEN, M.J. HERBECK, L. LEIPOLD, M. SCHOPPINGER, C. and SICKINGER, C. Boom deployment mechanism for large deployable antennas, 2002, 25th ESA Antenna Workshop on Satellite Technology, ESTEC, Noordwijk, The Netherlands.
95. VENDURA, G.J., MALONE, P. and CRAWFORD. L. *Novel, Light Weight Solar Array: Comparison with Conventional System*s, 1993, IEEE, Piscataway, NJ, USA.
96. http://www.st.northropgrumman.com/astro-aerospace, 2007, Astro Aerospace, Carpinteria, CA, USA.
97. http://www.sener.es, 2007, Sener, Spain.
98. DE FOCATIIS, D.S.A. and GUEST, S.D. Deployable membranes designed from folding tree leaves, *Math Phys and Eng Sci,* 2002, **360,** (1791), pp 227-238, Philosophical transactions of the Royal Society of London Series.
99. PERKINS, D.A., REED, J.L. and HAVENS, E. Morphing wing structures for loitering air vehicles, 2004, American Institute Aeronautics and Astronautics.
100. http://www.corex-honeycomb.com, 2007, Corex Honeycomb, Huntingdon, Cambridgeshire, UK.
101. http://composite.about.com/library/weekly/aa081197.htm, 2007, About: Composites, New York, USA.
102. YEE, J.C.H. and PELLEGRINO, S. Folding of woven composite structures. Composites Part A: *Applied Sci and Manuf,* 2005, **36,** (2 SPEC ISS), pp 273-278.
103. HAWKINS, G., O'BRIEN, M. and ZALDIVAR, R. Machine-augmented composites, 2002, American Institute Aeronautics and Astronautics.
104. MOLLERICK, R. New millenium inflatable structures technology, 1997, Mechanical Engineering Branch, NASA Goddard Space Flight Center.
105. GORINEVSKY, D. and HYDE, T.T. Adaptive membrane for large lightweight space telescopes, 2002, International Society for Optical Engineering.
106. MARKS, P. The next 100 years of flight — part one & two, 2003, NewScientists.com news service.
107. http://www.raytheon.com, 2007, Raytheon.
108. URSACHE, N.M., KEANE, A.J. and BRESSLOFF, N.W. Design of postbuckled spinal structures for airfoil camber and shape control. *AIAA J*, 2006, **44,** (12), pp 3115-3124.
109. REICH, G.W., SANDERS, B. and JOO, J.J. Development of skins for morphing aircraft applications via topology optimization, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
110. POTTER, K.D. and WISNOM, M.R.. Composites of extreme anisotropy initial experiments, *Plastics, Rubber and Composites*, 2002, **31**, (5), pp 226-234.
111. VERONDA, D.R. and WESTMANN, R.A. Mechanical characterization of skin-finite deformations, *J Biomechanics*, 1970, **3**, (1), pp 111-124.
112. PEEL, L.D., JENSEN, D.W. and SUZUMORI, K. Batch fabrication of fiber-reinforced elastomer prepreg, *J Advanced Materials*, 1998, **30**, (3), pp 3-10.
113. MURRAY, G., GANDHI, F. and BAKIS, C. Flexible matrix composite skins for one-dimensional wing morphing, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
114. TAMAI, M., WANG, Z., RAJAGOPALAN, G., HU, H. and HE, G. Aerodynamic performance of a corrugated dragonfly airfoil compared with smooth airfoils at low Reynolds numbers, 2007, 45th AIAA Aerospace Sciences Meeting and Exhibition, Reno, NV, USA.
115. BUTLER, G. Investigation of corrugated composite laminates for use in morphing wing skin applications, 2007, Department of Aerospace, University of Bristol.
116. FORTERRE, Y., SKOTHEIM, J.M., DUMALS, J. and MAHADEVAN, L. How the Venus flytrap snaps, *Nature*, 2005, **433**, (7024), pp 421-425.
117. HYER, M.W. Calculations of the room-temperature shapes of unsymmetric laminates. *J Composite Materials*, July 1981, **15**, pp 296-310.
118. HYER, M.W. Some observations on the cured shape of thin unsymmetric laminates. *J Composite Materials*, March 1981, **15**, pp 175-194.
119. HYER, M.W. The room-temperature shapes of 4-layer unsymmetric cross-ply laminates. *J Composite Materials*, July 1982, **16**, pp 318-340.

120. Dano, M.L. and Hyer, M.W. Thermally-induced deformation behavior of unsymmetric laminates. *Int J Solids and Structures*, 1998, **35**, (17), pp 2101-2120.
121. Dano, M.L. and Hyer, M.W. Snap-through of unsymmetric fiber-reinforced composite laminates. *Int J Solids and Structures*, 2002, **39**, (1), pp 175-198.
122. Kebadze, E., Guest, S.D. and Pellegrino, S. Bistable prestressed shell structures. *Int J Solids and Structures*, 2004, **41**, (11-12), pp 2801-2820.
123. Hufenbach, W., Gude, M. and Kroll, L. Design of multistable composites for application in adaptive structures, *Composites Science and Technology*, 2002, **62**, (16), pp 2201-2207.
124. Iqbal, K. and Pellegrino, S. Bi-stable composite shells, 2000, American Inst Aeronautics and Astronautics.
125. Weaver, P.M. On beneficial anisotropic effects in composite structures, 2002, 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, CO, USA.
126. Potter, K., Weaver, P., Seman, A.A. and Shah, S. Phenomena in the bifurcation of unsymmetric composite plates. *Composites Part A: Applied Science and Manufacturing*, 2007, **38**, (1) pp 100-106.
127. Potter, K.D. and Weaver, P.M. A concept for the generation of out-of-plane distortion from tailored FRP laminates, *Composites Part A: Applied Science and Manufacturing*, 2004, **35**, (12), pp 1353-1361.
128. Mattioni, F., Gatto, A., Weaver, P.M. and Friswell, M.I. The application of residual stresses tailoring of snap-through composites for variable sweep wings, 2006, 47th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Newport, RI, USA.
129. Diaconu, C.G., Weaver, P.M. and Mattioni, F. Solutions for morphing airfoil sections using bi-stable laminated composite structures, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
130. Mattioni, F., Weaver, P.M., Friswell, M.I. and Potter, K.D. Modelling and applications of thermally induced multistable composites with piecewise variation of lay-up in the planform, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
131. Norman, A.D., Guest, S.D. and Seffen, K.A. Novel Multistable Corrugated Structures, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
132. Ramrakhyani, D.S., Lesieutre, G.A., Frecker, M. and Bharti, S. Aircraft structural morphing using tendon-actuated compliant cellular trusses, *J Aircr*, 2005, **42**, (6) pp 1615-1621.
133. Varma, K.B.R. Morphology and dielectric properties of fish scales, *Current Science*, 1990, **59**, (8), pp 420-422.
134. Long, J.H., Hale, M.E., McHenry, M.J. and Westneat, M.W. Functions of fish skin: Flexural stiffness and steady swimming of longnose gar Lepisosteus osseus, *J Experimental Biology*, 1996, **199**, (10), pp 2139-2151.
135. Bechert, D.W., Bruse, M. and Hage, W. Experiments with three-dimensional riblets as an idealized model of shark skin, *Experiments in Fluids*, 2000, **28**, (5), pp 403-412.
136. Garner, L.J., Wilson, L.N., Lagoudas, D.C. and Rediniotis, O.K. Development of a shape memory alloy actuated biomimetic vehicle, *Smart Materials and Structures*, 2000, **9**, (5), pp 673-683.
137. Rediniotis, O.K., Wilson, L.N., Lagoudas, D.C. and Khan, M.M. Development of a shape-memory-alloy actuated biomimetic hydrofoil. *J Intelligent Material Systems and Structures*, 2002, **13**, (1), pp 35-49.
138. Gordon, B.O. and Clark, W.W. Morphing Structures by way of Stiffness Variations, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
139. Simpson, J.O., Wise, S.A., Bryant, R.G., Cano, R.J., Gates, T.S., Hinkley, J.A., Rogowski, R.S. and Whitley, K.S. Innovative materials for aircraft morphing, 1998, International Society for Optical Engineering.
140. Lendlein, A. and Kelch, S. Shape-memory polymers, *Angewandte Chemie - International Edition*, 2002, **41**, (12), pp 2035-2057.
141. Balta, J.A., Bosia, F., Michaud, V., Dunkel, G., Botsis, J. and Manson, J.A. Smart composites with embedded shape memory alloy actuators and fibre Bragg grating sensors: activation and control, *Smart Materials & Structures*, 2005, **14**, (4), pp 457-465.
142. Tzou, H.S., Lee, H.J. and Arnold, S.M. Smart materials, precision sensors/actuators, smart structures, and structronic systems, *Mechanics of Advanced Materials and Structures*, 2004, **11**, (4-5), pp 367-393.
143. Pons, J.L. *Emerging Actuator Technologies — A Micromechatronic Approach*, 2005, John Wiley & Sons, UK.
144. Zheng, Y.J., Cui, L.S. and Schrooten, J. Basic design guidelines for SMA/epoxy smart composites, *Materials Science and Engineering A,* 2005, **390**, (1-2), pp 139-143.
145. Dano, M.L. and Hyer, M.W. SMA-induced snap-through of unsymmetric fiber-reinforced composite laminates, *Int J Solids and Structures*, 2003, **40**, (22) pp 5949-5972.
146. Barrett, R. and Gross, R.S. Super-active shape-memory alloy composites, *Smart Materials & Structures*, 1996, **5**, (3), pp 255-260.
147. Lendlein, A., Jiang, H.Y., Junger, O. and Langer, R. Light-induced shape-memory polymers, *Nature*, 2005, **434**, (7035), pp 879-882.
148. Bellin, I., Kelch, S. Langer, R. and Lendlein, A. Polymeric triple-shape materials, *Proceedings of the National Academy of Sciences of the United States of America*, 2006, **103**, (48), pp 18043-18047.
149. Perkins, D.A., Reed, J.L. and Havens, E. Adaptive wing structures, 2004, Smart Structures and Materials and Nondestructive Evaluation for Health Monitoring and Diagnostics conference, San Diego, CA, USA, International Society for Optical Engineering.
150. Reed, J.L., Hemmelgarn, C.D., Pelley, B.M. and Havens, E. Adaptive wing structures, 2005, Smart Structures and Materials and Nondestructive Evaluation for Health Monitoring and Diagnostics conference, San Diego, CA, USA, International Society for Optical Engineering.
151. Belfourd, D.T. and Tsang, W.M. An investigation into shape memory materials, 2006, Department of Aerospace Engineering, University of Bristol.
152. Henry, C. and McKnight, G. Cellular variable stiffness materials for ultra-large reversible deformations in reconfigurable structures, 2006, International Society for Optical Engineering.
153. McKnight, G. and Henry, C. Variable stiffness materials for reconfigurable surface applications, 2005, International Society for Optical Engineering.
154. The Intelligent Material DIAPLEX, http://www.diaplex.com, 2007, Mitsubishi Heavy Industries.
155. Tupper, M., Munshi, N., Beavers, F., Gall, K., Mikuls, M. and Meink, T. Developments in elastic memory composite materials for spacecraft deployable structures, 2001, IEEE.
156. Lake, M.S. and Campbell, D. The fundamentals of designing deployable structures with elastic memory composites, 2004, IEEE.
157. http://www.ctd-materials.com, 2007, Composite Technology Development.
158. Abrahamson, E.R., Lake, M.S., Munshi, N.A. and Gall, K. Shape memory mechanics of an elastic memory composite resin, *J Intelligent Material Systems and Structures*, 2003, **14**, (10), pp 623-632.
159. Arzberger, S.C., Tupper, M.L., Lake, M.S., Barrett, R., Mallick, K., Hazelton, C., Francis, W., Keller, P.N., Campbell, D., Feucht, S., Codell, D. Wintergerst, J., Adams, L., Mallioux, J., Denis, R., White, K., Long, M., Munshi, N.A. and Gall, K. Elastic memory composites (EMC) for deployable industrial and commercial applications, 2005, International Society for Optical Engineering.
160. Hulse, M.J., Campbell, D., Ryan, K.C.J., Haynes, M.M. and Francis, W. Nonlinear effects in unidirectional elastic memory composite material, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
161. http://www.polyu.edu.hk, 2007, Hong Kong Polytechnic University — Institute of Textile and Clothing.
162. http://www.tfe.gatech.edu, 2007, School of Polymer, Textile and Fiber Engineering, Atlanta, GA, USA.
163. Ji, F.L., Zhu, Y., Hu, J.L., Liu, Y., Yeung, L.Y. and Ye, G.D. Smart polymer fibers with shape memory effect, *Smart Materials & Structures*, 2006, **15**, (6), pp 1547-1554.
164. Zhu, Y., Hu, J., Yeung, K.W., Choi, K.F., Liu, Y.Q. and Liem, H.M. Effect of cationic group content on shape memory effect in segmented polyurethane cationomer, *J Applied Polymer Science*, 2007, **103**, (1) pp 545-556.
165. Tellinen, J., Suorsa, I., Jaaskelainen, A., Aaltio, I. and Ullakko, K. Basic properties of magnetic shape memory actuators, 2002, Eighth Actuator conference, Bremen, Germany.
166. Sozinov, A., Likhachev, A.A., Lanska, N. and Ullakko, K. Giant magnetic-field-induced strain in NiMnGa seven-layered martensitic phase, *Applied Physics Letters*, 2002, **80**, (10), pp 1746.
167. Suorsa, I., Pagounis, E. and Ullakko, K. Magnetization dependence on strain in the Ni-Mn-Ga magnetic shape memory material, *Applied Physics Letters*, 2004, **84**, (23), pp 4658-4660.
168. Suorsa, I., Tellinen, J., Ullakko, K. and Pagounis, E. Voltage generation induced by mechanical straining in magnetic shape memory materials, *J Applied Physics*, 2004, **95**, (12), pp 8054-8058.

169. HAM-SU, R., HEALEY, J.P., UNDERHILL, R.S., FARRELL, S.P., CHENG, L.M., HYATT, C.V., ROGGE, R. and GHARGHOURI, M.A. Fabrication of magnetic shape memory alloy/polymer composites, *Smart Structures and Materials,* 2005, International Society for Optical Engineering.
170. HOSODA, H., TAKEUCHI, S., INAMURA, T. and WAKASHIMA, K. Material design and shape memory properties of smart composites composed of polymer and ferromagnetic shape memory alloy particles, *Science and Technology of Advanced Materials*, 2004, **5**, (4), pp 503-509.
171. MOHR, R., KRATZ, K., WEIGEL, T., LUCKA-GABOR, M., MONEKE, M. and LENDLEIN, A. Initiation of shape-memory effect by inductive heating of magnetic nanoparticles in thermoplastic polymers, *Proceedings of the National Academy of Sciences of the United States of America*, 2006, **103**, (10), pp 3540-3545.
172. VEJPRAVOVA, J.P., SECHOVSKY, V., NIZNANSKY, D., PLOCEK, J., HUTLOVA, A. and REHSPRINGER, J.-L. Superparamagnetism of co-ferrite nanoparticles, 2005, 14th Annual Conference Week of Doctoral Students (WDS), Prague, Czech Republic.
173. TOBUSHI, H., HARA, H., YAMADA, E. and HAYASHI, S. Thermomechanical properties in a thin film of shape memory polymer of polyurethane series, *Smart Materials & Structures*, 1996, **5**, (4), pp 483-491.
174. DAVIS, S., CALDWELL, D.G., TSAGARAKIS, N. and CANDERLE, J. Enhanced modelling and performance in braided pneumatic muscle actuators, *Int J of Robotics Research*, 2003, **22**, (3-4), pp 213-227.
175. RAMASAMY, R., JUHARI, M.R., MAMAT, M.R., YAACOB, S., NASIR, N.F.M. and SUGISAKA, M. An application of finite element modelling to pneumatic artificial muscle, *American J of Appl Sci*, 2005, **2**, (11), pp 1504-1508.
176. RAMASAMY, R., JUHARI, M.R. and SUGISAKA, M. Conceptual view of pneumatic artificial muscle, 2005, First Intenational Workshop on Artificial Life and Robotics (AROB), Kangar, Malaysia.
177. KLUTE, G.K., CZERNIECKI, J.M. and HANNAFORD, B. McKibben artificial muscles: Pneumatic actuators with biomechanical intelligence, 1999, IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), pp 221-226.
178. VANDERBORGHT, B., VERRELST, B., VAN HAM, R. and LEFEBER, D. Controlling a bipedal walking robot actuated by pleated pneumatic artificial muscles, *Robotica*, 2006, **24**, (4), pp 401-410.
179. VANDERBORGHT, B., VERRELST, B., VAN HAM, R., NAUDET, J., VERMEULEN, J. LEFEBER, D. and DAERDEN, F. LUCY, a bipedal walking robot with pneumatic artificial muscles, 2004, IEEE Mechatronics & Robotics Conference, Aachen, Germany.
180. KLUTE, G.K. and HANNAFORD, B. Fatigue characteristics of McKibben artificial muscle actuators, 1998, IEEE.
181. KLUTE, G.K. and HANNAFORD, B. Accounting for elastic energy storage in McKibben artificial muscle actuators, *Transactions of the ASME. Journal of Dynamic Systems, Measurement and Control*, 2000, **122**, (2), pp 386-388.
182. DEVEREUX, M.J. and TYLER, D. Pneumatic artificial muscles, 2006, Department of Aerospace Engineering, University of Bristol.
183. SATER, J. and MAIN, J. Plants and mechanical motion-nastic materials at DARPA, 2004, 15th International Conference on Adaptive Structures and Technologies (ICAST), Bar Harbor, Maine, USA.
184. GIURGIUTIU, V., MATTHEWS, L., LEO, D.J. and SUNDARESAN, V.B. Concepts for power and energy analysis in nastic structures, 2005, American Society of Mechanical Engineers.
185. MATTHEWS, L., SUNDARESAN, V.B., GIURGIUTIU, V. and LEO, D.J. Bioenergetics and mechanical actuation analysis with membrane transport experiments for use in biomimetic nastic structures, *J Materials Research*, 2006, **21**, (8), pp 2058-2067.
186. PHILEN, M., SHAN, Y., BAKIS, C.E., WANG, K.W. and RAHN, C.D. Variable stiffness adaptive structures utilizing hydraulically Pressurized flexible matrix composites with valve control, 2006, 47th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Newport, RI, USA.
187. SHAN, Y. Flexible matrix composites: Dynamic characterization, modelling, and potential for driveshaft applications, 2006, Department of Engineering Science and Mechanics, Pennsylvania State University.
188. SHAN, Y. and BAKIS, C.E. Flexible matrix composite actuators, 2005, 20th Annual Technical Conference of Amercian Society for Composites, Philapelphia, PA, USA.
189. SHAN, Y., PHILEN, M.P., BAKIS, C.E., WANG, K.-W. and RAHN, C.D. Nonlinear-elastic finite axisymmetric deformation of flexible matrix composite membranes under internal pressure and axial force, *Composites Science and Technology*, 2006, **66**, (15), pp 3053-3063.
190. PHILEN, M., SHAN, Y., WANG, K.W., BAKIS, C.E. and RAHN, C.D. Fluidic flexible matrix composites for the tailoring of variable stiffness adaptive structures, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.
191. PHILEN, M.K., SHAN, Y., PRAKASH, P., WANG, K.W., C.D. RAHN, ZYDNEY, A.L. AND BAKIS, C.E. Fibrillar network adaptive structure with ion-transport actuation, *J Intelligent Material Systems and Structures*, 2007, **18**, (4), pp 323-334.
192. CAMPANILE, L.F. AND ANDERS, S. Aerodynamic and aeroelastic amplification in adaptive belt-rib airfoils, *Aerospace Science and Tech*, 2005, **9**, (1), pp 55-63.
193. CAMPANILE, L.F. AND SACHAU, D. Belt-rib concept: a structronic approach to variable camber. *J Intelligent Material Systems and Structures*, 2000, **11**, (3), pp 215-224.
194. MCLENDON, W.R. Investigation into wing structure and composite fabrication, 2005, Department of Aerospace Engineering, Texas A&M University.
195. WOOTTON, R.J. The mechanical design of insect wings, *Scientific American*, 1990, **263**, (5), pp 114-20.
196. WOOTTON, R.J. Functional-morphology of insect wings, *Annual Review of Entomology*, 1992, **37**, pp 113-140.
197. WOOTTON, R.J. Support and deformability in insect wings, *J Zoology*, April 1981, **193**, pp 447-468.
198. BAKER, D., FRISWELL, M.I. and LIEVEN, N.A.J. Active truss structures for wing morphing, 2005, ECCOMAS Thematic Conference on Smart Structures and Materials, Lisbon, Portugal.
199. HUTCHINSON, R.G., WICKS, N., EVANS, A.G., FLECK, N.A. and HUTCHINSON, J.W. Kagome plate structures for actuation, *Int J Solids and Structures*, 2003, **40**, (25), pp 6969-6980.
200. TREASE, B.P. and KOTA, S. Synthesis of adaptive and controllable compliant systems with embedded actuators and sensors, 2006, ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Philadelphia, PA, USA.
201. LU, K.J. and KOTA, S. Design of compliant mechanisms for morphing structural shapes, *J Intelligent Material Systems and Structures*, 2003, **14**, (6), pp 379-391.
202. WEISS, P. *Ahead of the curve: Novel morphing wing may reduce aircraft's fuel use*, *Science News*, 2006, pp 406-407.
203. HETRICK, J.A., OSBORN, R.F., KOTA, S., FLICK, P.M. and PAUL, D.B. Flight testing of misson adaptive compliant wing, 2007, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, USA.