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Development, design and applications of structural capacitors

D.D.L. Chung

Composite Materials Research Laboratory, Department of Mechanical and Aerospace Engineering, University at Buffalo, The State University of New York, Buffalo, NY 14260-4400, USA

HIGHLIGHTS

- Structural capacitors are multifunctional structural materials.
- They provide the capacitor function for the purpose of electrical energy storage.
- This paper reviews the scientific development of structural capacitors.
- This paper also enunciates the design and applications of structural capacitors.
- Structural capacitors will provide an untapped form of energy storage.

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ABSTRACT

Structural capacitors are multifunctional structural materials that provide the capacitor function for the purpose of electrical energy storage. This paper reviews the development of structural capacitors and enunciates their design and applications. A structural capacitor is commonly a polymer-matrix structural composite with a dielectric film between the electrodes, which are an electronic conductor, commonly the continuous carbon fiber laminae that serve to reinforce the composite. The dielectric film is preferably small in thickness and serves to avoid short circuiting of the two electrodes. In order to maximize the capacitance by having the structural capacitor constitute capacitors in parallel, the dielectric film is preferably positioned at every interlaminar interface of the composite, such that alternating electrodes in the stack are connected to opposite polarities of the AC electric field source. A structural supercapacitor requires the matrix to be a solid electrolyte. From the viewpoints of structural performance, safety, service life and high frequency capability, structural dielectric capacitors are closer to commercialization readiness than structural supercapacitors. Structural capacitors have not yet been commercialized, but they are expected to provide an untapped, extensive, save and distributed means of energy storage, and allow aircraft, satellites, automobile, ships, wind turbines, buildings, solar panels, display panels, outdoor lighting, computers, cell phones, etc., to store energy in their structures.

1. Introduction

Due to the intermittent nature of the generation of electrical energy by photovoltaics, wind and other renewable energy sources, the storage of the generated electrical energy is needed. By storing the energy, energy can be available at times when no energy is generated by the renewable energy source. In addition, energy storage is needed to help manage the energy utilization of the electrical grid. The demand for electricity varies by hour, day and season. The energy management involves monitoring the electricity demand, supply, reserve margins and the mix of electricity generating technologies. For such energy management, large-scale energy storage is needed. Large-scale energy storage is to be distinguished from small-scale energy storage that is used to power devices such as sensors.

The global energy storage market is growing significantly to an annual installation size of 6 GW in 2017 and over 40 GW by 2022 [1]. This growth is from an initial base of only 0.34 GW installed in 2012 and 2013 [1]. In particular, the California Public Utilities Commission has approved a target that requires the three largest investor-owned utilities, aggregators, and other energy service providers in California to procure 1.3 GW of energy storage by 2020 [1].

Current technologies for energy storage [2–6] include batteries (electrochemical devices in which energy is stored in the form of chemical energy, e.g., lithium-ion, sodium-sulfur and lead-acid batteries) [7–11], flow batteries (rechargeable batteries that involve two chemical components dissolved in liquids that are contained within the system

E-mail address: ddlchung@buffalo.edu.
URL: http://alum.mit.edu/www/ddlchung.

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and most commonly separated by a membrane, such that each liquid circulates in its own respective space, e.g., vanadium redox and zinc-bromine flow batteries) [12–18], supercapacitors (electrochemical devices in which energy is stored in the form of electrical energy) [9,11,19,20], flywheels (device involving accelerating a rotor or flywheel to a very high speed and maintaining the energy in the system as rotational energy) [3,21,22], compressed air energy storage (device based on the principle that the compression of air creates heat and the expansion of air removes heat) [23–27], thermal energy storage (using stored excess heat to obtain energy when it is needed) [21,22,28–32] and pumped hydropower (energy derived from falling water or fast running water) [26,33]. For large-scale energy storage, scale-up is necessary. Compressed air energy storage and pumped hydropower are relatively suitable for scale-up. However, both underground compressed air energy storage and pumped hydropower energy storage are limited by geological and environmental constraints. Intense research is ongoing concerning energy storage using batteries, supercapacitors, flywheels and thermal means.

In order for batteries and capacitors to be able to provide large-scale energy storage, the size of these devices must be increased greatly. Such an increase can be enabled by the use of large structures as the form of these devices. This means that the structure serves not only the structural function, but also the energy storage function. Such multifunctional structures are known as structural batteries and structural capacitors. A further advantage of such multifunctional structures is that weight and volume are not issues, as the devices effectively vanish in the structures. Furthermore, the multifunctional structures enable energy storage to occur in a spatially distributed fashion (as in community energy storage that is grid-connected and utility owned and operated) rather than being limited to centralized locations, thereby increasing the total capacity of energy storage.

The operation of a capacitor does not involve energy conversion, as only electrical energy is involved, but the operation of a battery involves the conversion between chemical energy and electrical energy. Due to this energy conversion, a disadvantage of batteries is that the electrochemically active species can be depleted after a period of use and hence the battery ceases operation. This disadvantage is particularly serious for structural batteries, as a structure may be required to be in service for decades.

Capacitors excel in their high power capability, whereas batteries excel in their high energy capability. This difference in behavior is commonly expressed in terms of the Ragone plot. High power is needed for electric vehicles, hybrid vehicles, electric drive-trains, aircraft powertrains and shipboard power systems that need high power for acceleration. It is also needed for electric and hybrid propulsion systems, for regenerative braking (which helps improve the fuel efficiency of a vehicle that is operated under a stop-and-go urban driving condition), and for equipment that needs high pulse power, such as rail guns, electromagnetic armor and airborne lasers. Energy storage is also needed for self-powered structures and for structures that need emergency power.

There are two main types of capacitors, namely dielectric capacitors (also known as electrostatic or electrolytic capacitors) and supercapacitors (also known as ultracapacitors). The former is purely electrical in nature, whereas the latter is electrochemical in nature. Due to its electrochemical nature, a supercapacitor requires an electrolyte, which complicates multifunctional structural material design, limits the service life and poses safety concerns. In contrast, a dielectric capacitor does not involve any electrolyte. Since service life and safety are essential for structural capacitors, dielectric structural capacitors are more promising than structural supercapacitors, in spite of the fact that the capacity for small-scale energy storage tends to be greater for a supercapacitor than a dielectric capacitor.

Among supercapacitors, there are two types, which are the electric double layer capacitor (symmetrical, with the two electrodes being the same in composition) and the pseudocapacitor (asymmetrical, with the two electrodes being different in composition, so that a redox reaction as in a battery contributes to the capacitance). In relation to structural supercapacitors, both types suffer from the problems related to service life and safety.

The rendering of the capacitor function to a structural material makes the material multifunctional. The multifunctionality is attractive for smart structures. Non-structural functions that have been reported include strain/stress sensing [34], structural health monitoring [35], electric power generation [36,37], energy storage [38–47], heat dissipation [48], deicing [49] and vibration damping [50]. The attainment of multifunctionality without the embedment or attachment of devices (e.g., strain gages, commercial capacitors, commercial batteries, etc.) is particularly attractive. Compared to the use of devices, it gives lower cost, higher durability and absence of mechanical property loss.

Because of the desire for saving weight, a low-density structural material is commonly attractive. Thus, continuous fiber polymer-matrix composites [51], which are well-known for their combination of low density, high elastic modulus and high strength, are attractive for serving as the base material for modification to render the capacitor function. This review is thus focused on structural capacitors in the form of polymer-matrix composites.

The objective of this paper is to review the development of structural capacitors, with particular attention on the engineering design and applications. Engineering design is a practically important area that has not been enunciated coherently in prior work. The applications are critical to the implementation of the technology, but they have not been given the needed attention.

2. Polymer-matrix structural composites

The dominance of polymer-matrix composites among composites with various matrices (polymer, carbon, ceramic, metal, cement, etc.) stems from the relative ease (low cost) of fabrication and the relatively good bonding ability of polymers. Applications include aircraft, unmanned aerial vehicles, satellites, automobile, sporting goods, wind turbines, structural repair, etc.

The continuous fibers that are most commonly used for structural composites are carbon fiber, glass fiber and Kevlar (polyaramid) fiber. Carbon fiber is advantageous is its high tensile modulus and the low magnitude of the coefficient of thermal expansion, as well as its high temperature resistance, chemical resistance, electrical conductivity and thermal conductivity. In particular, the electrical conductivity is valuable for structural capacitors, as the carbon fibers can be used as the electrodes in the capacitor.

Continuous fiber polymer-matrix composites are structural composites that exhibit excellent mechanical performance, as widely used in advanced composites, such as those for airframes. Discontinuous fibers are not as effective as continuous fibers as a reinforcement, due to the imperfect bond between the fibers and the matrix. Nanofibers and nanotubes are not as effective as continuous fibers as a reinforcement, due to their discontinuity, limited degree of alignment, and limited volume fraction in a composite. In contrast, due to their continuity, high degree of alignment, and high volume fraction in a composite, continuous fibers are highly effective as a reinforcement. On the other hand, nanofibers and nanotubes can be used as a secondary reinforcement in a composite that contains continuous fibers as the primary reinforcement. Depending on the combination of the primary and secondary reinforcements, the secondary reinforcement serves to improve properties such as the vibration damping ability, electrical conductivity, thermal conductivity and dimensionless thermoelectric figure of merit [36,37,50,52,53]. The combined use of continuous fibers and nanofillers in the same composite provides hierarchical (multi-scale) composites.

Continuous fiber polymer-matrix composites that exhibit high mechanical performance are primarily of one of two forms. These forms include (i) multidirectional fiber laminates (made by the stacking and