Chapter 8

Conclusions and Future Outlook

8.1 Conclusions

This dissertation has described the dynamic response and rate effects in CNT foams with different microstructures. Our experiments have revealed correlations between variations of key structural features at the micro- and nano-scales and the foams' bulk functional properties and deformation mechanisms. To this end, we fabricated various CNT foams with different morphologies, bulk densities, microscale heterogeneities and microstructural geometries using standard CVD techniques and photolithography techniques. We studied their structure-function relations in the dynamic loading regime using the experimental platform we developed.

Using these CNT foams with engineered microstructures, we have shown that the bulk properties can be tailored significantly either by varying the bulk density and morphology or by engineering micro-architectures that take advantage of principles of structural mechanics. We identified which fundamental deformation mechanisms of structural features at different lengthscales are responsible for the bulk mechanical properties of the foams and their energy dissipative characteristics. For example, when the bulk VACNT foams undergo macroscale compression, the bundles of VACNTs buckle collectively in a sequential progressive fashion at the mesoscale. At the microscale, individual CNTs undergo bending and buckling, and at the nanoscale, CNT walls exhibit buckling-induced wrinkles. These structural deformation mechanisms specific to different geometries and structures can be exploited in order to enhance the bulk functional properties in the design of new materials. For example, we have shown that the stiffness and the specific energy absorption of VACNT foams can be significantly increased, while simultaneously reducing their density appreciably, by introducing microscale patterns of concentric tubes at the mesoscale. Similarly, engineering few-micrometers-thick heterogeneous bands in the VACNT foams can provide unique deformation responses. For instance, a microscale intermediate band with low-density and high-compliance in the VACNT foams can act as a deformation arrest barrier and result in controlled deformations.

We also identified rate-sensitive responses in different loading regimes. VACNT foams, for instance, exhibit rate-independent stress-strain responses in the quasistatic regime, rate-independent loading and rate-dependent unloading responses in low-velocity (sub-critical velocity) impacts and support shock formation in high-velocity (super-critical velocity) impacts. This knowledge of rate-sensitive material behavior can provide guidelines for the design of new materials with enhanced performance at specific loading regimes.

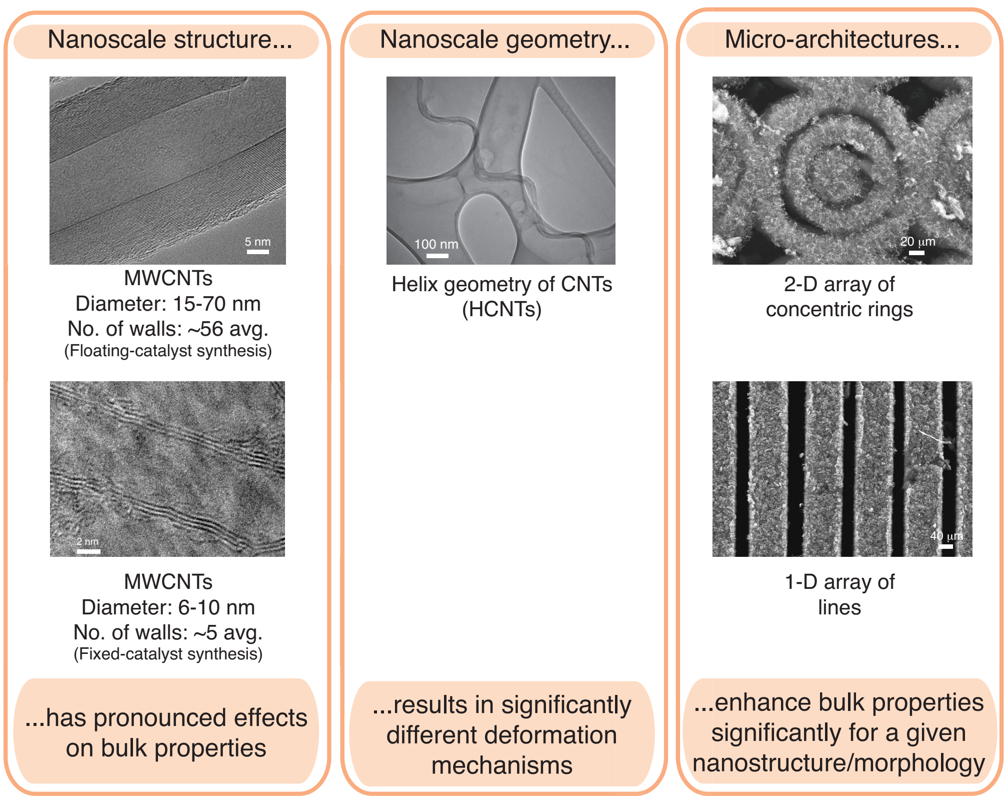

Figure 8.1. Synopsis of the key-findings.

Our studies have shown that VACNT foams have superior dynamic mechanical properties and energy dissipative characteristics that are desirable for protective applications. Their functional properties and deformation responses are sensitive to their micro- and nano-structures that can be tailored significantly for desired applications. As shown in Figure 8.1, we have found that the density of the CNT foams affects the bulk mechanical properties significantly and it can be varied through modifying the nanostructure (number of walls and diameter) of the MWCNTs. Modifying the nanoscale geometry of the CNTs from the usual straight to helical coil geometry does not affect the bulk properties significantly. However, the coil-geometry leads to unique rate-sensitive deformation mechanisms and improved elasticity compared to straight-geometry. Moreover, given a particular nanostructure and morphology, engineering the VACNT foam's structure in the mesoscale using periodically ordered structural geometries could have pronounced effect on their bulk mechanical properties. For example, the periodic arrays of concentric ring patterns have shown the highest specific energy absorption at ultra-low-densities. Their performance surpasses that of the continuous VACNT foams and many other crashworthy foam materials reported in literature (see Figure 5.5).

Above all, the VACNT foams have the ability to recover very high deformations of over a strain of 80%, a feature that is not present in other crashworthy materials—e.g.: metallic foams, carbon fiber tubes, stiff polymer foams, etc.—as they undergo plastic deformations or permanent crushing during the first impact itself. As this dissertation demonstrated, the micro and mesoscale interactions within the ensemble of CNTs lead to remarkable recovery of the bulk sample, even when the sample experiences damage/fracture at the nano and microscales during dynamic compression. Such phenomenal impact resilience of VACNT foams offers new pathways for engineering efficient crashworthy materials that can survive multiple impacts. The fundamental understanding developed in this dissertation concerning the relationships between the structural organizations at different lengthscales and the bulk functional properties of CNT foams could help in guiding the design of engineering materials and systems using hierarchical materials with fibrous morphology.

8.2 Future outlook

This dissertation provides new insights into the design, synthesis and high strain-rate mechanical characterization of novel materials for protective applications, which can be extended in different directions. A few prospects of the research presented in this dissertation are discussed below.

Experimental technique: The dynamic testing platform we developed during this study is not limited to characterizing the CNT foams alone and can be used to characterize many other soft, complex and/or hierarchical materials. With fewer modifications to the loading apparatus, the setup can also be applied to study stiffer structured materials. It can serve as a powerful tool to study the rate sensitivity and the complex microscale deformation mechanisms in hierarchical and structured materials, even with small sample sizes. Improving the current setup to accommodate very high strain rate deformations will enable the characterization of materials in the shock regime and allow the development of a complete description of shock Hugoniot. The shock Hugoniot for a material can be represented by the relationships between the shock velocity and the impact velocity or the Hugoniot strain (strain behind the shock) and the impact velocity. When these descriptions are found, all the mechanical parameters can be calculated without resorting to an assumed constitutive model [153].

Preconditioning effects in VACNT foams: One of the fundamental questions that needs further investigation is the source of the preconditioning effects that were observed in the cyclic stress-strain response of the VACNT foams. As previously described, when VACNT foams are subjected to multiple cycles of loading and unloading, the consecutive cycles differ significantly from the first cycle, exhibiting much narrower hysteresis. This preconditioning effect is commonly found in many synthetic and biological materials with hierarchical microstructures. In VACNT foams, the source of this preconditioning is often attributed to microstructural rearrangements of the CNT fibers within the foam sample. However, this claim stands without concrete experimental evidence (so far) to support it. One possible experimental tool that can facilitate probing into such a fundamental question would be Raman spectroscopy [204–206]. Characterizing the VACNT foams using Raman spectroscopy before and after deformation, or performing an *in-situ* Raman spectroscopy during cyclic mechanical tests, could provide further insights into the source and nature of preconditioning effects on hierarchical materials with fibrous morphology.

Composites of VACNT foams: This dissertation focused on investigating freestanding CNT foams and structures to understand the response of such materials at different length and time scales. However, when considering commercial applications, these CNT foams and structures are likely to be embedded in polymers or other materials, forming a composite. Future research could employ the fundamental understanding provided by this dissertation to the structure-function relations of soft materials to design composite materials with enhanced/tailored mechanical properties.

Numerical modeling: The one-dimensional multi-scale mass-spring model of VACNT foams is different from other bi-stable spring models, since it includes an intermediate mesoscale dissipative element in between the microscale bi-stable springs and the sample's macroscale. The model could be extended in the future to capture other phenomena such as preconditioning, Mullins-like effect, permanent deformations and rate-dependent bulk responses. One of the main advantages of the model is that it enables mechanical parameter identification in length scales that are much smaller than the sample height. Therefore, it can be employed to model the response of multilayered structures and to identify local mechanical parameters within each layer. Even though the model is used here to describe the VACNT foam's responses, it could be generalized to model many other hierarchical materials and foams with large hysteresis.