ABSTRACT

Restrepo Arango, David. Ph.D., Purdue University, December 2015. Programmable Cellular Materials. Major Professor: Pablo Zavattieri.

In this dissertation a new class of programmable materials based on cellular solids is introduced. Programmable materials refer to a group of materials whose effective mechanical properties can be modified after manufacturing without any additional reprocessing.

Programming of cellular solids is achieved by the introduction of controlled geometrical changes (also called programmed imperfections) into some or all the unit cell that forms the cellular microstructure, increasing the range of available properties on the baseline material. Programming of these materials is limited on the ability to lock the programmed imperfections. Two concepts of programmable materials are studied: (i) programmable materials where geometrical changes induced during programming are locked by the base material behavior (e.g. plastic/permanent deformation or shape memory effect) and (ii) programmable materials whose cellular microstructure exhibit multiple stable/metastable configurations. Hence, programmed morphological changes are lock by triggering changes of the cellular microstructure between stable configurations.

For the first concept, two programmable material systems are studied: a bending dominated honeycomb with a hexagonal unit cell and a stretching dominated honeycomb with a kagome unit cell. Locking of programmed morphological changes can be reversible or irreversible. In this study both material systems were fabricated out of shape memory polymer (SMP). These are materials with the ability to fix (or lock-in) a temporary deformation over an extended period of time and recover their original configuration in response to a thermo-mechanical programming process. As such, these cellular materials were programmed using the standard shape fixing process for SMPs and programming can be reversible. Experimental results of these systems show that significant changes in the effective mechanical properties can be attained with low levels of programmed morphological changes. For instance, a programmed imperfection corresponding to a global compressive strain of 5% in the bending dominated system leads to a 55% increase in initial in-plane effective elastic Young's modulus, a 81% increase in the propagation stress for in-plane compression and a 30% reduction in the out-of-plane effective flexural modulus. Further analysis of the same material systems using full scale finite element simulations, allowed to determine that programming is robust to exogenous factors like: boundary conditions, strain rates due to the viscoelastic nature of the base material and sample size; and defects derived from fabrication and handing like: wall thickness variations, joint fillets, joint misalignments and broken walls.

The second concept of programmable materials presented in this dissertation is achieved by designing cellular microstructures comprised by building blocks that exhibit bistable or metastable configurations. The mechanical behavior of these materials is analogous to the behavior of materials that undergo phase transformations, hence; this type of programmable materials is called phase transforming cellular materials or PXCMs. The key elements of the unit cell geometry to yield phase transformations is presented together with an analytical model that describes its constitutive behavior for these materials. Validation of the analytical constitutive model is made by combining experimental testing and finite element simulations. Extending the concept of phase transformations to programmable cellular materials, allow obtaining materials that exhibit a long serrated loading and unloading plateaus and hysteresis. A PXCM formed by two sinusoidal beams is presented. Using the concept of loss factor (η) as a measure of the ability of a material to dissipate energy when subjected to cycling loading, the sinusoidal PXCM presents a maximum η=0.23, which represents an amplification of 100-1000 times the one of the base material. On contrast, commercially available metal foams only produce amplification factors of 5-10 times. Studies of energy dissipation under in-plane crushing loading for the same PXCM, showed that these materials offer an energy absorption performance that is comparable to metal and polymeric honeycombs. However unlike these honeycombs, where energy absorption is due to plastic deformation, the base material of the PXCM remains in the elastic regime, hence, the deformation is fully recoverable.

Programming of cellular solids adds versatility to these materials by extending the range of the available properties of the baseline material. The concepts presented in this research to obtain programmable cellular materials set the foundations to enable the design of high performance systems that can be adapted in response of changes in loading and environmental conditions. Consequently, it is expected that these materials impact key industries and application areas ranging from structures with integrated energy absorption, energy harvesting, wave beaming capabilities, to adaptive catalyst substrates, soft robotics and shape morphing.