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Modeling, Topology Optimization and Experimental Validation of Glass-Transition-Based 4D-Printed Polymeric Structures

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Abstract : In recent developments in the field of multi-material additive manufacturing, differences in material properties are exploited to create printed shape-memory structures, which are referred to as 4D-printed structures. New printing techniques allow for the deliberate introduction of prestresses in the specimen during manufacturing, and, in combination with the right design, this enables new functionalities. This research focuses on bi-polymer 4D-printed structures, where the transformation process is based on a heat-induced glass transition in one material lowering its Young's modulus, combined with an initial prestress in the other material. Upon the decrease in stiffness, the prestress is released, which results in the realization of an essentially pre-programmed deformation. As the design of such functional multi-material structures is crucial but far from trivial, a systematic methodology to find the design of 4D-printed structures is developed, where a finite element model is combined with a density-based topology optimization method to describe the material layout. This modeling approach is verified by a convergence analysis and validated by comparing its numerical results to analytical and published data. Specific aspects that are addressed include the interplay between the definition of the prestress and the material interpolation function used in the density-based topology description, the inclusion of a temperature-dependent stiffness relationship to simulate the glass transition effect, and the importance of the consideration of geometric nonlinearity in the finite element modeling. The efficacy of topology optimization to design 4D-printed structures is explored by applying the methodology to a variety of design problems, both in 2D and 3D settings. Bi-layer designs composed of thermoplastic polymers are printed by means of the fused deposition modeling (FDM) technology. Acrylonitrile butadiene styrene (ABS) polymer undergoes the glass transition transformation, while polyurethane (TPU) polymer is prestressed by means of the 3D-printing process itself. Tests inducing shape transformation in the printed samples through heating are performed to calibrate the prestress and validate the modeling approach by comparing the numerical results to the experimental findings. Using the experimentally obtained prestress values, more complex designs have been generated through topology optimization, and samples have been printed and tested to evaluate their performance. This study demonstrates that by combining topology optimization and 4D-printing concepts, stimuli-responsive structures with specific properties can be designed and realized.

Keywords : 4D-printing, glass transition, shape memory polymer, topology optimization
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