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SINGLE VERSUS DOUBLE PHASE RESPONSE OF POLYMER-BASED ARCHITECTED COMPOSITE MATERIALS

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Abstract. The current contribution investigates the response of polymer-based, single and double-phase composite architected materials under static and low strain-rate loadings. The two material phases employed have elastic stiffness attributes that differ by more than two orders of magnitude in their static performance, one of them being particularly soft, with an elastic modulus of less than half a mega-Pascal. The Schoen's IWP lattice and random function stochastic sheet-based, single and double phase static responses are initially compared, establishing the substantial strengthening role of the second-soft material phase in the overall performance. Subsequently, the response of the double phase IWP and random function stochastic composite designs at a loading speed of 0.025 m/s are investigated. Thereupon, increased elastic modulus, plateau stress and overall energy absorption is observed. It is shown that the effective mechanical properties at a loading rate of 0.025 m/s are nearly two times higher than the static ones in terms of elastic attributes with the isotropic random function stochastic design to yield comparable energy absorption with the one obtained for the cubic symmetry double-phase IWP design.

Keywords: Composites; Additive manufacturing, Static; Strain-Rate; Mechanical properties

1 INTRODUCTION

Composite materials with interpenetrating phases, each of them having distinct mechanical properties have been shown to yield an effective mechanical response that well exceeds the

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one of their individual components [1], [2]. Typically, composites are created as a combination of hard and soft phase materials, with the topology of the hard phase to either follow continuous or regular architected designs [2], [3]. Up to now, different combinations of material components have been investigated including metal-polymer architectures upon a wide range of additive manufacturing methods [4].

The primal motivation for their development has been the possibility of performance increase upon reduced structural weights, notably expressed in enhanced energy absorption attributes and substantial plastification capabilities infeasible for single phase designs [5], [6]. However up to now, the double phase soft and strong polymeric based architected composite designs have not received considerable attention . In particular, the performance enhancement arising from the addition of a second soft material phase remains poorly understood with respect to the static loading case. What is more, the effect of low strain rates on the arising mechanical properties remains unknown. The current contribution quantifies the role of the soft phase addition for regular IWP and stochastic random function based architectures on the static and low loading rate effective mechanical properties. Differences in the elastic moduli, plateau stress and energy absorptions are reported, deriving important conclusions on the behavior of double-phase (DP) architected composite materials.

In Section 2, insights in the topologies and base static material properties employed are provided, while stress-strain curves of the static response are presented in Section 3. Concluding remarks are made in section 4.

2 MATERIALS AND METHODS

The double-phase composite material is composed of a hard phase that follows either an IWP triply periodic minimal surface topology or a random function stochastic iso-surface. In each case, the hard phase topology is defined as follows:

$$\varphi_{IWP}\left(x,y,z\right): 2\cdot\left(\mathrm{c}x\cdot cy+cy\cdot cz+\ cz\cdot cx\right)-\left(c2x+c2y+c2z\right)\ =t \tag{1}$$

$$\varphi_{stochastic}\left(\bar{X}\right)=\sum_{i=1}^{m}w_i(\bar{X}).\varphi_{IWP}\left(\bar{X}\right),\ w_i(\bar{X})=\left(1+\exp\left(k\left(\left\|\bar{X}-\bar{X}_j\right\|^2\right)\right)\right)/\sum_{j=1}^{m}\left(1+\exp\left(k\left(\left\|\bar{X}-\bar{X}_j\right\|^2\right)\right)\right) \tag{2}$$

Where in Eq. (1), the cx, cy and cz stand for the cosines of the x, y and z Cartesian coordinates adjusted to account for the number of unit-cells, dimensions and shape of the material, while $c2x$, $c2y$ and $c2z$ take 2 times the coordinates of the previously defined cosine terms. The stochastic variants of the base structure (Eq. (2)) are created through weight functions $w_i\left(\bar{X}\right)$ which modify the material distribution of the subdomain i to which the base IWP topology is assigned. The transition among the subdomains is controlled by the transition parameter k, here set to 0.1 for a smooth transition among the subdomains. Further details on the parametric construction of the metamaterial topologies can be found in [1], [7]. The single-phase topologies of both metamaterial architectures along with the double-phase additively manufactured samples are provided in Figure 1.

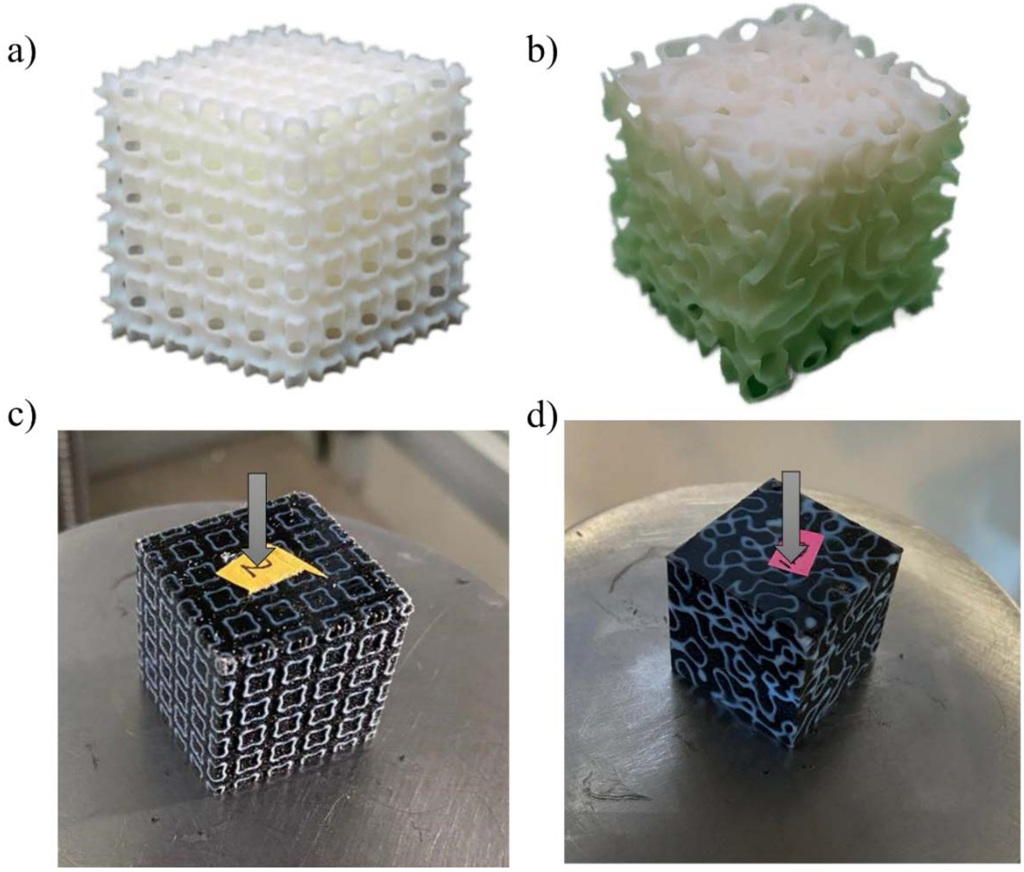

Figure 1: *Single phase IWP (a) and random function Stochastic (b) metamaterial topologies along with the additively manufactured soft (black) and hard (white) double-phase designs (c)-(d)*

Cubic specimens with dimensions of 24 mm were manufactured for all topologies with 5 unit-cell repetitions for the periodic architecture and 15 control points for the random function stochastic. The Stratasys J750 resin-based 3D printer was used for the fabrication of the specimens. The reinforcement phase both for the double-phase IWP and random function stochastic composite materials was based on Vero-white, while Tango-Black as the soft material phase. The static properties of each material phase are summarized in Table 1.

Table 1: Static material properties for the base reinforcement and matrix materials.

Phase/Material	Elastic Modulus (MPa)	Peak Stress (MPa)	Energy Absorption (J/m^3)
Reinforcement/VeroWhite	850	31.6	11.9
Matrix/TangoBlack	0.94	0.6	0.1

The elastic modulus of Table 1 indicates a nearly three orders of magnitude of difference for the reinforcement phase with respect to the matrix material in the static analysis range and more than two orders of magnitude for the energy absorption up to a macroscopic strain of 40%. The mechanical properties of the double phase materials are probed in the static regime with an Instron universal testing regime. For the strain-rate response, a servo electric linear motor machine with a testing speed of 25 mm/s corresponding to a strain rate of approximately 1 s^{-1} for the manufactured specimen dimensions.

3 RESULTS AND DISCUSSION

In Figure 2, the static stress-strain curves of single and double-phase IWP and random function stochastic architectures with a 20% volume fraction of reinforcement material are provided. For each case, two experimental repeats (T1 and T2) are presented, while averaged mechanical attributes are provided in each case. For the elastic modulus computation (Ec), the limiting elastic stresses (σ_{pl}) are denoted, while the toughness (UT) is computed up to an engineering strain magnitude of 40%.

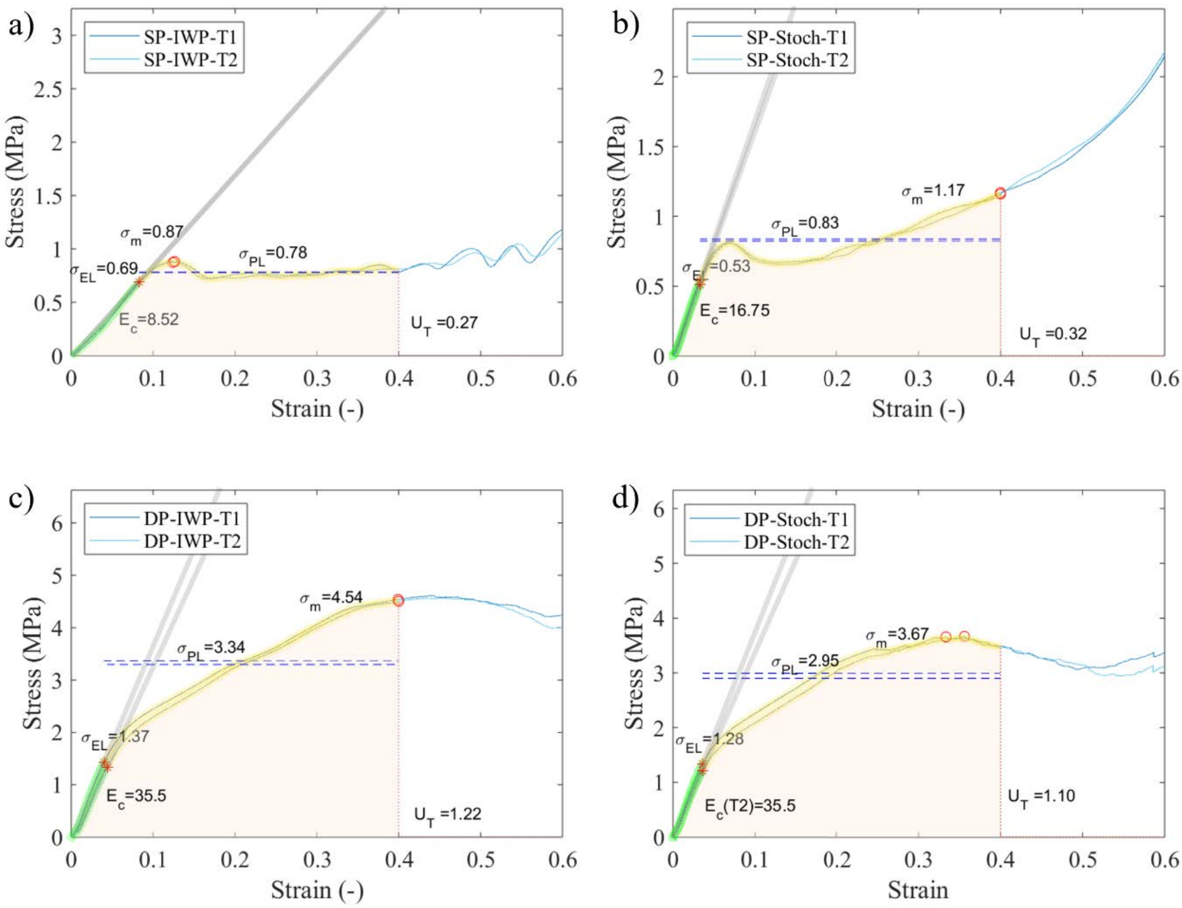

Figure 2:*Static response stress-strain curves for single phase IWP (a) and stochastic (b) metamaterial topologies along with the corresponding double-phase composite material response in (c) and (d) respectively*

The stress strain curves of regular single-phase IWP designs can be well separated from the one of stochastic architectures in their post-elastic performance. In particular, while a nearly flat post-elastic response is observed for the IWP architectures, the stochastic ones yield a substantial stiffening at strain magnitudes beyond 0.15. The post-elastic stiffening becomes more prominent for both regular and stochastic architectures with the addition of the second interpenetrating phase, where an increase from an elastic stress limit of approximately 1.3 MPa in both cases up to a maximum stress of 4.54 and 3.67 MPa of stress takes place within a 30% strain application. Detailed information on the scaling of the properties is provided in Figure 3.

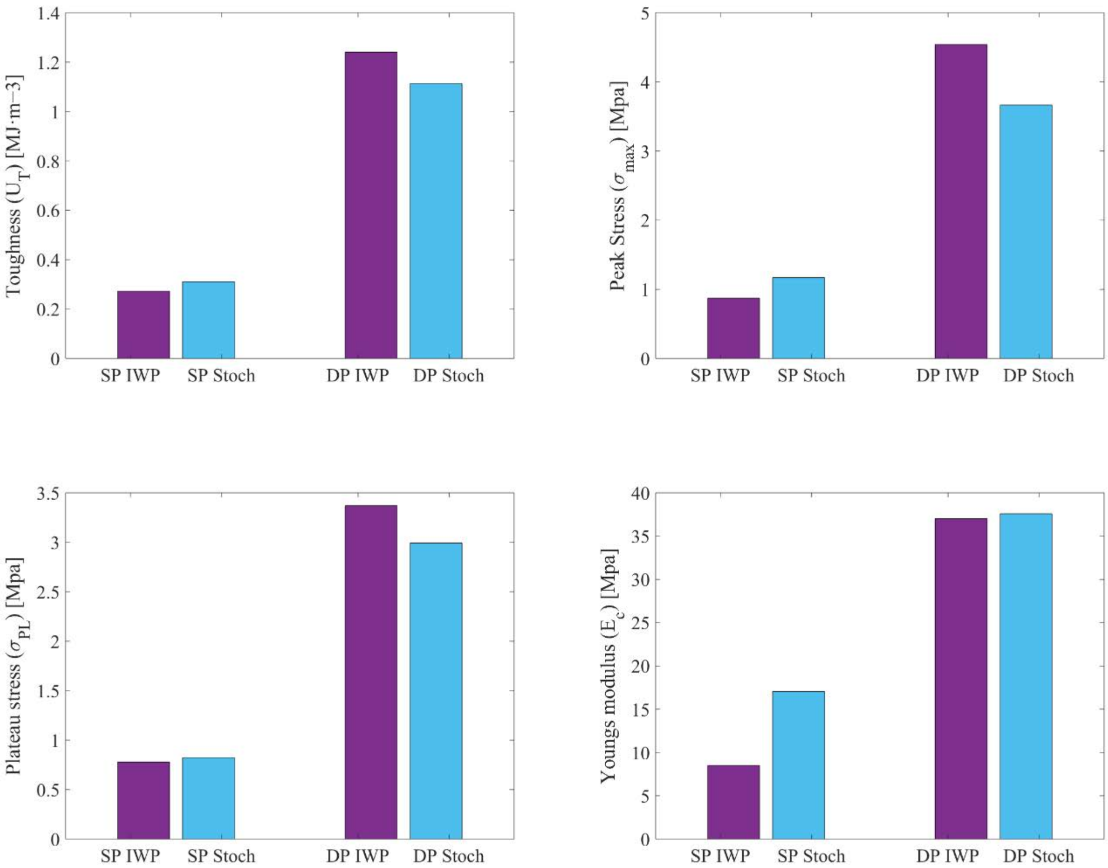

Figure 3*: Effective toughness (a), peak stress (b), plateau stress (c) and Young's moduli (d) for SP and double phase regular IWP and stochastic architectures under static loading with a reinforcement phase content of 20%*

The results of Figure 3 indicate comparable single-phase properties for IWP and Stochastic architectures. In particular, plateau, peak stress and toughness are in the order of 0.8, 1 MPa and 0.3 MJ/m3. Differences appear in the Young's modulus where SP stochastic architectures yield two times higher elastic modulus than SP IWP designs. The latter are smoothened for double-phase architectures, where nearly equal elastic moduli are recorded (36 MPa), more than two times the ones of single-phase designs. However, the plateau, peak stresses and toughness of double-phase regular designs exceed the ones of stochastic DP IWP designs, reverting the single-phase response. In Figure 4, the corresponding effective attributes upon an increased 30% content of the reinforcement phase are provided.

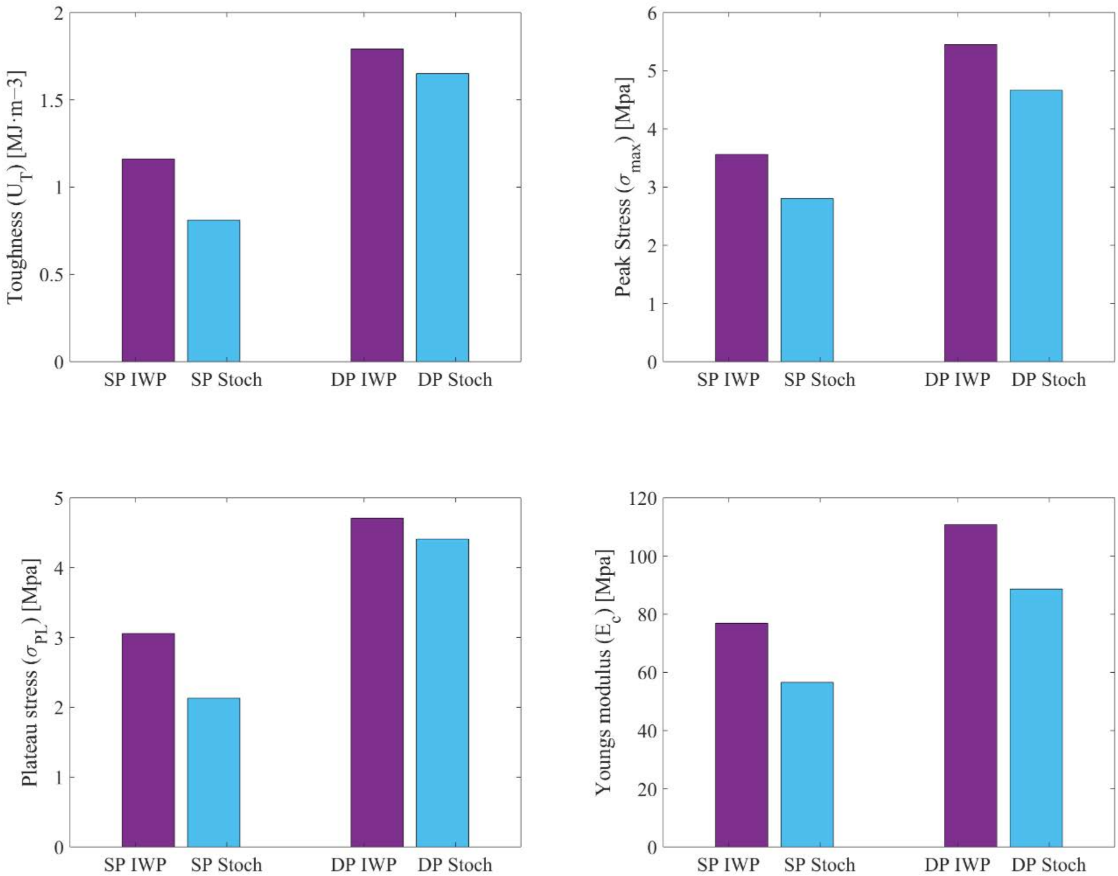

Figure 4*: Effective toughness (a), peak stress (b), plateau stress (c) and Young's moduli (d) for SP and double phase regular IWP and stochastic architectures under static loading with a reinforcement phase content of 30%*

In the increased reinforcement phase volume fraction case (30%), regular single phase IWP designs yield more than three times higher effective plateau, peak stress and toughness attributes compared to the 20% volume fraction case. In particular, the elastic modulus is in the order of 80 MPa, while the overall toughness exceeds 1 MJ/m3 being more than 3 times the ones reported in Figure 3. What is more, regular SP IWP topologies yield overall higher mechanical properties for all effective attributes compared to SP stochastic architectures. The relative differences are smoothened for DP designs, where the modulus of DP IWP designs exceeds 100 MPa, while the plateau and peak stress approach and exceed 5 MPa respectively. In Figure 5, the stress-strain responses of DP IWP and random function Stochastic composite materials with a 30% reinforcement phase content subject to a loading with a speed of 0.025 m/s are provided.

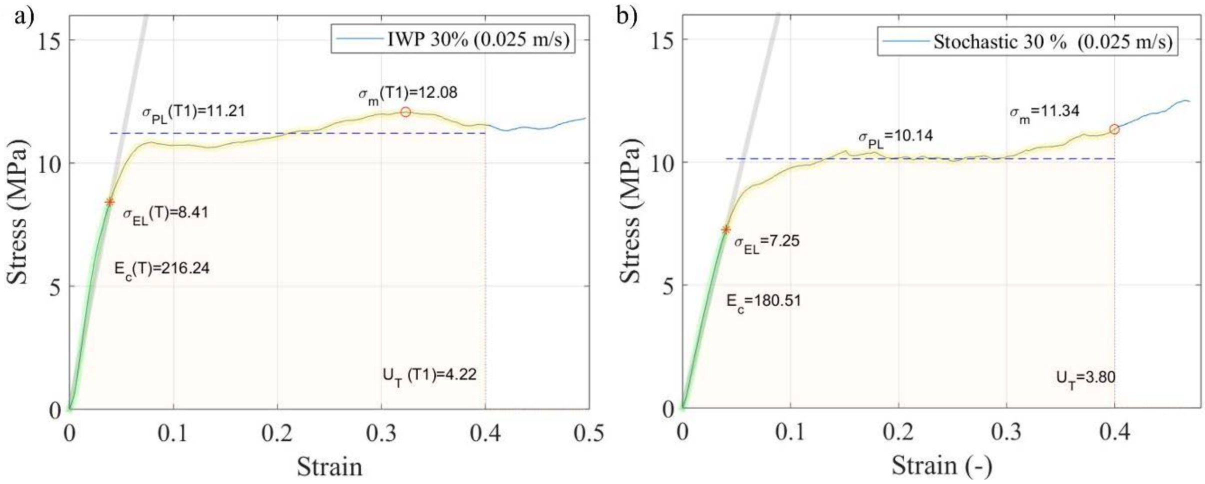

Figure 5*: Stress-strain response of double phase IWP and random function stochastic composite material architectures under a loading speed of 0.025 m/s*

The results of Figure 5 indicate an elastoplastic response for both DP composite material designs with an elastic stiffness that is nearly 2 times the one reported for the static 30% and a plateau stress that is more than 2 times the effective static properties reported in Figure 4. Moreover, the overall energy absorption (toughness) scales with a factor of nearly 3 for both composite designs with the IWP composite architecture to overall outperform the effective properties of the random function stochastic composite material.

4 CONCLUSIONS

Overall, the mechanical response of polymer-based, single and double-phase composite architected materials has been investigated. It has been shown that the addition of a soft phase with elastic properties that are more than two orders of magnitude lower than the ones of the strong reinforcement phase material, substantially modifies the effective static composite response both for Schoen's IWP and random function stochastic reinforcement architectures. Moreover, increased loading rates further enhance the elastic stiffness and overall energy absorption of the double phase composite materials leading to nearly four times higher toughness with respect to the single-phase architectures at a loading speed of 0.025 m/s.

Regular double phase IWP designs outperform the random function stochastic composite material response for the loading rates and reinforcement phase volume fractions investigated.

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