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2D Materials

LETTER

Spider silk reinforced by graphene or carbon nanotubes

Emiliano Lepore[1], Federico Bosia[2], Francesco Bonaccorso[3,4], Matteo Bruna[3], Simone Taioli[5,6], Giovanni Garberoglio[5], Andrea C Ferrari[3] and Nicola Maria Pugno[1,7,8]

[1] Laboratory of Bio-inspired & Graphene Nanomechanics, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, 38123 Trento, Italy
[2] Department of Physics and 'Nanostructured Interfaces and Surfaces' Centre, Università di Torino, Via P. Giuria 1, 10125, Torino, Italy
[3] Cambridge Graphene Centre, University of Cambridge, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, United Kingdom
[4] Istituto Italiano di Tecnologia, Graphene Labs, Via Morego 30, 16163 Genova, Italy
[5] European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Bruno Kessler Foundation and Trento Institute for Fundamental Physics and Applications, Trento, Italy
[6] Faculty of Mathematics and Physics, Charles University, Prague, Czechia
[7] School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
[8] Ket Lab, Edoardo Amaldi Foundation, Italian Space Agency, Via del Politecnico snc, 00133 Rome, Italy

E-mail: nicola.pugno@unitn.it

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Abstract

Spider silk has promising mechanical properties, since it conjugates high strength (~1.5 GPa) and toughness (~150 J g^{-1}). Here, we report the production of silk incorporating graphene and carbon nanotubes by spider spinning, after feeding spiders with the corresponding aqueous dispersions. We observe an increment of the mechanical properties with respect to pristine silk, up to a fracture strength ~5.4 GPa and a toughness modulus ~1570 J g^{-1}. This approach could be extended to other biological systems and lead to a new class of artificially modified biological, or 'bionic', materials.

Introduction

Silkworm silks have been widely used by mankind for millennia, but only recently their mechanical properties and structure have been investigated in depth [1, 2]. An increasing number of studies also focuses on spider silk, due to its promising mechanical (~10 GPa Young's modulus, ~1.5 GPa strength [3, 4], ~100% ultimate strain [5]) and thermal properties (~400 W $m^{-1} \cdot K^{-1}$ thermal conductivity [6]), combined with biocompatibility [7] and biodegradability [5, 7, 8]. This makes it potentially useful in practical applications, such as wear-resistant lightweight clothing [9], bullet-proof vests [10], ropes [11], nets [12], bandages [13], surgical threads [14], artificial tendons or ligaments [15], biodegradable food wraps [16], or rust-free panels on vehicles [17]. E.g., in [18], researchers used individual spider silk fibres braided together to create sutures for flexor tendon repair. Enhanced silk mechanical properties could further improve the fatigue strength and lifetime of these structures.

The production of silk is key to the spiders' evolutionary success and has been perfected over 400 million years [7]. Silk is generally described as a semi-crystalline [19], biocompatible [7], composite biopolymer [5], and comprises the amino acids alanine, glycine and serine, organized into semi-amorphous helical-elastic α-chains and β-pleated nanocrystals [20, 21]. From a mechanical point of view, it is considered amongst the best spun polymer fibres in terms of tensile strength [3, 4] and ultimate strain [5], therefore toughness [11], even when compared with the best performing synthetic fibres, such as Kevlar [22]. Silk spinning involves a number of biological, chemical and physical processes [23], leading to its superior mechanical properties.

The natural presence of biominerals in the protein matrix and hard tissues of insects [24], worms [25] and snails [26] enables high strength and hardness (>500 MPa) of teeth [27, 28], jaws [28, 29], and mandibles [30, 31]. Thus, the artificial incorporation of various nanomaterials in biological protein structures to obtain improved mechanical properties should, in principle, be possible. A number of groups introduced inorganic nanoparticles [32], semiconducting crystals [33] or carbon nanotubes (CNTs) [34] on the surface of spider silk fibres, achieving an

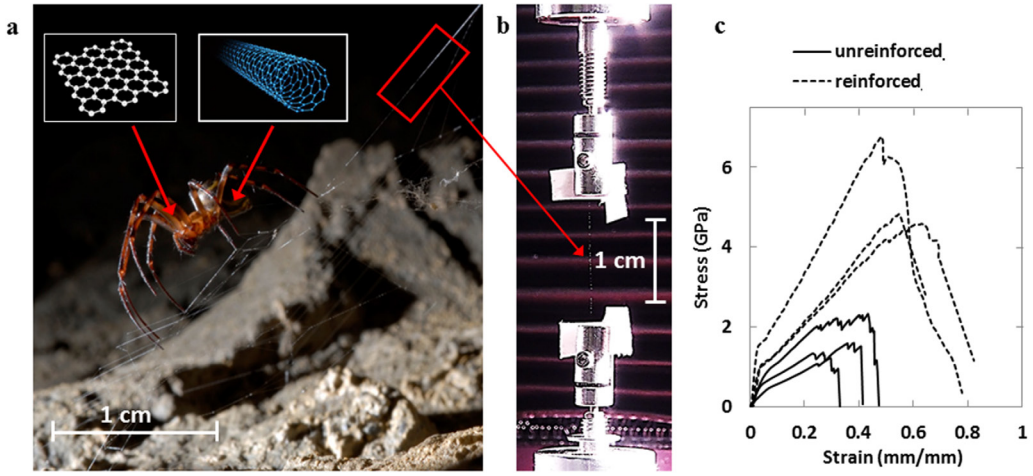

Figure 1. Schematic of the experimental procedure. (a) Spiders are fed with dispersions containing graphene or CNTs, (b) the corresponding spun silk is collected and tested in a nanotensile system; (c) stress–strain curves show improved mechanical properties when compared to pristine samples.

Table 1. Mechanical properties (average values) of RS samples.

Spider n.	Diameter (μm)	Number of threads	Young's modulus (GPa)	Ultimate strain (mm mm^{-1})	Fracture strength (MPa)	Toughness modulus (MPa)
1	0.51 ± 0.10	15	6.0 ± 3.6	0.29 ± 0.12	795.2 ± 500.1	128.2 ± 97.2
2	0.72 ± 0.15	7	27.3 ± 5.0	0.58 ± 0.23	2397.2 ± 635.5	713.0 ± 138.5
3	0.75 ± 0.11	10	13.4 ± 6.9	0.46 ± 0.40	1257.5 ± 1299.3	422.6 ± 567.6
4	0.69 ± 0.06	108	1.9 ± 0.6	1.38 ± 1.11	465.1 ± 119.0	235.6 ± 126.2
5	0.71 ± 0.06	128	3.2 ± 0.8	1.02 ± 0.30	534.7 ± 222.1	172.4 ± 77.4
6	0.72 ± 0.02	2	37.1 ± 19.6	0.28 ± 0.06	4045.9 ± 1391.6	732.1 ± 354.9
7	0.86 ± 0.07	10	15.1 ± 6.4	0.39 ± 0.07	1726.6 ± 565.3	476.4 ± 257.8
8	0.65 ± 0.05	113	2.1 ± 2.0	0.69 ± 0.40	179.7 ± 164.0	61.1 ± 79.3
9	0.51 ± 0.04	95	5.9 ± 5.0	0.53 ± 0.44	580.7 ± 482.9	205.3 ± 179.8
10	0.81 ± 0.09	48	3.0 ± 1.5	0.55 ± 0.08	281.2 ± 179.6	75.3 ± 45.8
11	0.51 ± 0.05	111	24.3 ± 13.5	0.75 ± 0.29	1969.1 ± 1158.8	764.7 ± 640.5
12	0.83 ± 0.06	17	3.1 ± 0.1	0.77 ± 0.10	173.4 ± 0.1	48.9 ± 0.1
13	0.66 ± 0.06	74	5.5 ± 5.0	0.88 ± 0.74	648.6 ± 501.9	320.3 ± 385.8
14	1.02 ± 0.03	64	3.8 ± 1.1	1.71 ± 0.87	364.0 ± 164.1	247.8 ± 111.2
15	0.54 ± 0.02	4	9.2 ± 1.5	0.26 ± 0.06	825.2 ± 182.9	101.8 ± 9.6

enhancement of toughness [35], or novel properties, such as magnetism [32] or electrical conductivity [34]. This type of reinforcement or functionalization could further make silk potentially attractive for a wide range of applications, from garment textiles [9] to sensing devices [34], from medical applications, such as suture threads [14] or tissue regeneration materials [15], to defence applications such as flak jackets [10], currently limited by the silk large deformability [36–39].

Successful attempts to improve the mechanical properties of spider silk have been limited [34, 40]. This is due to the difficulty of developing an adequate spinning methodology, balancing extrusion, drawing, yield and purity [41]. Naturally-spun fibres, obtained by forcible spinning [42], harvesting [43] or extracting spidroin (i.e. the main protein in dragline silk [2]) from glands [44], have reduced mechanical characteristics with respect to naturally-spun ones, e.g. due to the CO_2 anaesthesia of spiders [45] and the consequent loss of active control of their silk spinning [46]. From a technological point of view, wet-spinning [47], electro-spinning [48], hand-drawing [42] or microfluidic approaches [49] have been investigated to produce an artificial silk at the laboratory scale, mechanically [34], structurally [40] or chemically [49] modified with respect to the natural one. However, a critical step is still needed to reach commercial-scale.

Here, we present a method for producing reinforced spider silk directly spun by spiders after their exposure to water dispersions of CNTs or graphene, as schematically shown in figure 1. This leads to improved mechanical properties, and a toughness modulus (defined as the area under the load-displacement curve, from the origin up to fracture [50, 51], per unit mass) surpassing synthetic polymeric high-performance fibres [52] and even the current toughest 'knotted' fibres [53–55].

Table 2. Mechanical properties (average values) of the first collection of silk samples produced after exposure of the spiders to CNTs or graphene (Spiders n. 1–6 with SWNT-1, spiders n. 7–10 with SWNT-2, spiders n. 11–15 with graphene). The largest increments in the silk mechanical properties are observed for spider 5 whereas the highest absolute values are observed for spider 7.

Spider n.	Diameter (μm)	Number of threads	Reinforcement	Young's modulus (GPa)	Ultimate strain (mm mm^{-1})	Fracture strength (MPa)	Toughness modulus (MPa)
1	0.57 ± 0.04	27	SWNT-1	3.9 ± 3.9	0.62 ± 0.65	326.1 ± 150.6	66.7 ± 60.9
2	0.43 ± 0.02	4	SWNT-1	40.1 ± 48.4	0.20 ± 0.16	3914.6 ± 5038.3	587.2 ± 820.3
3	0.77 ± 0.09	72	SWNT-1	8.7 ± 6.9	0.68 ± 0.37	1195.8 ± 1037.5	387.0 ± 384.7
4	0.76 ± 0.07	44	SWNT-1	2.4 ± 0.6	0.95 ± 0.52	579.4 ± 313.1	187.6 ± 66.7
5	0.78 ± 0.08	4	SWNT-1	37.9 ± 4.4	0.60 ± 0.28	3907.2 ± 874.1	1144.0 ± 555.3
6	0.84 ± 0.068	12	SWNT-1	9.6 ± 5.2	0.50 ± 0.24	954.3 ± 278.2	210.2 ± 87.3
7	1.00 ± 0.12	62	SWNT-2	47.8 ± 18.0	0.75 ± 0.09	5393.5 ± 1202.4	2143.6 ± 684.6
8	0.42 ± 0.08	34	SWNT-2	3.1 ± 1.1	0.41 ± 0.11	315.7 ± 124.7	47.8 ± 22.8
9	0.42 ± 0.04	82	SWNT-2	19.3 ± 6.3	0.34 ± 0.14	2034.9 ± 212.8	419.8 ± 96.2
10	0.81 ± 0.09	48	SWNT-2	0.2 ± 0.0	0.32 ± 0.02	20.1 ± 3.5	2.6 ± 1.8
11	0.67 ± 0.02	43	GS	0.8 ± 0.6	0.33 ± 0.19	58.0 ± 22.9	7.9 ± 3.4
12	0.74 ± 0.13	41	GS	4.9 ± 1.1	0.43 ± 0.06	607.5 ± 219.2	148.5 ± 71.6
13	0.66 ± 0.06	74	GS	3.1 ± 1.7	0.52 ± 0.37	421.8 ± 251.3	130.3 ± 129.0
14	1.02 ± 0.03	64	GS	0.4 ± 0.2	0.29 ± 0.08	45.9 ± 17.1	6.0 ± 2.8
15	0.61 ± 0.06	14	GS	13.0 ± 6.5	0.43 ± 0.24	1245.6 ± 559.4	254.7 ± 164.3

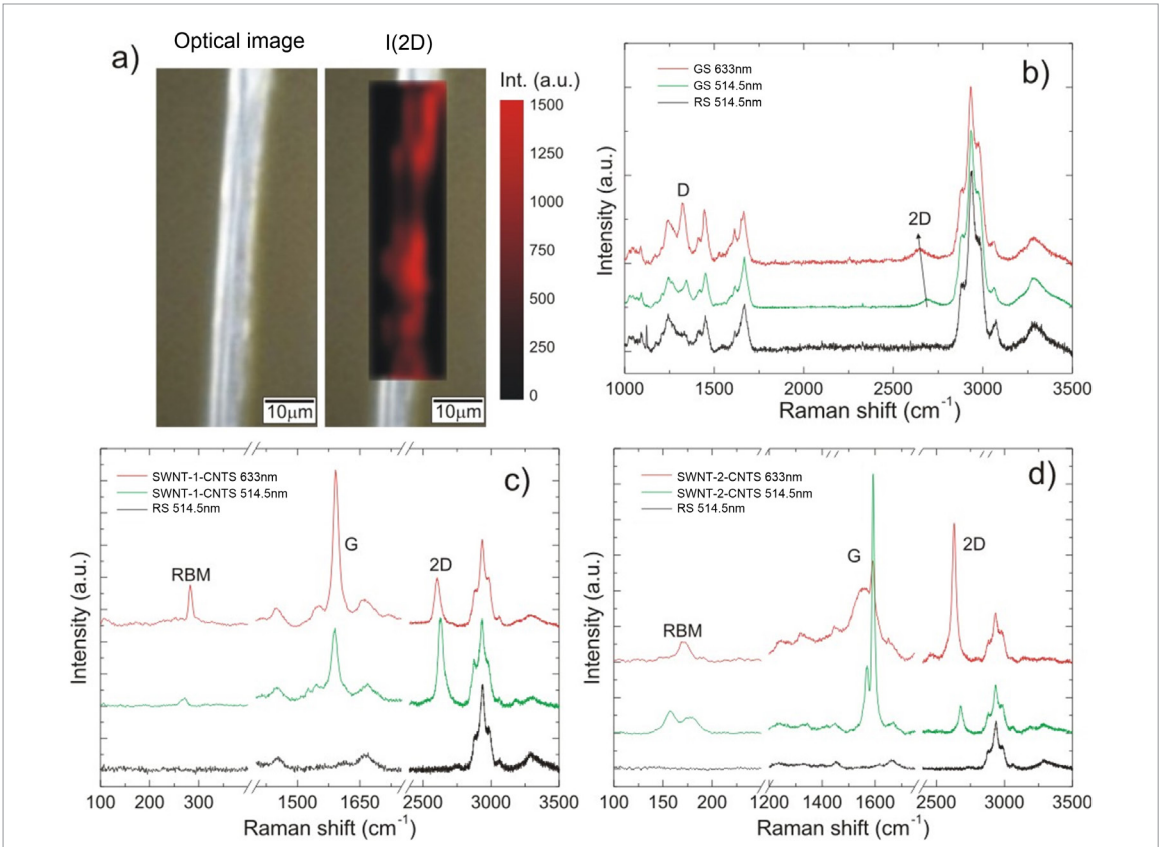

Figure 2. (a) Optical picture of a spider silk fibre suspended by a mechanical support (left) and map of I(2D) overlapped to the optical picture of the spider silk spun by spiders after exposure to graphene (right). (b) Raman spectra of RS (black line, at 514.5 nm), GS at 514.5 nm (green line) and 633 nm (red line). Raman spectra of (c) SWNT-1-CNTS (d) SWNT-2-CNTS at 514.5 nm (green line) and 633 nm (red line) excitation wavelengths.

Results

Two types of CNTs are used in this study. The first is CoMoCAT [56] (~0.6–1.35 nm diameter) single-wall nanotubes (SWNT-1). The second is electric arc discharge SWNTs (P2) from Carbon solutions inc. (SWNT-2). CNT dispersions are prepared by adding 1 mg/10 ml weight-to-volume ratio of each CNT source to an aqueous solution of 2% w/v sodium deoxycholate (SDC, from Sigma-Aldrich Ltd) in deionised water. This surfactant is not harmful for the spiders, as discussed in the supplementary information (SI) (stacks.iop.org/TDM/4/031013/mmedia). De-bundling is obtained via ultrasonication using a Branson Ultrasonic Processor

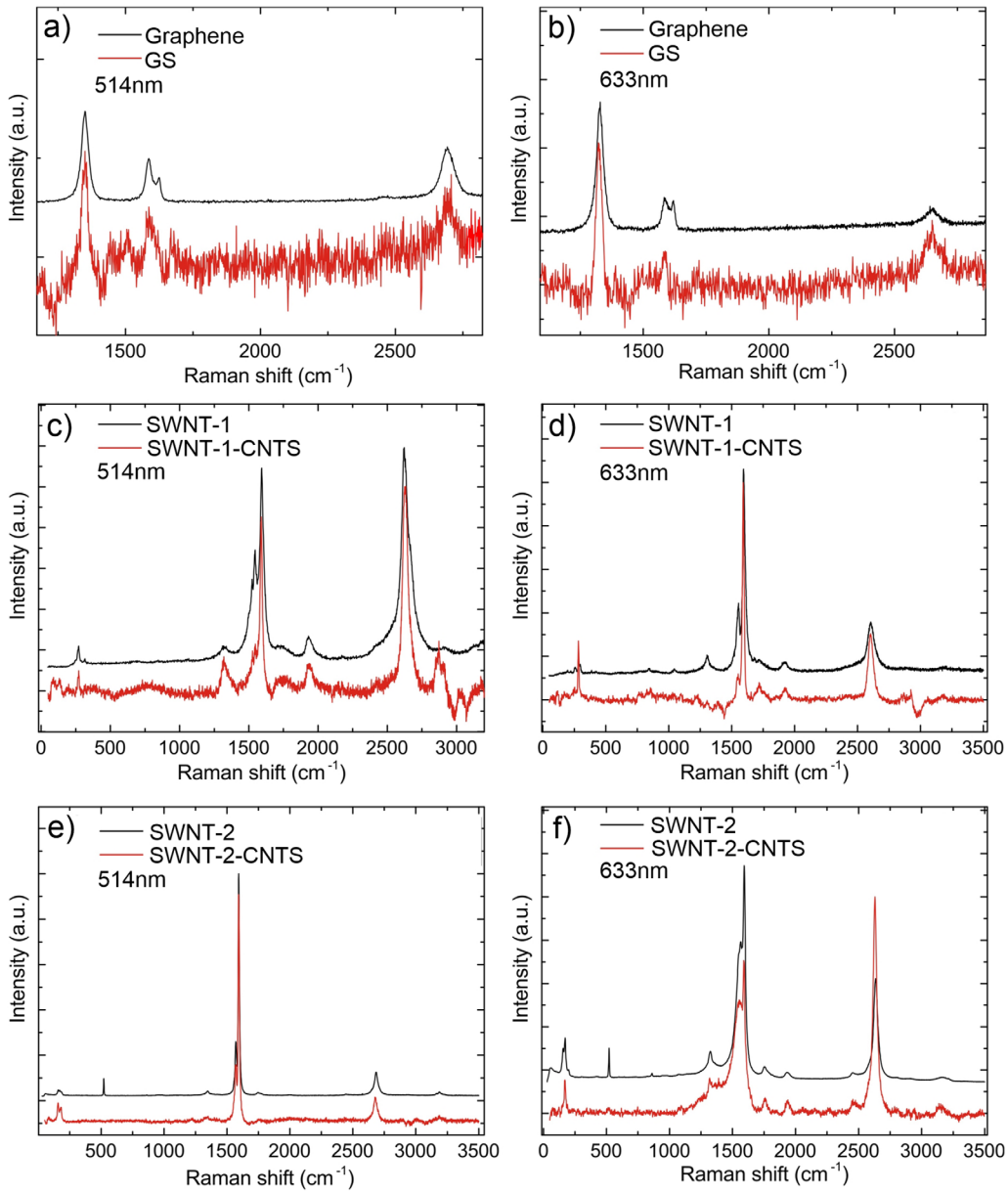

Figure 3. Raman spectra of graphene (black line) and GS (red line) at (a) 514.5 nm and (b) 633 nm. Raman spectra of SWNT-1, SWNT-2 and SWNT-1-CNTS and SWNT-2-CNTS at (c) and (e) 514.5 nm and (d) and (f) 633 nm excitation wavelengths.

for 2 h (450 kW at 20 kHz). The dispersions are ultracentrifuged using a TH-641 swinging bucket rotor in a Sorvall WX-100 at 200 000 g for 2 h at 18 °C to remove bundles and other impurities, such as amorphous carbon and catalyst residuals [57]. The supernatant of the two dispersions after ultracentrifugation is collected using pipettes and used for the characterization. Graphite flakes are sourced from Sigma Aldrich Ltd. 100 mg are dispersed in 10 ml water with 2% volume to weight (v/w) SDC. The dispersion is then ultrasonicated for 10 h and subsequently ultracentrifuged, exploiting sedimentation-based separation (SBS) [58] using a TH-641 swinging bucket rotor in a Sorvall WX-100 ultracentrifuge at 5000 rpm for 30 min. After ultracentrifugation, the supernatant is extracted by pipetting. The concentration of graphitic flakes is determined from the optical absorption coefficient at 660 nm [59]. A full optical and spectroscopic characterization of the samples is presented in SI. This shows that the samples consist of ~60% single- (SLG) and ~40% few-layer (FLG) graphene flakes [60].

21 spiders of three species were selected (*Pholcidae Holocnemus*, *Pholcidae Pholcus* and *Theridiidae Steatoda*) as described in the SI. The spiders are exposed to the aqueous dispersions by spraying them in a corner of the box they are contained in, avoiding intentional direct spraying on the animals. The dragline silk is collected from 2 to 12 days later, in order to allow sufficient time for ingestion of the aqueous dispersions and the production of silk. 29% of the spiders died before the first silk collection, and a further 24% after 12 days, during which starvation could have come into play. The silk fibres consist of multiple threads of approximately circular cross-section. The average diameter of the single threads is determined for each sample through field emission

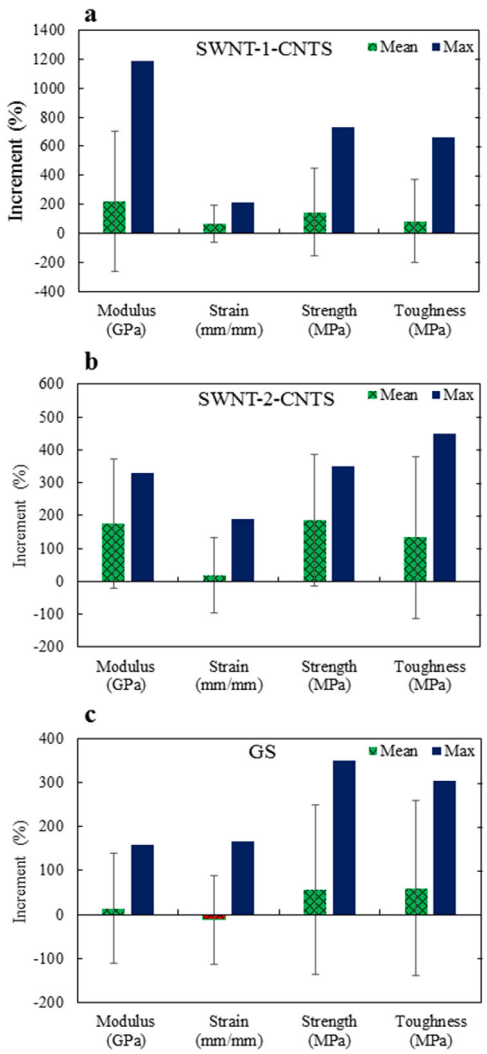

Figure 4. Percentage increment (green bars) or decrement (red bars) of the mechanical properties measured from RS and (a) SWNT-1-CNTS, (b) SWNT-2-CNTS or (c) GS. To calculate toughness values, a mean silk density value of 1.34 g cm^{-3} is used.

scanning electron microscopy (see SI), at two different cross-sections along their length. The number of threads in each fibre is also counted. The presence of CNTs and graphene is monitored by Raman spectroscopy.

Nano-tensile tests are performed under controlled conditions as described in the SI. Samples are prepared by fixing silk fibre ends to 'C' shaped cardboard holders (then cut after mounting in the sample holder, figure 1(b)), and subjected to traction up to failure in an Agilent T150 nanotensile system at a constant strain rate of 0.1% s^{-1}, consistently with previous studies on spider silk mechanics [4, 61–63]. The stress σ, strain ε, and Young's modulus E, are calculated as $\sigma = F/A_0$, $\varepsilon = \Delta l/l_0$, $E = \mathrm{d}\sigma/\mathrm{d}\varepsilon|_0$, where F is the force measured by the nanotensile system (see SI for details), A_0 is the cross-section area of the fibre, l_0 its initial length, and Δl the change in fibre length during the test. The area underlying the stress–strain curve corresponds to the energy per unit volume required to break the fibre, the so-called toughness modulus T, also alternatively given in energy per unit mass, as derived by dividing the energy per unit volume by the density of the material: $T = \frac{1}{\rho}\int \sigma \mathrm{d}\varepsilon$ [53].

The diameter of the cross-sectional area of the silk fibres is between ~5 and ~10 μm, as obtained by multiplying the mean value of the measured cross-sectional area of the threads by their total number. The resulting diameters and number of threads for each fibre are reported in tables 1 and 2 for the reference spider silk (RS) and that collected from spiders exposed to dispersions of graphene (GS) and SWNTs (CNTS).

Figure 2 shows an optical image of a suspended fibre (figure 2(a)) and compares the Raman spectra of RS with that of GS (figure 2(b)) and CNTS (figures 2(c) and (d)). The RS Raman spectrum comprises several peaks in the 1000–1800 cm^{-1} and 2700–3500 cm^{-1} regions. The peaks at ~1088 and 1160 cm^{-1} are characteristic of the n(C–C) skeletal band of polypeptide chains [64, 65]. Two intense bands are also seen at ~1230 cm^{-1}, characteristic of amide III groups in π-sheets structured proteins [66, 67] and at ~1444 cm^{-1} assigned to CH_2 bending modes, both bands typically found in the Raman spectrum of spider silk [68]. The peaks at 1615 cm^{-1} and 1665 cm^{-1} are assigned to n(CO) amide I bands characteristic of the π-sheets configuration for the polypeptide backbone [66, 68]. The Raman peaks in the region 2700–3500 cm^{-1} are typical of C–H and N–H vibrations [67].

Raman spectra from GS and CNTS samples are shown in figure 3. The spectra are normalized with respect to the C–H band at ~2934 cm^{-1}, the most intense in RS. The normalized RS spectrum is then subtracted from the GS and CNTS ones. Figures 3(a) and (b) show that the spectrum of the flakes in the dispersion is compatible with that of GS. At both 514 and 633 nm, the D to G and 2D to G intensity ratios, I(D)/I(G) and I(2D)/I(G), as well as the positions of the G and 2D peaks, Pos(G) and Pos(2D), are very similar. The comparison indicates that graphene detected in GS has a similar level of disorder [69–72] as the original material. The same holds for CNTS. Figures 2(c)–(f) show that the spectra of the original SWNTs and those measured on CNTS are similar, indicating a negligible change in the structural properties.

A summary of the mechanical properties of RS, GS and CNTS is reported in tables 1 and 2, and typical stress–strain curves of the silk fibres are presented in figure 1(c) and in the SI. Scatter in the data is large, mainly due to the variability in the properties of the collected silk samples, deriving from spiders of different species and ages (see SI), but also from factors such as the sensitivity of silk density to humidity [73]. However, fibre slippage in the loading frame can be excluded, since this would be noticeable in the stress–strain curves, given the high-sensitivity (50 nN load resolution and 0.1 nm displacement resolution) of

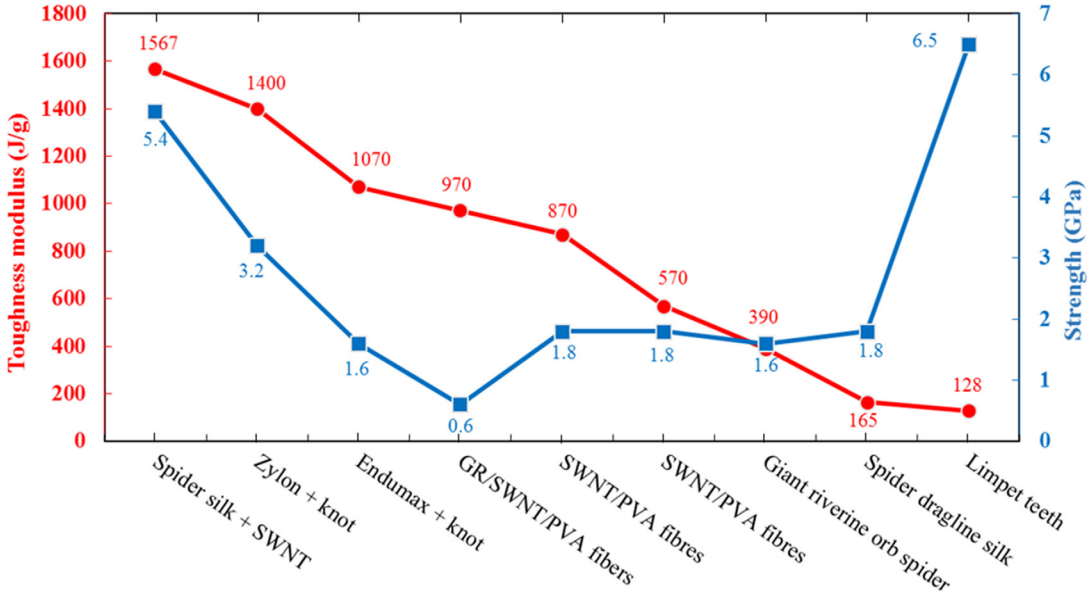

Figure 5. Toughness modulus and strength of different materials and composites.

the nanotensile testing system. Ultimate strain values have smaller scatter, since they are not dependent on parameters such as fibre cross-sectional area. In CNTS and GS, the scatter is greater due to the varying CNTs and flakes concentrations, since there is no control on the nanoparticle uptake mechanism at this stage. Apart from this, there is an intrinsic variability of mechanical properties of different samples of the same silk, in line with previous studies [62, 74–76].

To avoid these problems, we focus on the variation in mechanical properties of the silk fibres from individual spider specimens before and after exposure. The average and maximum variations are shown in figure 4. Fracture strength, Young's modulus and toughness increase on average between 80 and 220% in CNTS and between 15% and 60% for GS. The highest fracture strength and Young's modulus increments are +731% (3.9 GPa) and +1183% (37.9 GPa) for CNTS, with an increment ~+663% in toughness (2.1 GPa). This corresponds to 1567 J g^{-1}, calculated using an average silk density value ~1.34 g cm^{-3} [53], neglecting changes due to humidity or the presence of CNTs or graphene, as discussed in the SI, with a 41% decrement of ultimate strain (0.6 mm mm^{-1}). This should be compared to the toughest silk fibres found to date, having a toughness ~520 MJ m^{-3} [62], and a strength ~1.65 GPa [62]. The combination of increment in toughness and decrement in ultimate strain is peculiar and fundamental in applications such as parachutes or bullet-proof vests, where high performance textiles are required to stop bullets in millimetres [77]. The second highest increments ~+350% (2.0 GPa) in fracture strength and +330% (19.3 GPa) in Young's modulus are found for SWNT-2-CNTS, corresponding to an increment ~+204% in toughness (0.4 GPa), with a decrement ~36% in ultimate strain (0.3 mm mm^{-1}). A smaller, but still significant, increment is also observed for some of the fibres containing GS, with +151% (1.2 GPa) in fracture strength and +142% (13.0 GPa) in Young's modulus, corresponding to an increment of both toughness and ultimate strain of +250% (0.3 GPa) and +166% (0.4 mm mm^{-1}), respectively.

We note that Wang *et al* [78] reported a similar approach to that described here, based on the initial posting of the present manuscript [79], cited as reference [19] in [78] and applied it to silkworm silk. This demonstrates that our approach is reproducible in other biological systems. However, Wang *et al* [78] achieved far inferior mechanical properties to those reported here. Indeed, in the best case we get here a strength ~5.4 GPa and toughness modulus ~1567 J g^{-1}, whilst Wang *et al* [78] achieves maximum values ~0.6 GPa and ~400 J g^{-1}, respectively. This is mainly due to lower mechanical properties of silkworm silk with respect to spider silk [1–4].

Discussion

Figure 5 compares the strength and toughness of various natural and artificial materials. The best fibre obtained in this study displays higher strength than high-performance polymeric fibres like Zylon or Endumax [52, 53], or SWNT/carbon-reinforced polymeric fibres [80–82], and is surpassed only by T1000® Carbon fibres [83] or goethite nanofibers found in limpet teeth [27]. At the same time, its toughness is significantly higher than the toughest spider silks found in nature [62, 75] or high-toughness SWNT/PVA fibres [80]. Indeed, it exceeds the previous largest recorded toughness value for synthetic polymer fibres or CNT microfibres with integrated knots as energy dissipators [54].

Molecular Dynamics simulations reported in the SI show that CNTs have the strongest interaction with the mannose-associated serine protease 1 (MASP1) spider silk fibers, in the amorphous region where

they affect the structure of the bundle. The measured strength and stiffness data can be compared to analytical predictions for the reinforcing effect of graphene or CNTs on silk using the direct and inverse rule of mixtures [84] and simulations using the Hierarchical Fibre Bundle Model [85] (see SI). These can estimate the concentration of reinforcements by fitting the corresponding experimental strength values, giving equivalent volume fractions in GS and CNTS between 1% (spider 15) and 15% (spider 7), with an average ~7%.

Graphene flakes appear to be a less effective reinforcement than CNTs (figure 4(c)). This could be due to the shape of the flakes. The lateral characteristic dimensions of our flakes (~200–300 nm), two orders of magnitude larger than the characteristic CNT diameter, could give rise to less efficient load transfer, since their longitudinal dimension could be smaller than the critical length (of the order of microns and dependent on the interface properties) predicted by the shear lag theory for optimal load transfer [86]. Inefficient load transfer could also be due to the crumpled configuration of the flakes or a larger misalignment with respect to CNTs. Finding solutions for these problems could potentially enable GS with mechanical properties superior to CNTS, thanks to the two surfaces available for load transfer in flakes [86]. Tuning the constitutive law of the silk could also maximize the robustness of an entire structure [87].

Conclusions

Spiders placed in an environment with water solutions containing nanotubes or graphene may produce dragline silk with enhanced mechanical properties, realizing the highest fibre toughness to date, combined with a strength comparable to that of the strongest carbon fibres or of limpet teeth. Our proof-of-concept experiment paves the way to exploiting the naturally efficient spider spinning process to produce reinforced silk fibres, thus further improving one of the most promising silk materials, as compared to synthetic recombinant silks. This procedure of natural integration of reinforcements in biological structural materials could also be applied to other animals and plants, leading to a new class of 'bionicomposites' for innovative applications.

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ORCID iDs

Federico Bosia https://orcid.org/0000-0002-2886-4519
Francesco Bonaccorso https://orcid.org/0000-0001-7238-9420
Simone Taioli https://orcid.org/0000-0003-4010-8000
Giovanni Garberoglio https://orcid.org/0000-0002-9201-2716
Nicola M Pugno https://orcid.org/0000-0003-2136-2396

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