From atoms to structures – how spiders turn weakness into strength

Markus J. Buehler*

Laboratory for Atomistic and Molecular Mechanics, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA

* E-mail: mbuehler@MIT.EDU

Max Bergmann Lecture, Max Bergmann Center Of Biomaterials, Dresden, Germany, Oct. 10, 2011

Funding: DOD-MURI & DOD-PECASE, National Science Foundation

Steel: strength ~1 GPa

Spider silk: strength ~1-2 GPa & 60% strain @ failure

Weak bonds

Made @ room temperature via self-assembly

Natural construction material

Steel: strength ~1 GPa

Spider silk: strength ~1-2 GPa & 60% strain @ failure

Weak bonds

Made @ room temperature via self-assembly

Natural construction material

Blackledge et al.

spider web across rivers

Structure & mechanical response of spider silk

Universality-diversity paradigm

Create multifunctionality (diversity) by changing structural arrangements of few (universal) constituents rather than inventing new building blocks

Features structure from nano (H-bond, protein, nanostructure, etc.) to macro (spider web)

Important chemical bond: H-bond

Z. Shao and F. Vollrath, Nature, 2002; N. Du et al., 2010

M. Buehler, Nature Nanotechnology, 2010
Overarching goal: bioinspired design

Synthetic fibers (CNTs, polymer, etc.)

Natural fibers (silk, wood, etc.)

Protein structure, from gene to molecule

Sequence controls structure (AH vs. BS)

H-bonds

Collagen (tropocollagen)

Alpha-helix

Beta-sheet

Random coil (unstructured)

Four letter code “DNA”

Genetic information

Combination of 3 DNA letters equals one amino acid (AA)

E.g.: Proline – cct, ccc, cca, ccg…

Sequence of amino acids (polypeptide): 1D structure

Transcription/translation

N-terminal (start)

C-terminal end

Hierarchical assembly forms protein material

(silk, bone, tendon, …)

Material failure – across all scales

Airplane crash: failure of engineering structure

Earthquake: failure of the earth’s crust

Approach & general impact

Combine theory & experiment at multiple scales

Functionality

Non-reactive MD

Non-meso models

Meso-scale models

Continuum models

Optical microscopy

Chemistry

DFT

QM

MD

Nanoindentation

Meso-mechanics

Microcrack

New paradigm to describe materials: Powerful bottom-up description of material mechanical properties by explicitly considering hierarchical structure from chemical level upwards

Basis: chemistry force field models derived from quantum mechanics (i.e., QM, first principles)

Three-pronged research approach: “materiomics”

1. Simulation of different systems
2. Generalize insight through comparative study
3. Develop analytical models


**Linking chemistry, structure and mechanics**

Molecular dynamics: Fundamental model of materials “bottom-up”

\[ U_{\text{system}} = U_{\text{bond}} + U_{\text{angle}} + U_{\text{torsion}} + U_{\text{Coulomb}} + U_{\text{vdW}} + \ldots \]

- Covalent bonds
- Electrostatic bonds
- Weak bonds

**Coarse-graining approach – MARTINI**

Time step ~20…40 fs (vs. 1-2 fs in MD)

1/10th of particles


**Molecular simulation – movie**

Large-scale simulation of complex biomolecules now possible

**Emergence of opportunity**

Source: TIME magazine
Supercomputing is a key tool

Pulling on a single collagen molecule

Coarse-graining

Mechanism:
Entropic elasticity
(change in configurational entropy)

Advancement in experimental equipment:
Have quantitatively confirmed predictions from our simulations

Sun et al., J. Biomechanics, 2004; Buehler and Wong, Biophys. J., 2007

Use approach to understanding healthy collagen: bottom-up material description

Intellectual challenge: Push chemical concepts to larger scales (H-bonds, reactivity...)

Achievement: Predicted large-scale mechanical properties by systematically studying properties and mechanisms (s.a.: stretching, bending, slip, molecular breaking...) at different scales and linking them

Validate by direct comparison with experiment

Push mechanics concepts to smaller scales (modulus, strength...)

Buehler et al., Nano Letters, 2011
Impact: Understanding collagen mechanics in disease conditions

Bottom-up model enables changing chemical properties of molecules (e.g. mutation that causes osteogenesis imperfecta (OI) or brittle bone disease)

Based on a systematic analysis predict properties at fibril scale: change of deformation mechanism (stretching, slip, breaking)

Impact: Through these efforts understand physiological and disease mechanisms—correlate chemical with mechanical signatures with clinical disease severity

Results in potential new concepts for disease diagnosis and treatment

Analytical scaling law of physiological and disease collagen

Through simulation: identified how molecule length controls strength of fibrils

At $L = L_0 \sim 200-400$ nm: homogeneous stress state $\rightarrow$ maximum strength

Analytical model explains mechanism in disease state

Physiological collagen molecule length: $L \sim 300$ nm

Model critical molecular length & scaling for transition from homogeneous to localized slip using mechanics theory (fracture mechanics & shear lag model):

$$L_0 \sim \sqrt{\frac{2F}{\tau_{shear}}} \quad \frac{L}{L_0}$$
Enables a multi-scale approach

- The basis of multi-scale methodology is the parameterization of “coarse-grain” models through analysis of more complex and sophisticated “fine-grain” models.
- Already a common practice to “train” atomistic force-fields for molecular dynamics simulations via results from quantum mechanics (e.g. DFT), extended across all scales.

Mechanical response of spider silk

How can we explain the mechanical properties of spider silk from a fundamental & mechanistic perspective?

2.5–4 μm (diameter)

http://www.microlabnw.com/


Spider silk’s hierarchical structure

Key: Molecular structure ???

Beta-crystal

Amorphous phase

Structure prediction and functional properties

Genetics

Amino acid sequence

Replica Exchange Simulations

Validation (experimental results)

Ensemble of final structures

Mechanical characterization (multiscale)

Mechanics (functionality)

S. Keten, M. Buehler, APL, 2010

Folding —structure

...GGLGGQGAGA

AAAAAGGAGQG ...

GGLGGQGAGA

AAAAAGGAGQG

Under polarized light

1-2 GPa

Stress (MPa)

Silk

Elastic region

Strain-weakening

Strain-hardening

Time and Length Scales

Macro

Spider web (macro)

Skin

Fibrils

Beta-crystal

H-bonded beta-crystals

H-bonded beta-strand

H-bond (chemical structure)

Amorphous phase

Nano

S. Keten, M. Buehler, APL, 2010

Structure prediction and functional properties
Replica Exchange approach (parallelized)

Simulate copies of the same system with different temperatures
Exchange configurations between them
Evaluate most stable configurations obtained at low temperature = solution “ensemble” of structures

S. Keten, M. Buehler, APL, 2010

Detailed view of structure & mechanics

Composite of ordered-semi-amorphous structure (sequence controlled)

Nanoscale mechanism of deformation

Semi-amorphous region (A) provides ductility (molecular unfolding of $3_1$-helices)
Beta-sheet crystal (B) provides strength (controls maximum force; breaking of crystal) – features weak H-bonding

Weakness of H-bonds (inferior building block)

H-Bond energy: 2-10 kcal/mol

Thermal energy scale $k_B T \approx 0.6$ kcal/mol (room temp)

controls unique properties of water
Water: liquid @ 300K
Protein: solid @ 300K

WHY?

Water: liquid @ 300K
Protein: solid @ 300K

individual H-bonds in water
Strength prediction of beta-strands

Energy dissipation model (cWLC and dWLC)

Strength prediction variations in persistence length variations in H-bond energy


Validation against experiment

Simple model explains many experiments, has implications for a wide range of polymeric materials

Theory predicts near-equilibrium strength of beta-proteins accurately to be around 50-300 pN.


Scaling of strength of H-bond assemblies

Characteristic maximum number of H-bonds work cooperatively: 3..4 bonds

Many small segments with 3-4 HBs each enhance the strength multiple times

Intrinsic energetics, nanomechanics, and structural confinement control strength properties: Reach strength at characteristic dimension of H-bond clusters


Scaling laws define constraints on architecture (laws); operate at each scale

High cooperativity requires: weak bonds AND soft polymer

Scaling empirically confirmed: H-bond cluster size in natural proteins


Nanoscale mechanism of deformation

Each node has maximum of two connections

Each node has maximum of three connections (here: full percolation since fully connected)

Thus: Larger stacks of beta-sheets leads to better percolation and thus better material properties

How does the stack height (crystal size) influence mechanical properties?

test with lateral loading model
Size effects in silk nanocrystals

- Stick-slip mechanism
- Crack formation & propagation

How weakness is turned to strength

- Natural silk: $L^* = 2-7$ nm and $h^* = 2-3$ nm

Model explains experimental results: increase in beta-sheet crystal size results in loss of strength

- Derived critical length scales from atomistic and analytical model
- Critical length scales measured in experiment

Confirms hypothesis (predicted using mechanics theory)
 Fundamental challenge: Scaling up…

Molecular-level properties are very similar to macroscale experimental results (surprising when compared to other materials)

WHY?

T. Giesa, M. Arslan, M. Buehler, Nano Letters, 2011

Approach to understanding silk: bottom-up material description

Intellectual challenge: Push chemical concepts to larger scales (H-bonds, reactivity…)

Push mechanics concepts to smaller scales (modulus, strength…)

Nanoscale mechanism of deformation

- Semi-amorphous region (A) provides ductility (molecular unfolding of 3_1-helices)
- Beta-sheet crystal (B) provides strength (controls maximum force; breaking of crystal)

Particle-based mesoscale model of silk

- Geometry of the silk fibril
- Triangular mesh mesoscale particle-spring model setup
- Stress–strain curves obtained from fitting the atomistic simulations of the silk fibril

T. Giesa, M. Arslan, M. Buehler, Nano Letters, 2011
Particle-based mesoscale model of silk

Multiscale approach of fibrils

Confinement critical for macroscale strength
Confinement critical for macroscale strength

Critical fibril length-scale $H^*=20-80$ nm
Reach theoretical strength of material
All material participates in unfolding and failure, specifically all beta-sheet nanocrystals
Toughness modulus $\approx 200-500$ MJ/m$^3$ (experiment)
$\approx 200$ MJ/m$^3$ (prediction here)

Fibers are bundles of fibrils

Confinement found in natural silk fibrils

Experimental reference:
Fibril size ranges from 20-100 nm
• **Functional properties** emerge due to interactions of building blocks at different scales

• **Scaling laws** govern how structures at specific scales must form in order to be used as “new” building blocks as next hierarchy levels

• Scaling laws may involve parameters from different hierarchical levels

Can we formulate this in a self-consistent way, i.e. to describe it in a generic mathematical model that can be solved for different situations (similar to BCs)?

Category theory—describe system by relationships between elements: ologs

Category theory: S. Eilenberg S. MacLane (1942–45)

- Functionality emerges from interplay between building blocks
- Defined by interactions between them, use physics from theory/simulation/experiment to build olog

### Challenges and opportunities

**Biology (building blocks)**

- **alpha-helix**
- **beta-sheet**
- random coil (unstructured)

Can **NOT** predict function

**Architecture & civil engineering**

Can **PREDICT** function

### Category theory representation

**Hierarchical biological material (e.g. silk) or synthetic material**

Description of how “function” emerges is identical/similar in silk or language, albeit building blocks are different

**Solve olog for different “BCs”: change building blocks**

---

<table>
<thead>
<tr>
<th>Type</th>
<th>Type</th>
<th>Labels</th>
<th>Protein Specific</th>
<th>Social network Specific</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>a one dimensional system of bricks, glue and glue</td>
<td>beta-helix</td>
<td>social network with wireless/physical passegeways</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>a one dimensional system of bricks and glue without lifetime</td>
<td>beta-sheet nanocrystal</td>
<td>social network with wireless, without physical passegeways</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>a brittle system</td>
<td>brittle protein filament</td>
<td>brittle social network</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>a “tensile” system</td>
<td>chain shape for protein</td>
<td>chain shape for network</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>a ductile system</td>
<td>ductile protein filament</td>
<td>ductile social network</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>a one dimensional system</td>
<td>beta-helix</td>
<td>beta-helix/ beta-sheet nanocrystal</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>a system consisting of bricks connected by glue and lifetime, both connected as in graph G</td>
<td>lifeline proteins of specified shape</td>
<td>lifeline social network of specified shape</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>a graph</td>
<td>shape of protein</td>
<td>shape of network</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>a thermoregulating building blocks, serving as bricks, glue, and lifetime</td>
<td>amino acid cluster, H-bond, backbone</td>
<td>transcrip, will system, physical passegeways</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>a system consisting of bricks connected by glue, structured as in graph G</td>
<td>protob of specified shape</td>
<td>social network of specified shape</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>a thermoregulating building blocks, serving as bricks, glue, and lifetime</td>
<td>amino acid cluster, H-bond, backbone</td>
<td>transcrip, will system, physical passegeways</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>a pair of building blocks, serving as bricks and glue</td>
<td>amino acid cluster, backbone</td>
<td>transcrip, physical passegeways</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>a pair of real numbers such that g x 100 = 23.45</td>
<td>e.g. g = 205 r = 23.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>a pair of building blocks, serving as bricks and glue</td>
<td>amino acid cluster, H-bond, backbone</td>
<td>will system</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>a pair of real numbers such that g x 100 = 23.45</td>
<td>e.g. g = 100 r = 23.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>a pair of real numbers such that g x 100 = 23.45</td>
<td>e.g. g = 263.5 r = 50.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>a pair of real number</td>
<td>e.g. g = 263.5 r = 50.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>a brick</td>
<td>amino acid cluster</td>
<td>transcrip</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>a glue</td>
<td>H-bond cluster</td>
<td>will connection</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>a fiber</td>
<td>backbone</td>
<td>physical passegeways</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>a real number</td>
<td>e.g. 181.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>a real number</td>
<td>e.g. 61 Angstrom</td>
<td>e.g. 1/100 mm</td>
<td></td>
</tr>
</tbody>
</table>

---

Merger of structure and material: structural engineering at all scales

We can use simple building blocks, assembled in different geometries, to create enhanced material properties (do not need complex or functional building blocks)

Silicon and silica are brittle materials

Example: fracture of silicon crystal

Diatoms – Nature’s flexible armor

Nanopores create strong & tough material (no longer brittle)


Garcia and Buehler, Comp. Mat. Sci., 2010
Hierarchies result in defect tolerant behavior

Sen, Buehler, Scientific Reports, 2011

Summary: Universality-diversity paradigm

Paradigm uncovered:
• Create multifunctionality (diversity) by changing structural arrangements of few (universal) constituents: geometry controlled by confinement/scaling laws
• No reliance on invention of new building blocks
• Departure from widely used engineering approach: Turn weakness to strength

Engineering impact: Bioinspired materials; i.e. define properties, geometry etc. of materials other than protein, e.g. metal-polymers by applying scaling laws: Use silica (sand), clay, and soy beans transformed to create high tech materials

M. Buehler, Nature Nanotechnology, 2010; Nano Today, 2010