Tailoring Materials Behavior Using Geometry

Hossein Ebrahimi, Hessein Ali, Ranajay Ghosh

Complex Structures and Mechanics of Solids Laboratory (COSMOS Lab)
University of Central Florida, Department of Mechanical, Materials, and Aerospace Engineering, Orlando, FL 32816

OBJECTIVES

• To derive static and dynamic models that represent the behavior of scale-covered structures under different mechanical loading including bending and twisting.
• To thoroughly investigate the nonlinear behavior stemming from scales engagement.
• To develop structure-property-architecture correlations under various loading conditions.

APPLICATION

• A keylor glove partially covered with ceramic scales which were fabricated by R. Martins and F. Bartholat (2016).
• Scales prove their functionality to be involved in the design of synthetic composite materials to accommodate both flexibility and protection (Browning, 2012).

MOTIVATION

• Many applications require materials whose response can be tuned such as morphing wings for supermaneuverable vehicles, soft robotics and space structures.
• Nature achieves this objective using external dermal features – skin, fur, teeth, feathers.
• These nonlinearities are generated using the geometry and topology of the scales.
• The scales provide distinct structural advantages such as protection and tailorable response from scales contact.
• Scales also aid in highly dynamic life functions – such as locomotion, anti-fouling, flapping flights, swimming.
• Material to structural correlations are highly nonlinear due to scale topology.
• We aim to reveal structure-property-architecture correlations for automated 3D printed designs.

EXPERIMENT

• The properties of materials of the fabricated sample (PLA and silicon polymer) are found using MTS testing device.
• A quantitative experiment to show the benefit of scales in twisting responses of the scale-covered beam as compared to plain samples.

FUNCTIONAL GRADATION

• Functional gradation to change displacement.

LOAD CASES

Static Bending:
• A theoretical approach is derived via tracking each individual scale assuming the substrate bending to follow $\gamma = y(x)$.
• $\gamma$: Amplifier and $f(\gamma)$: Substrate Bending Shape
• The mechanics follows the variational energy $\delta W$.

Static Twisting:
• Nonlinear dimensionless relation between $\phi$ and $\Gamma$:

$$\frac{\delta W}{\delta \phi} = \frac{\partial \phi}{\partial \psi} \frac{\partial f}{\partial \psi}$$

where $\theta = \frac{\gamma}{\delta}, \lambda = \frac{1}{\delta}$ the overlap ratio, dimensional scales width, and dimensional substrate thickness.
• The torque-twisting rate relationship:$\Gamma (\theta) = \frac{G}{2} \phi \left( 1 - \frac{\theta}{\lambda} \right) \left( 1 - \frac{\theta^2}{\lambda^2} \right)$

Dynamic Bending:
• The equation of motion is derived based on the concept Hamilton principle needed with local periodicity approach for the engagement of scales.
• $\mu$: Density
• $E$: Flexural Rigidity
• $\theta$: Scales Angle
• $\beta$: Friction Angle
• $A$: Area, $C$: Viscous Damping

Load Simulations and Design Charts

• Phase map of the scale-covered beam for different $\theta$ spanned angle of scales ($\theta$) and local twist angle ($\phi$), which shows three kinematic regimes of operations under twisting, including linear, nonlinear, and rigid regions. Black dotted lines represent FE results.
• Phase map of dimensionless torque $\Gamma (\theta)$ versus global twist rate (\(\phi\)) for the scale-covered beam with different \(\theta\). $C_{\theta}$ in inclusion correction factor of scales into the substrate and $G_{\theta}$ is the warping coefficient for beam with rectangular cross-section.

CONCLUSION

• Scale-covered slender shows geometrically tailorable nonlinear response under different loading including static and dynamic bending and twisting.
• The gained stiffness from scales is highly nonlinear, reversible, and tailorable, distinct from simply coating or embedding with a stiffer material or a composite.
• Scales are excellent template for metamaterials synthesis.

REFERENCES


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