MECHANICS OF ARCHITECTED MATERIALS

COURSE INFORMATION

- **Catalog Number:** ME 193H
- **Units:** 4
- **Meeting Times / Classroom Location:** TBD
- **Online Resources:** Canvas, Piazza

INSTRUCTOR INFORMATION

- **Instructor:** Andrew Chen (he/him)
- **Office:** 1-314
- **Office Hours:** Tuesdays, 1–3 pm
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Can materials be damage-tolerant by design?
Can material properties be determined through geometry rather than chemistry?
How can we engineer materials that change their stiffness on demand?

Course Description

In the last two decades, architected materials (or mechanical metamaterials) have transformed the way engineers approach design problems, unlocking new potentials across disciplines like aerospace engineering, automotive engineering, and sports medicine. The modern field of architected materials has its roots in the study of the mechanical behavior of foams, which later evolved into beam-, plate-, and shell-based geometries derived from "architecting" the morphology of open-cell, foam-like structures. These materials have already been shown to approach theoretical bounds for strength and stiffness, to absorb or redirect energy in a highly tunable manner, and to unlock new perspectives on "traditional" materials – such as through the realization of highly flexible, ultrathin ceramics. New perspectives on the structure-property relationships of these materials derived from experiments, simulations, and theory continue to shape the landscape of what we can achieve through architecting morphology.

In this course, we will take a ground-up approach to discuss the mechanics of architected materials in a variety of settings and applications. First, we will discuss the fundamental theories that underlie the mechanics of architected materials, and the main differences that separate metamaterials from their continuous counterparts. We will cover the state-of-the-art manufacturing techniques for realizing these materials together with methods for the experimental and numerical characterization of their behavior. We will also explore novel frontiers in the field, including morphologies of current research interest (such as composite architectures) and testing under extreme conditions (e.g., supersonic impact). Because this is such a dynamic and evolving field, assignments will involve reviewing recent, relevant, and exciting works from the literature. Moreover, through hands-on laboratory experience, we will immerse you in current work in the field with the ultimate goal of inspiring your potential to contribute to it!

The course will build up to and culminate with a design competition in which teams will aim to design and manufacture an architecture to achieve a particular goal (e.g., reflect energy from an incident projectile without developing damage) subject to realistic engineering constraints (e.g., be of least mass). Throughout the semester, you will apply their fundamental mechanics knowledge together with the computational and experimental approaches discussed in class to iterate on and optimize their designs. The ultimate goal of the course is to bring you to the forefront of the design, fabrication, and analysis techniques that have produced these outstanding materials and have enabled them to supplement and extend traditional principles of design across disciplines.

Intended Learning Outcomes

By the end of this course, you will be able to...

- Define the concept of an architected material and identify how an architected material differs from a monolithic material.
- Discuss how and why architected materials are used and recognize current limitations to their fabrication, scalability, and applications.
- Apply theoretical concepts from previous solid mechanics courses to predict the behavior of an architected material given its morphology.
- Identify and discuss state-of-the-art methods, findings, and conclusions in the literature on architected materials.
- Design an architected material that achieves a given design target as optimally as possible under a set of given constraints.

Prerequisites / Corequisites

This course is designed as an upper-level undergraduate or introductory graduate course. A first course in solid mechanics is a required prerequisite.

Course Materials

There are no required texts for this course. Relevant reading material will be taken from seminal works in the field of architected materials, as well as current work that reflects the ever-changing state of the art.

It is recommended, though not required, that you have access to your course notes or textbook from your prior course in solid mechanics, as these concepts will be heavily applied here. If you don't already have a favorite solid mechanics textbook, mine is *Mechanics of Materials* by R. C. Hibbeler (Pearson), which is available in the campus library. Any edition will do.

Another suggested reference (not required) is *Engineering Materials 1: An Introduction to Properties, Applications, and Design* by M. F. Ashby and D. R. H. Jones (Elsevier), also available at the library. Again, any edition is fine.

What to Expect in This Course

This course is designed to immerse you in the wide world of architected materials and place you at its forefront, while equipping you with the tools you will need to design, analyze, and understand their mechanics from first principles. We'll approach this goal in a variety of ways. Lectures will present foundational theory but will also serve as forums for discussion about seminal and current literature alike; you should expect to explore and critically interpret approximately one journal article per week. In laboratory sessions, you'll practice your hands-on skills in design and characterization, working in groups to use CAD software, run finite-element simulations, and perform mechanical testing. Finally, you will put all of these skills together over the term as you work towards designing and developing your own architected material for the design competition.

Preparation. To get the most out of lecture discussions, we ask that you prepare by reading the posted materials (typically journal articles) ahead of time. This will allow you to brainstorm questions that will help drive our class discussions. Since the content of the course can be tailored to your interest, it will be advantageous to identify particular topics or ideas from the readings (or otherwise) that you will want to discuss.

Feedback. We aim to provide feedback at several points throughout the semester, not limited to problem sets and lab reports. In particular, we designed the course project to be broken down into sub-parts, each associated with a checkpoint where you will present your results to the class. Not only will this allow you to practice formulating and communicating your thoughts in a scientific manner, but it will allow us — and the rest of the class – to provide targeted and specific feedback on analysis and experiments of your own design. Particularly, we want to give you the opportunity to present your original ideas, concepts, and thoughts in an open forum before you commit to them late in the semester, so that meaningful iterations can be done. This process is designed to mirror the feedback-iteration process you will undoubtedly encounter whether in an academic or industry setting.

Active learning. Seeing the methods we will discuss is entirely different from experiencing them, so a significant portion of our course will be centered around actively practicing the techniques for design and characterization you will use for your final project and beyond. We will integrate experiments, simulations, and other design and analysis tools throughout the semester. Ultimately, you will gain the experience you need to use these tools independently with your project group.

Laboratory Sessions

Engineering, like most disciplines, is not a spectator sport! You will gain practical experience with modeling and characterization over the course of the scheduled laboratory sessions, presented in parallel with the lectures, during the semester. With the support of lab instructors, you will have the opportunity to directly apply core concepts and — most importantly — gain feedback on your learning. Our goal in designing the laboratory component is to equip you with the skills you will need not only for this course but in your future career as an engineer and scientist. For this reason, your attendance and participation will be required. We will measure your attendance using a brief writeup assignment that will be due one week after each lab session. These assignments will mainly focus on summarizing the goals and intent behind the lab activities - we want you to understand why you are performing a certain experiment. Secondarily, your lab writeups will help us give you feedback on things like data analysis and other quantitative procedures.

Lab writeups are tangible ways of learning. If you turn in a completed lab writeup that reflects a reasonable amount of effort, you will receive full credit. Example writeups reflecting this standard will be shared during the first week of lab.

The subject of laboratory sessions will be:

1. Computer-aided design (CAD) of architected materials
2. Finite element simulations I: linear-elastic homogenization
3. Mechanical characterization I: tension, compression, and flexure experiments
4. Finite element simulations II: nonlinear analysis of deformation
5. Mechanical characterization II: experiments under extreme conditions (dynamic impact, etc.)
6. Fabrication and characterization at the microscale and below

Assessments

There are no exams in this course. You will practice your new modeling and analysis abilities through problem sets, the lab writeups discussed previously, and a semester project.

Problem sets. Throughout the course, targeted problem sets will be assigned with the goal of reinforcing and extending the fundamental topics presented in lecture. In these problem sets, you will be asked to demonstrate your understanding of core concepts related to the mechanics of architected materials by analyzing real architectures, drawing conclusions from geometrical arguments paired with your knowledge of mechanics. By the end of the course, your experience solving these types of problems will equip you well to iterate on the design of your own architected material, understanding how it will behave. There will be six problem sets assigned, but in computing your final grade we will only consider the highest five individual scores (see the full policy below).

Semester project. In parallel, you will work in teams throughout the semester towards the final project: a competition in which you will design your own architected material to achieve a constrained objective (which will be revealed early in the semester). We will incrementally work towards this objective through a series of laboratory activities where you will experience some of the tools used to evaluate architected materials in practice, e.g. finite-element analysis and structural/mechanical characterization. You will also have the opportunity to iterate on your design to immediately and directly apply your findings and maximize the performance of your architecture.

Grading breakdown. The course grade will be split between these three aspects:

- 40% of the course grade will come from problem sets (5 graded problem sets, each worth 8%);
- 30% of the course grade will come from lab writeups (6 writeups, each worth 5%);
- 30% of the course grade will come from the final project (3 checkpoints, each worth 5%, and a final presentation outlining your design rationale, experimental and numerical findings, etc., worth 15%). The performance of your architected material in the competition will not directly affect your grade, but bonus points will be available for the highest-performing teams!

Since this is an upper-division course, there are no grading quotas or cutoffs. In other words, if the entire class puts the effort in to get an A, then everyone will get an A.

Course Expectations and Policies

Attendance and class participation. Your participation in class is strongly encouraged, because this is the easiest way you can interact with the course content. Specifically, we want to tailor the specific content of the course based on your (and your classmates') interests! To this end, we welcome your questions, ideas, and feedback throughout the semester. For example, we will regularly offer the opportunity for you to present to the class a journal article or other work of your interest relating to the field of architected materials.

Laboratory sections. We will assign laboratory sections during the first week of class based on time preferences. You are expected to attend the section to which you are assigned. If you need to miss a laboratory section, your first course of action should be to attend a different section in the same week. If this is not feasible, your second course of action should be to contact the lab instructors and organize a make-up section. If this is not feasible, you will be required to watch a recording of a live lab session from which your lab writeup will be based.

Collaboration. You are encouraged to work with your colleagues on the problem sets, but only you will know how much of the material you understand. While some of the questions will be challenging, our ultimate goal is to demonstrate how mechanics concepts can be applied to realistic problems. Completing the problem sets by your own hand, and in doing so learning how to approach, troubleshoot, and solve these problems, will make you a better mechanician.

Late assignments. This course consists of content which largely builds off of previous material. For this reason, completing assignments by their assigned deadlines is important for your success. However, since you are a busy student and life gets in the way, only (your best) five of the six assigned problem sets will be considered in computing your final course grade. The astute (or experienced) student will observe that this is equivalent to dropping one assignment altogether. While this is mathematically true, we highly recommend that you complete all assignments for practice, even if you do not turn one in.

Contingency. If you experience a situation in which you will need to miss multiple laboratory sessions and/or assignments, please let me know as soon as you can. These things happen, and our plan is to handle these instances on a case-by-case basis.

Inclusivity Statement

Architected materials are built from the deliberate arrangement of diverse elements; the same principle strengthens our learning community. Naturally, our classroom will be an inclusive environment. We hope to foster a sense of community in this classroom and consider this classroom to be a place where you will be treated with respect. We welcome individuals of all backgrounds, beliefs, ethnicities, national origins, gender identities, sexual orientations, religious and political affiliations – and other visible and nonvisible differences. All members of this class are expected to contribute to a respectful, welcoming, and inclusive environment for every other member of the class. If this standard is not being upheld, please feel free to speak with me.

Academic Integrity

In this course, I will hold you to the high standard of academic integrity expected of all students at the Institute. I do this for two reasons. First, it is essential to the learning process that you are the one doing the work. I have structured the assignments in this course to enable you to gain a mastery of the course material. Failing to do the work yourself will result in a lesser understanding of the content, and therefore a less meaningful education for you. Second, it is important that there be a level playing field for all students in this course and at the Institute so that the rigor and integrity of the Institute's educational program is maintained.

Violating the Academic Integrity policy in any way (e.g., plagiarism, unauthorized collaboration, cheating, etc.) will result in official Institute sanction. Possible sanctions include receiving a failing grade on the assignment or exam, being assigned a failing grade in the course, having a formal notation of disciplinary action placed on your record, suspension from the Institute, and expulsion from the Institute for very serious cases. Please review the Academic Integrity policy and related resources (e.g., working under pressure; how to paraphrase, summarize, and quote, etc.) and contact me if you have any questions about appropriate citation methods, the degree of collaboration that is permitted, or anything else related to the Academic Integrity of this course.

Accommodations and Disability Support

If you need disability-related accommodations, I encourage you to meet with me early in the semester. If you have not yet been approved for accommodations, please contact Student Disability Services at sds-all@mit.edu. I look forward to working with you to assist you with your approved accommodations.

Mental Health Resources

Being a student can be difficult! As a student, you may experience a range of challenges that can interfere with learning, such as strained relationships, increased anxiety, substance use, feeling down, difficulty concentrating and/or lack of motivation. These mental health concerns or stressful events may impact your ability to attend class, concentrate, complete work, take an exam, or participate in daily activities.

Support for undergraduate and graduate students is available through the doingwell@mit site. Support for postdocs is available through MyLifeServices. For urgent or after-hours concerns, please visit DoingWell's page of 24/7 resources. These include:

- MIT Student Mental Health & Counseling Services - Clinicians on Call [617-253-2916],
- Urgent Care @MIT Medical [617-253-1311],
- ULifeline Crisis Text Line [Text: "START" to 741-741], and
- MIT Police [617-253-1212].

Course Structure

1. Introduction: what are architected materials?
    (a) Ashby plots and the materials selection problem: why do we need architected materials?
    (b) The homogenization problem: representative volume elements and scale separation
    (c) Beam theory and its applications in architected materials
    (d) Plate- and shell-based architected materials
2. Fabrication of architected materials
    (a) Additive manufacturing across scales
    (b) Self-assembly processes
3. Characterization of architected materials
    (a) Mechanical testing across length and time scales
    (b) Non-destructive characterization techniques
    (c) Failure, damage, and instabilities in architected materials
4. New frontiers in architected materials
    (a) Active and multifunctional architected materials
    (b) Composite and hierarchical architectures
    (c) Bio-inspired and bio-integrated materials
    (d) Topology optimization and inverse design: data-driven and ML methods

Sample Unit Description

Introduction: what are architected materials?

This course is all about architected materials, which means that we must carefully define what makes a material architected. We start by asking a fundamental question: why do we need architected materials? The answer lies in a decision that engineers of all types must face: how to choose a material for a given application. We will study the so-called "materials selection problem" first under the traditional lens of using natural or man-made monolithic materials, then understand the motivation for creating architected materials that exceed these boundaries. To do this, we start by reviewing the mechanics of the building blocks of architected materials: beams, plates, and shells.

Unit-level learning goals

At the end of this unit, you will be able to:

- Define an architected material and explain how an architected material differs from a monolithic material
- Use the Ashby material selection strategy to compute the material parameter combination to optimize for a given loading and constraint
- Describe separation of scales and articulate the difference between structural and material responses
- Explain the fundamental assumptions underlying beam, plate, and shell theories and identify the limits of their application
- Examine the structure of a given architected material and understand the design rationale behind its morphology