Advanced structural design by the Finite Element Method

SUMMER QUARTER

This course will discuss the use of Advanced Finite Element Analysis of composite, nanocomposite and multi-functional composite structures for aerospace applications. First, the main opportunities and challenges introduced by the advent of advanced composite materials in aerospace engineering will be critically discussed. Particular focus will be devoted to the computational issues arising with the typical strain localization phenomena in composites. Fracture size effects in composites and nanocomposites, as well as their importance for structural design, will be critically analyzed. Methods for the size effect characterization and its modeling will be presented. Then, the Spectral Stiffness Microplane Model (S^2M^2), an advanced formulation capable of capturing the main damage mechanisms in composites and other quasibrittle materials, will be introduced and described in detail. The use of S^2M^2 for the crashworthiness analysis of composites structures will be presented along with its application for the analysis of another type of composite material: Discontinuous Fiber Composites (DFCs). DFCs, in which the reinforcing phase takes the form of carbon fiber platelets randomly distributed throughout the system, are gaining more and more interest from the aerospace engineering community thanks to the excellent manufacturability and interesting mechanical properties. The course will describe their application and computational modeling. Finally, the course will focus on the modeling and characterization of the thermo-chemo-mechanical process of crosslinking in epoxy-based composites leveraging advanced FEA. Simulations showing the emergence of curing stresses and their dependence on the curing cycle will be presented. Then, ongoing investigations on the use of graphene nanoplatelets to mitigate the curing stresses and damage will be presented critically.

INSTRUCTOR: *Marco Salviato,* Assistant Professor, William E. Boeing Department of Aeronautics and Astronautics, University of Washington, Seattle, WA, USA.

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Office Hours: On request. Contact instructor by email.

COURSE LOCATION / DAYS / TIMES: TBD

SUGGESTED READINGS:

Salviato, M., Ashari E. S., Cusatis G. "Spectral stiffness microplane model for damage and fracture of textile composites." *Composite Structures* 137 (2016): 170-184.

Salviato, M., Kirane K., Ashari S.E., Bažant Z.P., Cusatis G. "Experimental and numerical investigation of intra-laminar energy dissipation and size effect in two-dimensional textile composites." *Composites Science and Technology* 135 (2016): 67-75.

Mefford, C. H., Qiao Y., Salviato M. "Failure behavior and scaling of graphene nanocomposites." *Composite Structures* 176 (2017): 961-972.

Qiao Y., Salviato M., "A Cohesive Zone Modeling Study on the Fracturing Behavior of Thermoset Polymer Nanocomposites" *33th ASC conference proceedings*, (2018).

Ko S., Chan K., Hawkins R., Jayaram R., Lynch C., El Mamoune R., Nguyen M., Pekhotin N., Stokes N., Wu D., Tuttle M.E., Yang J., Salviato M., "Experimental and Numerical Characterization of the Intra-laminar Fracturing Behavior in Discontinuous Fiber Composite Structures" *33th ASC conference proceedings*, (2018).

Heinrich, C., Aldridge M., Wineman A.S., Kieffer J., Waas A.M., Shahwan K.W. "Generation of heat and stress during the cure of polymers used in fiber composites." *International Journal of Engineering Science* 53 (2012): 85-111.

REFERENCE BOOKS:

Daryl L. Logan, "A First Course in the Finite Element Method", sixth Edition.

Zinkiewicz O.C., Taylor R.L., Zhu J.Z. "The Finite Element Method. Its Basis and Fundamentals" Elsevier, 2013.

Belytschko T., Liu W-K, Moran B., Elkhodary K.I. "Nonlinear Finite Elements for Continua and Structures" 2nd edition, Wiley, 2013.

Bažant Z.P., Planas J., "Fracture and Size Effect in Concrete and Other Quasibrittle Materials", CRC press, 1998.

COURSE OUTLINE:

DAY 1

Multi-Functional Composites and Nanocomposites for Aerospace Applications: Opportunities and Challenges (90 min)

Structural Computational Modeling of Composites and Other Quasibrittle Materials: How to Deal with Strain Localization in a FE Framework (90 min)

In Day 1, the use of Advanced Finite Element Analysis of composite, nanocomposite and multi-functional composite structures for aerospace applications will be presented. In the first part of the day, the main opportunities and challenges introduced by the advent of advanced composite materials in aerospace engineering will be critically discussed. Then, in the second class, particular focus will be devoted to the computational issues arising with the typical strain localization phenomena in composites.

DAY 2

Size Effect on the Structural Behavior of Composites, Nanocomposites and other Quasibrittle Materials: Theoretical Background (90 min)

Size Effect on the Structural Behavior of Composites, Nanocomposites and other Quasibrittle Materials: an Examples in Graphene Nanocomposites (90 min)

Day 2 will focus on a very important aspect related to the structural behavior of composite and nanocomposites which is, unfortunately, often overlooked: type I and type II size effect. In the first part of the day, the theoretical derivations of size effect will be introduced and demonstrated rigorously with clear reference to materials used in aerospace engineering including unidirectional composites, textile composites, nanocomposites and ceramics. The second part of the talk will exemplify size effect and its importance for the structural design of graphene nanocomposites and other nanocomposites.

DAY 3

Spectral Stiffness Microplane Model (S^2M^2) for the Computational Modeling of Composites: Theoretical Framework (90 min)

Spectral Stiffness Microplane Model (S^2M^2) for the Computational Modeling of Composites: Implementation in FE and Applications (90 min)

In Day 3, the Spectral Stiffness Microplane Model (S2M2), an advanced formulation capable of capturing the main damage mechanisms in composites and other quasibrittle materials, will be introduced and described in detail. The use of S2M2 for the crashworthiness analysis of composites structures will be presented along with its application for the analysis of another type of composite material: Discontinuous Fiber Composites (DFCs).

DAY 4

Discontinuous Fiber Composites (DFCs): Advantages and Challenges for their Structural Applications (90 min)

Discontinuous Fiber Composites (DFCs): Experimental Characterization and Modeling of Their Fracturing Behavior (90 min)

Day 4, will focus on Discontinuous Fiber Composites (DFCs). In DFCs, the reinforcing phase takes the form of carbon fiber platelets randomly distributed throughout the system. It will be shown that, the randomness of the platelet orientations leads to a significant spatial distribution of mechanical properties whereas the large dimensions of the platelets generally promote damage tolerance. By experiments on geometrically-scaled specimens and computational modeling, it will be also shown that the scaling of the fracturing behavior of DFCs is particularly interesting. In fact, the behavior transitions from quasi-ductile to brittle for increasing system sizes compared to the platelet dimensions. Leveraging these results, it is possible to design the platelet as a function of the size and geometry of the system to achieve quasi-ductility. To conclude the talk, a stochastic computational framework to capture the large variability in mechanical performance of the system will be presented. The use of the model for designing and certification of aerospace components will be discussed.

DAY 5

FE Modeling of Curing Stresses in Thermoset Composites: State-of-the-Art and Future Challenges (90 min)

Graphene Nanoplatelets for the Mitigation of Curing Stresses in Ultra-Thick Composites (90 min)

Day 5 will focus on the modeling and characterization of the thermo-chemo-mechanical process of crosslinking in epoxy-based composites leveraging advanced FEA. Simulations showing the emergence of curing stresses and their dependence on the curing cycle will be presented. Then, ongoing investigations on the use of graphene nanoplatelets to mitigate the curing stresses and damage will be presented critically.

DAY 6

Mitigation of Stress Intensity in Bodies of Revolution Reinforced by Curvilinear Fibers: Closed-Form Solution (90 min)

FEA Modeling of Composites Reinforced by Curvilinear Fibers (90 min)

Day 6 will discuss the new opportunities arising with the use of reinforcements following curvilinear paths. In the first part of the talk, a recent closed-form solution for the stress fields, stiffening effect and optimum fiber path in structures subject to shear and torsional loadings will be derived rigorously. It will be shown that, if proper paths are choses, not only the stiffening and strengthening effects can be maximized but also the stress intensity in the presence of notches or crack can be minimized. The second part of the talk discuss the formulation of an Iso-Geometric Analysis framework for the analysis of curvilinear fiber composites.

Bio-Sketch

Dr. Salviato is assistant professor at the Department of Aeronautics and Astronautics of University of Washington where he serves as the PI of the laboratory for *Multiscale Analysis of Materials and Structures* (*MAMS*). Dr. Salviato obtained a Ph.D. in Theoretical and Applied Mechanics from the University of Padova (Padova, Italy) with a doctoral dissertation focusing on the experimental characterization and computational modeling of polymer nanocomposites. He later joined the Department of Civil and Environmental Engineering at Northwestern University as postdoctoral scholar (2013-14) and research assistant professor (2014-15).

Dr. Salviato's research and teaching interests lie in the area of *Computational Mechanics* and *Fracture Mechanics of Quasibrittle Solids*. His focus is the understanding the mechanical behavior of materials and structures at multiple length-scales through the formulation of advanced computational and analytical approaches and new experimental techniques. He believes that the next-generation, damage-tolerant infrastructure will be enabled by the elimination of the old dichotomy between the concepts of "*structure*" and "*material*".

In 2017, Dr. Salviato received the prestigious *ASME Haythornthwaite Young Investigator Award* for "excellence in theoretical and applied mechanics". He also co-authored the book "*Quasibrittle Fracture Mechanics and Size Effect: First Course*".