PennState

PHRC

4TH BIENNIAL
RESIDENTIAL BUILDING DESIGN & CONSTRUCTION CONFERENCE

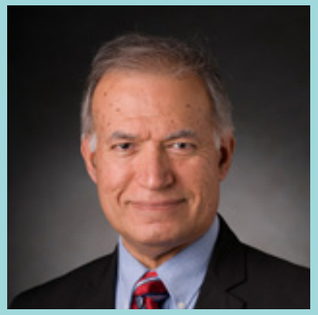
FEBRUARY 28—MARCH 1, 2018

THE PENN STATER CONFERENCE CENTER & HOTEL

WELCOME

REGISTRATION OPENS AT 7:30 AM

Dear Residential Building Design and Construction Conference Attendees,



It is my great pleasure to welcome you to the Fourth Residential Building Design and Construction (RBDC) Conference held February 28-March 1, 2018 at the Pennsylvania State University in State College, PA. This biennial conference is organized by the Pennsylvania Housing Research Center (PHRC) at Penn State and is being held in conjunction with the 26th Annual PHRC Housing Conference at The Penn Stater Conference Center & Hotel.

The Annual Housing Conference has been a successful PHRC program for 26 years with emphasis on topics of interest to developers, builders, remodelers, design professionals, planners, regulatory and code officials, modular and HUD code builders, and housing product manufacturers. On the other hand, the Biennial RBDC Conference that is being held for the fourth time is a program organized by the PHRC to provide a forum for researchers, design professionals, manufacturers, builders, and code officials to exchange knowledge and understanding on the latest research and development advancements and to discuss and share their own findings, innovations ,and projects related to residential buildings.

At the 4th RBDC Conference, we are very excited to have two keynote speakers: Professor Dr.-Ing. Bohamil Kasal, Director of the Fraunhofer Institute for Wood Research at Fraunhofer Wilhelm-Klauditz-Institut in Germany, and Professor Ryan E. Smith, Associate Dean of Research + Community Engagement and Director, Integrated Technology in Architecture Center (ITAC), University of Utah, College of Architecture + Planning. Professor Kasal will share with us the German experience of home building through his presentation titled “German Residential Construction -- What Can We Learn from It?”. Professor Smith will present new developments in the off-site aspects of home building in his presentation titled “Global Innovations in Residential Building: Prefabrication, Modularization and Automation”.

Most of the presentations at the conference are by university professors, researchers, graduate students, architects, consulting engineers, product manufacturers, and product related associations / councils. For this conference, we have also organized two special sessions, one is on Cross Laminated Timber (CLT) that is gaining recognition as a new material/system for multi-story building construction. The other one is on Building Science Education, which is a highly important aspect of implementing energy efficiency and saving in buildings. This session focuses on the essentials of the basics of building science for enclosure design to accommodate high performance buildings in undergraduate curricula in relevant university majors.

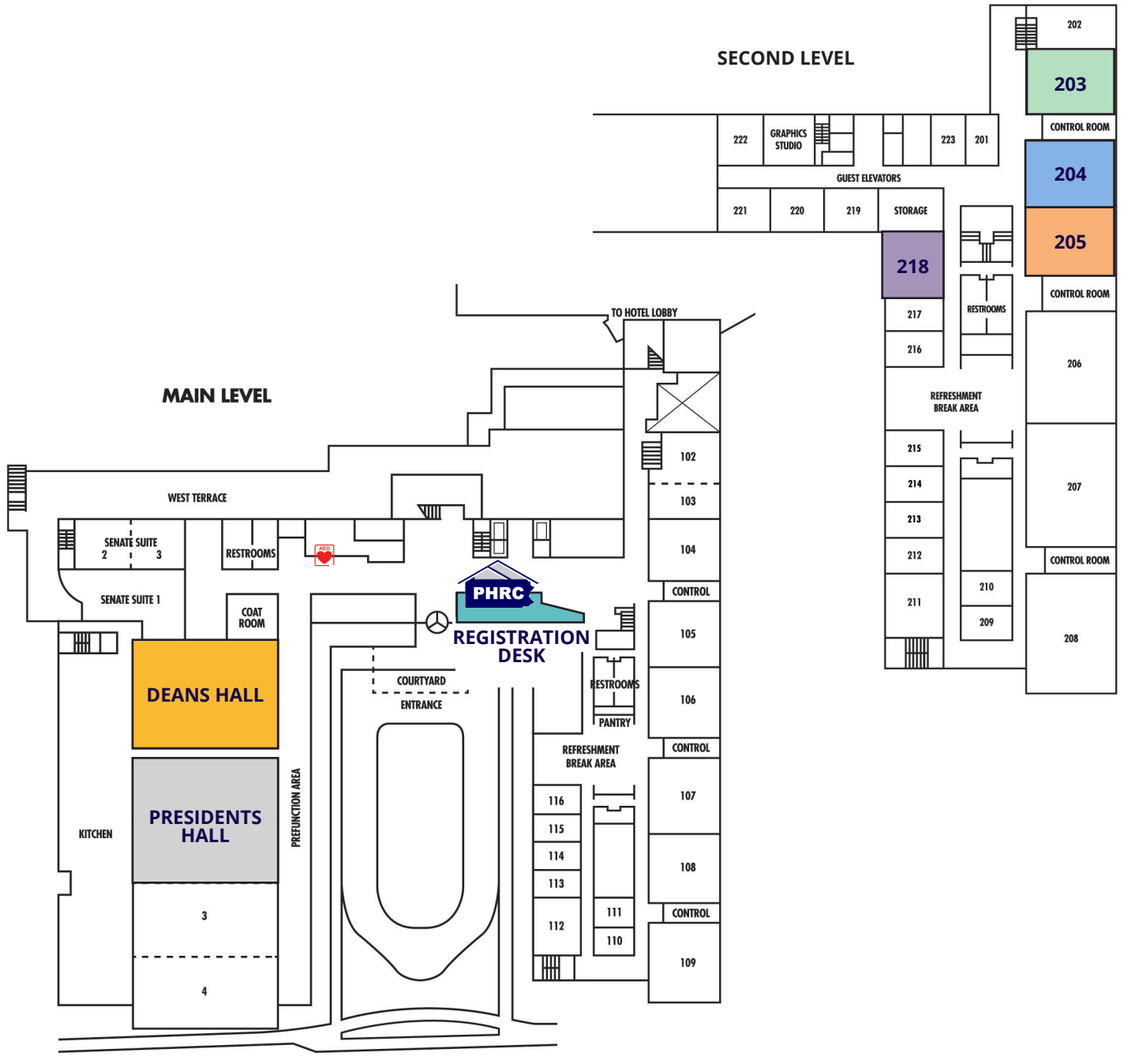
The details of most presentations in the form of full papers can be found in the proceedings of the conference. The conference papers and slide presentations (if a full paper was not submitted) can be found at this Dropbox link, *http://bit.ly/RBDCC2018 password: RBDCC2018!* and on the PHRC website after the conference. As in the past three RBDC conferences, the authors of papers are invited to consider expanding/enhancing their papers to submit for possible publication in the ASCE Journal of Architectural Engineering, Special Selection on Housing and Residential Building Construction. I hope that you find the technical content of the conference beneficial and you enjoy the opportunities for interaction and networking with colleagues.

Ali M. Memari, Ph.D., P.E., F.ASCE, Professor

4th RBDC Conference Chair
Bernard and Henrietta Hankin Chair in Residential Building Construction
Director, The Pennsylvania Housing Research Center (PHRC)
Department of Architectural Engineering and Department of Civil and Environmental Engineering
The Pennsylvania State University

Conference Papers
Password: RBDCC2018!

FACILITY MAPS



	WEDNESDAY	THURSDAY
DEANS HALL	Happy Hour on the Exhibit Floor	Lunch
PRESIDENTS HALL	Lunch	N/A
ROOM 207	Keynote	Keynote
ROOM 203	Track 1	Track 1
ROOM 204	Track 2	Track 2
ROOM 205	Track 3	Track 3
ROOM 218	Track 4	Track 4

SCHEDULE

Tuesday, February 27

4:00pm - 5:30pm	**3D Printing Concrete Robot & Building Enclosures Research Lab (BCERL) Tour** (optional)
5:30pm - 7:30pm	**Research & Education Night Reception @ Hintz Alumni Center** (optional)

Wednesday, February 28

8:30am - 10:15am **Room 207**	**Keynote | German Residential Construction: What Can We Learn From It?** *Prof. Dr-Ing. Bohumil Kasal, Director of the Fraunhofer Institute for Wood Research, Fraunhofer Wilhelm-Klauditz-Institut, Germany* *Opening Remarks : Dr. George Lesieutre & Prof. Kevin Parfitt*
10:15am - 10:45am	**Break**

10:45am - 12:15pm — **Conference Breakout #1**

TRACK 1 - Rm. 203 Design Considerations: Small Homes	TRACK 2 - Rm. 204 Building Enclosures: Moisture	TRACK 3 - Rm. 205 Design Considerations: Development	TRACK 4 - Rm. 218 Building Science Education: Essentials
The Big Picture on Tiny Houses *Matthew Lutz | Norwich University School of Architect & Art*	**Stucco System Performance: A Review of Reported Data and Code and Standard Development** *Theresa Weston | Dupont*	**The in Between: Between Custom Residential + Developer Housing** *Alistair Dearie & Brian Grieb | GriD architects & Morgan State University*	**Building Science Education Essentials** *Sam Taylor & Pat Huelman| Energy & Resource Efficiency & University of Minnesota*
Concept Paper: MODs - Next Generation Mobile Housing *Anthony Jellen | Dawood Engineering*	**Comparison of Measured Hygrothermal Performance of Wood Frame Walls Built with Continuous Exterior Insulation versus Walls Built with Housewrap and OSB Sheathing in Single Family Homes in a Cold Climate** *Greg Stewart | DOW*	**IRC and IBC Provisional Requirements for Different Scale Residential Building Products** *Ryan Solnosky | Penn State*	**At the Core: Fundamental Building Science Education Matters More Than Building Type** *Cheryn Metzger | Pacific Northwest National Laboratory*
	A Scientific Approach to Understanding the Safety Features of Roofing Underlayments *John Johnston & William Coulter| Dupont*	**Residential Building Lifespan and Community Resilience** *Alex Ianchenko | University of Washington*	**Building Science Education for Tomorrow's Architects & Engineers** *Nina Baird | Carnegie Mellon*

12:15pm - 1:15pm	**Lunch @ Presidents Hall 1 & 2**

1:15pm - 2:45pm — **Conference Breakout #2**

TRACK 1 - Rm. 203 High Performance Homes	TRACK 2 - Rm. 204 Building Enclosures: Multifamily Considerations	TRACK 3 - Rm. 205 Design Considerations: Senior Housing	TRACK 4 - Rm. 218 Building Science Education: Hands-On Learning
An Exploratory Study of Three Paths to Green Homes: Energy Star Homes, LEED for Homes, & the National Green Building Standard *Jawanda Jackson|Michigan State*	**Evaluate Compartmentalization as a Stack Effect Mitigation Strategy** *Junting Li | University of Toronto*	**Aging-in-Place Housing: Industry Trends in Pennsylvania** *Dorothy Gerring & Rob Wozniak | Penn College*	**One Book/Many Topics: But Are They Enough?** *Walter Grondzik | Ball State University*
Measuring Sustainability in Low-Energy Residential Buildings *Joshua Kneifel | NIST*	**Numerical Studies on Blockage of Fire Spread and Water Curtain** *Y.K. Woo | Hong Kong Polytechnic University*	**Housing Technology for Smart Cities** *Joe Colistra | University of Kansas*	**Experiential Learning Exercises to Further Understanding of Complex Building Science Principles** *Georg Reichard | Virginia Tech*
Is Green Housing Healthy Housing? Examining the Evidence *Sherry Ahrentzen, Elif Tural, & James Erickson | University of Florida & Virginia Tech*		**The Longitudinal Impact of Energy Education on Affordable Energy Efficient Multifamily Housing** *Frederick Paige, Philip Agee, & Andrew McCoy | Virginia Tech*	**Implementation of Project Based Learning in a Building Science Curriculum** *Jamie Russell | Appalachian State*

2:45pm - 3:00pm	**Break**

3:00pm - 4:30pm — **Conference Breakout #3**

TRACK 1 - Rm. 203 High Performance: Passive House	TRACK 2 - Rm. 204 Building Enclosures: Energy & Windows	TRACK 3 - Rm. 205 Design Considerations: Policy & Social Components	TRACK 4 - Rm. 218 Building Science Education: Race to Zero + Next Steps
Can Zero Net Carbon Buildings Scale? Passive House Data Tells the Story. *Brandon Nicholson|Nicholson Kovalchick Architects*	**Building Envelope as an Effective Strategy for Achieving Sustainable Building Energy Efficiency** *Joseph Iwaro | University of the West Indies, Trinidad & Tobago*	**Housing Technology and the Contemporary Policy Context in the U.S.** *Carlos Martín, Andrew McCoy & Frederick Paige | Urban Institute & Virginia Tech*	**Three Courses/Four Typologies: Experiences with the 2017 Race to Zero Competition** *Tom Collins & Walter Grondzik | Ball State University*
Passive Building (Passive House) *Adam Ugliuzza | Intertek*	**Energy Efficient Geometrical Design Parameters of Windows in Residential Building: A comparison between hot and cold climates in the United States** *Reza Foroughi | Penn State*	**Social Housing Architecture as a Generator of Social Practices** *Gülcan Ay | Istanbul Technical University*	**2016-2017 Race to Zero Competition: A Case Study Design for Zero Energy Ready Townhomes** *Chris Hazel & Sarah Klinetob Lowe | Penn State*
	Windows of Opportunity: Fenestration Innovations, Driven by Demand *Bob Dudish | Marvin Windows*	**Context-Specific Cultural Drivers & Barriers to Sustainable & Resilient Building Systems: Lessons from the hot and humid Tanzanian Coast** *Esther Obonyo | Penn State*	**Building Science Education: Where Do We Go From Here? Discussion Forum** *Sam Taylor & Pat Huelman*

6:00pm - 9:00pm	**Happy Hour on the Exhibit Floor! @ Deans Hall**

Thursday, March 1

8:30am - 10:15am **Room 207**	**Keynote | Global Innovations in Residential Building: Prefabrication, Modularization & Automation** ***Professor Ryan E. Smith | Associate Dean of Research + Community Engagement & Director, Integrated Technology in Architecture Center (ITAC) at University of Utah, College of Architecture + Planning*** ***Opening Remarks : Dr. Ali Memari***
10:15am - 10:45am	**Break**

10:45am - 12:15pm — **Conference Breakout #4**

TRACK 1 - Rm. 203 Designing for Resiliency	TRACK 2 - Rm. 204 HVAC Design	TRACK 3 - Rm. 205 Cross Laminated Timber #1	TRACK 4 - Rm. 218 Penn State & the UN Global Building Network
Measuring Sustainability & Resilience Tradeoffs across Post-Disaster Temporary Housing ***Lauren Badeaux & Elaina J. Sutley| University of Kansas***	**Balancing Ventilation & Airtightness in Residential Buildings** ***Sean O'Brien & Scott Bondi | Simpson, Gumpertz & Heger***	**Building Energy and Hygrothermal Analysis of Single Family Residential Building with Laminated Timber** ***Lewis Setter, Eric Smoorenburg & Paulo Tabares| Colorado School of Mines***	**The Global Building Network: Achieving High Performance for Everyone, Everywhere** ***Tom Richard & Jim Freihaut | Institute of Energy & the Environment & Penn State***
Amphibious House: A Novel Flood Mitigation Strategy ***Anthony Graham | Western Kentucky University***	**A Net-Zero Energy, High Performance Residential Building Testbed: Performance Comparisons Between Two Equipment Configurations** ***Brian Dougherty | NIST***	**Numerical Model of Creep Behavior for Axially Loaded CLT Panels** ***Thang Dao | University of Alabama***	
Enhancing the Damage Prediction Capability of a Tornado Risk Assessment Tool ***Anant Jain | University of Florida Gainesville***	**Integrated Space & Water Heating (Combi) Systems for High-Performance Homes in Cold Climates** ***Pat Huelman | University of Minnesota***	**Fire Performance of CLT Adhesives in Residential Floor Applications** ***Shiling Pei | Colorado School of Mines***	**50 Houses: Global Building Network Passive House Retrofit Project through passivhausMAINE** ***Naomi Beal| passivhausMAINE***

SCHEDULE

12:15pm - 1:15pm	**Lunch at Deans Hall**

1:15pm - 2:45pm — Conference Breakout #5

TRACK 1 - Rm. 203 Energy Modeling	TRACK 2 - Rm. 204 Building Enclosures: Quality & Affordability	TRACK 3 - Rm. 205 Cross Laminated Timber #2	TRACK 4 - Rm. 218 Community Impacts
Closing the Post-Occupancy Gap in Zero Energy Housing *Philip Agee | Virginia Tech*	**An Innovative Building System for High-Performance Affordable Housing** *Pat Huelman | University of Minnesota*	**Cross Laminated Timber as an Alternative for Single Family Construction: A Comparative Cost Study** *Shiling Pei | Colorado School of Mines*	**The value of campus-based solar demonstration homes for students, faculty, and communities** *Mahsa Safari | Penn State*
Impact of Occupant Behavior in Data-driven Energy Use Modeling in Diverse Residential Buildings Across Multiple Climates *Huyen Do | Iowa State*	**Racking Testing Facility to Evaluate In-Plane Performance of Structural Insulated Panels** *Ryan Solnosky | Penn State*	**The Use of Cross-Laminated Timber for Mixed-Use Tall Wood Buildings in the US** *Shaobo Liang | North Carolina State University*	**Participatory Learning through the Race to Zero Competition** *Chris Hazel & Sarah Klinetob Lowe | Penn State*
	Experimental & Numerical Study of Moisture Movement in Sealed Attics *David O. Prevatt|University of Florida*	**Cross Laminated Timber & Beetle Kill Lumber** *Eric Holt | University of Denver*	**GreenBuild: University-Industry Collaboration for an Affordable, Energy Efficient Duplex** *Jason Grottini, Jordan Robb, & Chris Hazel | Envinity Inc. & Penn State*

2:45pm - 3:00pm	**Break**

3:00pm - 4:30pm — Conference Breakout #6 / Tour Option

3:00pm - 4:30pm Tour Option	**Tour of GreenBuild Duplex** 1394-1396 University Drive	*Hosted by the Energy Efficient Housing Research Group / Hamer Center for Community Design*	*** Please pre-register for this tour at the registration desk; space is limited!**

TRACK 1 - Rm. 203 Residential BIM	TRACK 2 - Rm. 204 Building Enclosures: Innovative Materials	TRACK 3 - Rm. 205 Concrete + 3D Printing	TRACK 4 - Rm. 218 Building Enclosures: Control Layers
The Role of BIM in Designing Zero-Net Energy Homes *Shahryar Habibi | University of Ferrara, Italy*	**Designing High R-value Walls using Stone Wool Insulation** *Antoine Habellion | ROCKWOOL*	**A Brief Literature Study of Nanoparticles Supplementation in Civil Cementitious Materials** *Mehrzad Zahabi | Penn State*	**Site Quality Assurance Programs – How This Has Improved Air Barrier Installations** *John Arcidiacono | Air Barrier Association of America*
Software Tool for Automation in Building Energy Simulation Using Building Information Modeling (BIM) *Ehsan Kamel | New York Institute of Technology*	**Impact of Positioning Phase Change Materials (PCMs) within Building Enclosures on Thermal Performance** *Abdullah Abuzaid | Virginia Tech*	**Seamless Architecture: Design & Development of Functionally-Graded Green Materials for Building Construction** *Maryam Hojati, Shadi Nazarian, and José Duarte | Bucknell University & Penn State*	**Exterior Sheathing, WRB's, & AB's: Moisture-related material properties and implications on design & in-service performance** *Danko Davidovic | Huber Engineered Woods*
	Performance Evaluation of Wall Panels Incorporating New and Innovative Materials Developed with High Insulation Properties *Xinrui Lu | Penn State*	**Additive Manufacturing of Building Parts: Towards Seamless Architecture** *Flavio Craveiro, José Duarte, & Shadi Nazarian | Penn State*	

KEYNOTE

WEDNESDAY | 8:30 AM – 10:15 AM | ROOM 207

GERMAN RESIDENTIAL CONSTRUCTION: WHAT CAN WE LEARN FROM IT?

PROF. DR-ING. BOHUMIL KASAL

DIRECTOR OF THE FRAUNHOFER INSTITUTE FOR WOOD RESEARCH, *FRAUNHOFER WILHELM-KLAUDITZ-INSTITUT, GERMANY*

German residential construction systems are mostly designed and built heavy masonry or concrete block systems. A relatively small percentage of homes are built in timber, and relatively heavy timber systems are used. Various factors ranging from code requirements to public perceptions and expectations influence the preferences of the German market. The German codes required homes to be designed based on performance criteria that specify requirements related to energy consumption, structural, and fire performance. The energy and fire performance criteria are relatively strict and must be reflected in the material and constructions systems used. In addition, the German consumer requires a virtually maintenance-free house, which results in using high-quality and durable materials such as copper or stainless-steel flashing, stainless steel in exterior conditions, ceramic tile roofs, natural stone, etc. A number of high performance hollow bricks, concrete masonry units, and insulation and cladding systems are available on the market, which makes the price of the all-masonry units and systems highly competitive compared to wood construction.

The requirements on acoustic performance, dictated mostly by market expectations, are not favorable for implementation of light-frame systems, and this favors the higher mass solutions offered by the heavy masonry or concrete floor systems.

The construction of single-family homes and apartment houses range from classical on-site construction to highly prefabricated and/or panelized systems. The prefabrication is especially used in wood-based systems but the masonry and concrete buildings use the prefabricated units as well.

The presentation will overview the German housing market, code requirements, market expectations, and will use examples to demonstrate the residential construction process in Germany.

Prof. Dr.-Ing. Kasal has been the Director of Fraunhofer Wilhelm-Klauditz-Institut WKI in Braunschweig, Germany, the world´s largest research institute focusing on lignocellulosic materials since October 2010.

Professor Kasal concurrently holds a Chair in Organic and Wood-based Construction Materials at the Technische Universität Braunschweig, Germany. He holds an Ing. degree (engineer) from the University of Zvolen, Slovakia, an MS in Wood Science from Virginia Tech, and a MS in Civil Engineering and PhD in Wood Structures from Oregon State University. He was also a Senior Fulbright Fellow in Germany in 2001 to 2002.

From 2005 to 2010 Professor Kasal held the prestigious Bernard and Henrietta Hankin Chair and two professorships (Civil Engineering and Architectural Engineering) at the Pennsylvania State University, and was the Director of the Pennsylvania Housing Research Center. Prior Professor Kasal was a Professor at the North Carolina State University in Raleigh, NC. In addition, he has over seven years of outside-academia experience. Professor Kasal's research is focused on wood structures under natural hazard loads, combination of wood and high-strength composites, and in-situ evaluation of wood structures. He authored over 200 papers and research reports, serves in editorial board of Journal of Materials and Structures, Wood Science Journal, Acta Facultatis Xylologiae Zvolen, chairs RILEM committee on in-situ evaluation of timber structures and actively participates in national and international professional organizations. Professor Kasal has lectured at universities around the world including Joseph Fourier University, Chalmers University and Universities in Graz, Vienna, Dresden, Stuttgart, Sopron, and others.

His research in seismic performance of timber frames was selected by the European Community as an example of a successful international project; the National Science Foundation used Kasal's work in historic structures in its report to the Congress of the United States, and his work addressing the wind performance of residential structures was discussed on various media outlets including CNN, CNN International, NBC and ABC networks.

Professor Kasal holds Professorships at the Czech Technical University in Prague, University of Primorska, Slovenia, North Carolina State University (associate status) and is an Honorary Research Fellow at the University of New Brunswick, Canada.

PROGRAM | BREAKOUT 1

WEDNESDAY | 10:45 AM – 12:15 PM

DESIGN CONSIDERATIONS: SMALL HOMES | 203

THE BIG PICTURE ON TINY HOUSES

SPEAKER: Matthew Lutz, *Norwich University School of Architect & Art*

In August, 1970, the newly formed United States Council on Environmental Quality (CEQ) published "Environmental Quality, The First Annual Report of the Council on Environmental Quality together with the President's Message to Congress." While the CEQ estimated in 1970 that 9 trillion kWh's would be produced annually by 2000, real-world figures put global electricity production at 14.6 trillion kWh's, with a staggering 23.3 trillion kWh's electricity produced in 2013. A small, but notable trend that may offset energy consumption is emerging in a grassroots architectural counterculture movement focused on designing and building tiny houses. These small dwellings, ranging between 120 square feet and 400 square feet, have a dual mission. They simultaneously aim to consolidate, simplify, and minimize the energy requirements of the average size house while relieving its occupants of the burdens that come with owning a typical house. Tiny houses are entering the mainstream, with half a dozen reality television programs airing on cable networks, many municipalities adapting local codes to allow for 'accessory' dwelling units, and some banking institutions developing interest in tiny house lending models. This paper will examine the driving forces behind the tiny house movement and question how that movement might evolve and adapt to accommodate future scenarios. Full-scale design / build prototypes developed at Norwich University serve as the case-studies that prove, disprove, and bring into question the effectiveness of the tiny house.

CONCEPT PAPER: MODS - NEXT GENERATION MOBILE HOUSING

AUTHORS: Anthony Jellen, *Dawood Engineering* & Ali Memari, *Penn State*

SPEAKER: Anthony Jellen

Mobile homes have provided an affordable housing alternative for many over recent decades, but the design concept has changed little over recent years and designs have become increasingly less "mobile." In this paper, we introduce the concept of an alternative plug-in type mobile housing system that puts "mobile" back in mobile home design. The MOD concept reexamines the notion of affordable housing and puts forth a next generation mobile housing solution that considers the differences in this generation of potential homeowners, utilizes modular construction techniques, incorporates recent technological advances and can be contemporary in appearance. The units can be inserted into a multi-story structural framing system specifically designed for MOD units or be used in a stand-alone setting. A MOD unit is wholly owned by its occupant and provides an affordable housing solution that is appropriate for the transient lifestyle of this generation of young adults.

BUILDING ENCLOSURES: MOISTURE | 204

STUCCO SYSTEM PERFORMANCE: A REVIEW OF REPORTED DATA AND CODE AND STANDARD DEVELOPMENT

AUTHOR: Theresa Weston, *DuPont*

SPEAKER: Theresa Weston

Stucco is a widely used and growing exterior cladding in residential construction, comprising 24% of the primary exterior wall material in 2015, up from 16% in 1995, according to the US Census Bureau. Stucco use is regional being concentrated in the West (56% in 2015) and South (21%). Despite stucco's popularity over the last 20 years, stucco systems have been associated with a number of performance questions, including cracking and water intrusion, which have in some cases resulted in construction litigation. Additionally, industry codes and standards which govern the use of stucco systems over wood based construction have had significant changes during this time period. This paper reviews the treatment of stucco systems in industry guidelines, codes and standards, with specific focus on the stucco applied over wood based substrates. These industry codes and standards and their development are analyzed against a framework developed from a data and literature review. The framework was created from the review of data presented industry reports and publications, including laboratory testing, field testing and case studies. Individual variables included in the review include: stucco material and its application, the stucco substrate and its installation, assembly interface detailing and edge effects, regional construction practices and climatic conditions.

COMPARISON OF MEASURED HYGROTHERMAL PERFORMANCE OF WOOD FRAME WALLS BUILT WITH CONTINUOUS EXTERIOR INSULATION VERSUS WALLS BUILT WITH HOUSEWRAP AND OSB SHEATHING IN SINGLE FAMILY HOMES IN A COLD CLIMATE

SPEAKER: Greg Stewart, *DOW*

Many wall assembly options exist for wood frame construction and typically a choice is made between assemblies which include continuous exterior insulation and assemblies that include housewrap. Often this decision is made by considering a dew point analysis of cavity condensation potential or by considering the prediction of wall drying mechanisms based on modeling. Six single family occupied homes have been constructed with continuous exterior insulation and six identical homes have been constructed with housewrap, in the same neighborhood in climate zone 5. Moisture content measurements of the condensation plane, continuously recorded for the past 4 years, in the rim joist and above grade walls are compared. Additionally, similar test wall assemblies with moisture sensors are installed in a long term exterior exposure test unit which allows comparison between long term semi-controlled tests, i.e. those where the interior climate is carefully controlled, and homes where occupant behavior controls interior conditions and wall performance. Finally the measured results are compared to predicted modeled performance. Forensic investigation and sampling of wall and rim joist areas of select homes in the study are presented for comparison of observed material condition and expected condition based on moisture exposure, both predicted and observed.

A SCIENTIFIC APPROACH TO UNDERSTANDING THE SAFETY FEATURES OF ROOFING UNDERLAYMENTS

SPEAKERS: John Johnston & William Coulter, *DuPont*

Safety is a top priority and daily concern for roofing contractors. The purpose of this study was to provide a greater understanding of the physical properties that affect the safety characteristics of roofing underlayments. This was done in a three step process by defining levels of safety performance with respect to grip and traction, identifying the mechanical properties of underlayments that enhance grip and traction properties, and then developing the scientific explanation for the efficacy of these mechanisms. In residential roofing, there are several grades of roofing felt and dozens of brands of synthetic roofing underlayments, each offering some type of safety feature in the areas of traction and grip, also known as "walkability". The challenge has been the lack of a measurement system that accurately translates the physical properties of underlayments into walkability. In order to meet this challenge, this study started with the concept of walkability by having roofing contractors rate and rank various types of underlayment materials in terms of walkability. Because roofing installers work under a number of different environmental conditions, the scope of the walkability evaluation process included conditions where the test materials were dirty, wet and dry, as well as under warm and cold conditions. In the ratings and ranking of these products by roofing contractors, it was found that the performance of some products increased at lower temperatures, while the performance of other products was diminished at lower temperature. It was also found that the some underlayment materials maintained a good level of walkability under wet and dry conditions, while other materials did not. Thus, the measurement systems developed to characterize these products considered all of these conditions, as well as correlated to the input provided by the contractors.

DESIGN CONSIDERATIONS: DEVELOPMENT | 205

THE IN BETWEEN: BETWEEN CUSTOM RESIDENTIAL + DEVELOPER HOUSING

AUTHORS: Alistair Dearie, *GriD architects* & Brian Grieb, *Morgan State University*

SPEAKERS: Alistair Dearie & Brian Grieb

We all know architects are often perceived as exclusively accessible to the rich. Architects themselves, on the other hand, lament the lack of design thoughtfulness associated with suburban sprawl and the "cookie cutter house". But what about the in between? There seems to be a gap in architects providing design for the extremely wealthy and the demographic of the middle class family marketed to by the suburban developer. The talents of architects have even been significantly leveraged on low income housing. In a world where everything can and should be thoughtfully designed how can architects fill the gap and provide design services on projects for modest budgets? We have a significant portfolio of single-family residential projects that accomplish this goal. Call it "custom without being custom". These projects have all been executed at less than $200/SF and provide extremely sustainable homes that employ both passive and active strategies to maximize comfort and indoor air quality. They are also beautiful - skillfully crafted to meet the specific needs of our clients and the particular aspects of their homes site.

IRC AND IBC PROVISIONAL REQUIREMENTS FOR DIFFERENT SCALE RESIDENTIAL BUILDING PRODUCTS

AUTHORS: Wangjae You & Ryan Solnosky, *Penn State*

SPEAKER: Ryan Solnosky

Residential construction projects can vary vastly in size from single family homes to vast residential high-rise towers and everything in-between. Due to this residential scale in the building industry, the governing building codes and standards for residential construction are complex and spread across multiple documents. On the small size, designs are governed by the IRC while large projects are governed by the IBC. Specific wording within IBC mandates special requirements for large projects that are used for residential applications thus making the code more cumbersome to navigate through. To clarify design requirements, this paper will discuss a comparison of provisions through guidelines between the IBC and IRC in relationship to other relevant codes and standards. Details will focus on the differences, limitations, and general processes necessary to ensure different residential projects meet all design code requirements. The results will give designers and builders a better understanding of the complexity of code provisions and prevailing factors that influence and scope the design through clarifying code intent.

RESIDENTIAL BUILDING LIFESPAN AND COMMUNITY RESILIENCE

AUTHORS: Alex Ianchenko, *University of Washington*; Kathrina Simonen, *University of Washington;* Yingjun Wang, *University of Oklahoma*; Naiyu Wang, *University of Oklahoma*

SPEAKER: Alex Ianchenko

Developing meaningful estimates of the life cycle impacts of a building relies on setting an appropriate estimate of the building's lifespan. Nevertheless, most conducted LCA studies are based on an arbitrary building lifetime. This research, focuses on modeling the lifetime of housing stock divided by decade of construction (a 'cohort') in order to generate a probabilistic assessment of residential building turnover. Data from the American Housing Survey (AHS) National Summary Reports and the New Residential Construction Housing Starts (NRC) was compiled and analyzed. Relevant data was extracted and then analyzed both in its raw format and as a set of normalized curves. The results show that each cohort of housing from the 20th century behaves in a similar way when normalized, although there is not yet enough data to definitively pinpoint the average lifespan of housing stock since the available data does not suggest a "peak" in the number of demolitions reached. The existing data suggests that housing longevity exceeds the previously accepted average of 61 years and can vary from cohort to cohort, potentially due to economic conditions at the time of construction and demolition. Assuming a range of possible lifespans for individual buildings, a Monte Carlo Simulation was performed and further revealed that the turnover time of a community housing stock is determined by the characteristics of the typical housing units within the community and can be significantly longer than average housing lifespan estimates.

BUILDING SCIENCE EDUCATION: ESSENTIALS | 218

BUILDING SCIENCE EDUCATION ESSENTIALS

SPEAKERS: Samuel Taylor, *Energy & Resource Efficiency* & Pat Huelman, *University of Minnesota*

Building science fundamentals and more advanced courses are taught in a few North American schools, particularly schools in Canada. [However, the quality of building science education varies widely.] In general, when design/construction students take these building science courses, if offered, it is a graduate or senior elective course. Non-engineering design/construction students often struggle with the curriculum, particularly the critical hygrothermal performance and analysis lessons. Priority building science concepts should be introduced earlier, perhaps infused into traditional freshman and sophomore classes, and a regular part of studio/project learning. [Perhaps, "an integrated building science education program from freshman to graduate to post graduate courses", that is a core requirement for future design/construction professionals, is needed?] During the last Penn State Conference, at the building science education (BSE) session, we addressed "not so difficult steps" for implementing building science education in university programs for future design/construction professionals. What we lacked was actual content in a form that could be immediately implemented. At the conference, we also took steps to form a Joint Task Group (JTG) between BETEC and the Joint Committee on BSE of building scientists to provide such content and address certain priority needs. These included: development of a hygrothermal performance and analysis guide (initially for DOE Race to Zero competition students and faculty), and teaching resources for infusion, including lesson modules, of priority building science into traditional courses. Progress of the JTB and related DOE funded research will be presented. Recommendations would be provided on priority BSE essentials that can be implemented, and how they could fit into crowded curriculum. Learning objectives, resources, and possibly a model course module for building enclosure and hygrothermal (H.A.M.) issues would be addressed.

AT THE CORE: FUNDAMENTAL BUILDING SCIENCE EDUCATION MATTERS MORE THAN BUILDING TYPE

AUTHORS: Cheryn Metzger, *Pacific Northwest National Laboratory*; Samuel Rashkin, *Department of Energy*; Pat Huelman, *University of Minnesota*; Anne Wagner, *Pacific Northwest National Laboratory*
SPEAKER: Cheryn Metzger

As building technologies become more advanced, the need for highly skilled and qualified workers has increased. Both residential and commercial building industries struggle to capture the full benefit of these new technologies because of the limited building science knowledge base of the professionals researching, designing, building, and selling these structures. To help address this need, the U.S. Department of Energy's (DOE's) Residential Building Integration (RBI) program initiated the Guidelines for Building Science Education (GBSEs). These guidelines provide guidance on the fundamental building science knowledge base that is helpful for a wide range of building industry jobs. This effort provides a mechanism for training organizations to align core curriculum that can be applied to any building type. At the same time, DOE's Commercial Building Integration (CBI) program has been spearheading a full suite of impactful initiatives including the Better Buildings Workforce Guidelines (BBWGs), which provide voluntary national guidelines from which select stakeholders can develop high-quality and nationally recognized training and certification programs. The BBWG framework helps to improve quality and scalability issues for five energy efficiency-related jobs: Building Energy Auditor, Building Commissioning Professional, Building Operations Professional, Building Operations Journey-Worker and Energy Manager. The residential and commercial building programs are both interested in helping to create better buildings through an improved workforce. The two program initiatives complement each other in many ways. The GBSEs pave the way for more specialized training and education offered by industry and academia, which lead to credentials that signify competency. The BBWGs cover credentialing for energy efficiency jobs—a critical area that DOE believed could benefit from incentives for credentialing bodies and building operators that would improve the energy efficiency of commercial buildings. This paper summarizes the steps DOE programs have taken to work together and the outcome of this symbiotic relationship.

BUILDING SCIENCE EDUCATION FOR TOMORROW'S ARCHITECTS & ENGINEERS

SPEAKER: Nina Baird, *Carnegie Mellon*

Carnegie Mellon University's School of Architecture has one of the largest cohorts of architecture faculty and graduate students engaged in building science in North America and a long record of excellence in teaching building science by bringing graduate coursework, research and design practice activities into the undergraduate program. To engage today's design undergraduates in building science topics, however, requires methods beyond lecture and calculators. Experiential learning methods engage architecture students in tangible and intangible ways. Structured hands-on opportunities improve learning outcomes by making visible and explicit the connection between fundamental science, applied knowledge and the process of synthesis. This presentation describes course content and illustrates student outcomes for building science education in Carnegie Mellon's undergraduate BArch program. It also proposes updates to building science curricula based on emerging issues of health and durability in building performance that arise from climate change and global urbanization.

BREAKOUT 2

HIGH PERFORMANCE HOMES | 203

AN EXPLORATORY STUDY OF THREE PATHS TO GREEN HOMES: ENERGY STAR HOMES, LEED FOR HOMES, & THE NATIONAL GREEN BUILDING STANDARD

AUTHORS: Jawanda Jackson, Matt Syal, & Sinem Mollaoglu, *Michigan State*
SPEAKER: Jawanda Jackson

Residential green building rating systems are known for their ability to assist in the development of high-efficiency residential buildings, also known as green homes. Because these systems seemingly deliver similar products, there is much confusion among builders, consumers, and local governments about the similarities and differences of these programs. The Energy Star for Homes, LEED (Leadership in Energy and Environmental Design) for Homes, and National Green Building Standard (NGBS) are three nationally adopted residential green building rating systems that have a common goal, but utilize different processes for awarding certification. This study aims to compare the certification processes of these three systems. When comparing credit and documentation requirements, phases of the certification process and delivery process were considered. Credit requirements for the LEED and NGBS systems were evaluated in a side-by-side comparison to determine in which phase credits were earned. Process flow diagrams were used to map the certification process and identify points for documentation requirements. Eighteen builders and third-party raters that had previous experience with at least one of these three nationally adopted systems were interviewed to discuss their experience with the certification process. The findings of this study expand existing comparisons when considering the similarities and differences of the systems and gives insights to rating system selection to meet the needs of builders, consumers, and local municipalities.

MEASURING SUSTAINABILITY IN LOW-ENERGY RESIDENTIAL BUILDINGS

AUTHORS: Joshua Kneifel & Eric O'Rear, *National Institute of Standards and Technology*
SPEAKER: Joshua Kneifel

The Applied Economics Office (AEO) of the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST) has extended its metrics and tools for sustainable building products, known as BEES - Building for Environmental and Economic Sustainability (http://ws680.nist.gov/bees), to whole buildings to provide practical metrics, data, and tools to support decisions related to sustainable building designs, technologies, standards, and codes. Whole building sustainability metrics have been developed based on innovative extensions to life-cycle assessment (LCA) and life-cycle costing (LCC) approaches involving whole building energy simulations. The measurement system evaluates the sustainability of both the materials and the energy used by a building over time. It assesses the "carbon footprint" of buildings as well as 11 other environmental performance metrics, and integrates economic performance metrics to yield science-based measures of the business case for investment choices in high-performance green buildings. Building Industry Reporting and Design for Sustainability – BIRDS (http://ws680.nist.gov/Birds) – applies these sustainability metrics to three extensive whole building performance databases. Two databases allow for analysis of increased energy efficiency for commercial and residential buildings based on building requirements defined in industry consensus standards (ASHRAE 90.1) and codes (IECC). A 3rd database allows for analysis across energy, economic, environmental, and indoor environmental quality impacts from incremental energy efficiency measures across 10 building components based on a validated model of NIST's Net-Zero Energy Residential Test Facility (NZERTF) in Gaithersburg, MD. This paper gives an overview of the BIRDS web interface, the data available in the current Low-Energy Residential Database, future data additions to the Low-Energy Residential Database, and a case study using the database to evaluate and compare the sustainability performance of alternative building designs achieving net-zero energy performance to that of a state energy code compliant design.

IS GREEN HOUSING HEALTHY HOUSING? EXAMINING THE EVIDENCE

AUTHORS: Sherry Ahrentzen, *University of Florida*; Elif Tural, *Virginia Tech*; & James Erickson, *Arizona State University*
SPEAKER: Sherry Ahrentzen

For many in the housing industry and in the general public, "green design and construction" may seem to also reflect building performance for occupant health. A 2006 report of research conducted by the National Center for Healthy Housing demonstrated, however, that this was not necessarily a safe assumption. This paper presents research that expands and updates that earlier 2006 research, by examining the extent to which today's green building certification programs for residential structures achieve a building performance that maximizes a healthy living environment for occupants. Two national health-related building certification standards – WELL and National Healthy Housing Standard – represent benchmark resources for identifying health-related design and building measures for multifamily residential. Our analysis examined the correspondence of the health provisions of these two standards with design, construction, operations and management measures of two green certification programs for housing: LEED for Homes (version 4) and Enterprise Green Communities 2015 Criteria. Results of this correspondence are described for: biological contaminants in indoor air quality (IAQ), chemical contaminants in IAQ, and ventilation. The results indicate that these green building programs address a segment of health-related occupancy concerns, but are far from being as comprehensive as the health-related housing certification standards. In a few instances, possible conflicts between green programs and healthy housing guidelines may actually exacerbate or compromise occupant health. The paper ends with suggestions for advancing a healthier housing stock in light of green building programs.

BUILDING ENCLOSURES: MULTIFAMILY CONSIDERATIONS | 204

EVALUATE COMPARTMENTALIZATION AS A STACK EFFECT MITIGATION STRATEGY

AUTHORS: Junting Li, Brenda McCabe, Kim Pressnail, & Arash Shahi, *University of Toronto*
SPEAKER: Junting Li

Air movement can have a major effect on the energy performance and serviceability of tall residential buildings. Airflow occurs vertically, through elevator shafts and stairwells, or laterally through doorways, operable windows, and leakage openings in the building envelope. Air movement is caused by pressure differences created by a combination of stack effect, wind effect, mechanical ventilation, and elevator piston effect. However, during the heating season, stack effect is a major contributor to air movement in tall residential buildings in cold climates. The first objective of this paper is to review stack effect related issues in tall residential buildings. Three problems are summarized from issues commonly reported, which are life safety, serviceability, and ventilation related issues. Several mitigation strategies including active and passive strategies are discussed in this paper, as well as their limitations when applied to tall residential buildings. This paper then identifies 'compartmentalization' as a reliable approach to mitigating stack effect induced problems. Compartmentalization is an effective solution for controlling airflows in tall residential buildings, especially air flows related to occupants opening windows or balcony doors. Assessing the extent to which tall residential buildings are currently being compartmentalized is difficult because field measurement data are generally, unavailable. Hence, the third goal of this paper is to investigate ways in which airtightness data can be gathered in order to evaluate the effectiveness of compartmentalization. This paper examines three common challenges when conducting airtightness test in tall residential buildings, which are inconsistency in testing method, airtightness metric and documented normalized surface area.

NUMERICAL STUDIES ON BLOCKAGE OF FIRE SPREAD AND WATER CURTAIN

AUTHORS: K.W. Lau, Y.K. Woo, and W.K. Chow, *Hong Kong Polytechnic University*
SPEAKER: Y.K. (Wilson) Woo

This paper presents the results of application of water curtain system for blockage of fire spread as it is widely used in fire protection of lives and properties in Hong Kong. By using the system, water is discharged in the form of a linear curtain for protection against internal or external exposure to fire spread; or as a fire separation barrier between the fire side and the non-fire side. Many studies on the physics and chemistry of the water curtain in fire protection conducted by the researchers and scientists in the past both experimentally and academically, provide valuable results and findings. The relationship amongst the operating physical factors for the water curtain in radiation attenuation is investigated and general equations on their co-relation are established. Computational Fluid Dynamics (CFD) is adopted to identify the radiation intensity. Radiation attenuation performance by water curtain system is defined by the radiation attenuation ratio when there is or there is no water curtain protection under different designed fire scenarios. Multiple regression analysis is used to evaluate the coefficient and power factors of the variables in the derived formula. Data test is also conducted to verify the formula for the prediction of radiation attenuation by water curtain. The result shows that water curtain performs well in the attenuation of radiation from fire.

DESIGN CONSIDERATIONS: SENIOR HOUSING | 205

AGING-IN-PLACE HOUSING: INDUSTRY TRENDS IN PENNSYLVANIA

SPEAKERS: Dorothy Gerring & Rob Wozniak, *Penn College*

Aging-In-Place Housing? What is it? Sometimes is designed and built under the name of Universal Design, where as a result of birth, age, accident or disease, such housing is not specific to a particular age or disability. What does it look like? And when it comes to Pennsylvania, do we know what the demand is and where these homes are being built? This presentation will communicate the data collected describing the locations where these homes are being built in Pennsylvania; residence square footages; housing costs; building systems and amenities; and market forces. Statistics will be used to look at how residential based construction Aging-In-Place / Universal Design in Pennsylvania compares to the national trends; how the value of such housing is marketed to the public by industry; current market share, and the demand for such. The focus will be on one and two family housing starts since 2010 rather than the remodeling industry through surveys of architectural and contracting firms. Conclusions from current and future market trends will be presented and this information can help to define employment opportunities for graduates and alumni desiring to make a difference by working within the residential market sector to provide residences that everyone can live in - for the rest of their life. This is SustainAble design.

HOUSING TECHNOLOGY FOR SMART CITIES

AUTHOR: Joe Colistra, *University of Kansas*
SPEAKER: Joe Colistra

This paper will present research being conducted to develop sustainable and affordable housing that leverages Population Health strategies for Smart Cities. We are currently developing a multifamily prototype housing unit that demonstrates best practices in aging-in-place strategies and telehealth technology. We are also investigating prefabricated construction methodologies that will be utilized to bring plug-and-play technology infrastructure to the exploding senior housing demographic. Gigabit networks allow Smart Cites to collect and analyze vast amounts of data. This data is like a new kind of natural resource; one that will have as much impact on the way we plan cities as water and electricity did one hundred years ago. (KCUR, 2017) Sensors embedded in the built environment are able to collect such information as 1) Human Vital Signs (heart rate, breathing, body temperature, weight, blood pressure, hydration), 2) Physical Activity (Activities of Daily Living, falls, gait, sleep), 3) Environmental Factors (temperature, humidity, air quality, water quality, weather), and 4) Pharmaceutical Regiments (over dosing, missing doses). Population Health strategies utilize the collection and analysis of such data to deliver health care more affordably, affectively, and sometimes before we know we need it. Some of the more advanced technologies will include: Motion Sensors/Fall Detection, Gait-Analysis (determination of early onset Alzheimer's and Parkinson's), Automated LED Smart-Spectrum Lighting (optimizing circadian rhythms), Smart Mirrors, Smart Toilets (hydration monitoring/diuretic dosage), Sleep Sensors (ballistic cardiogram), and Automated Medicine Dispensers (coupled with Smart Toilet for heart medication).

THE LONGITUDINAL IMPACT OF ENERGY EDUCATION ON AFFORDABLE ENERGY EFFICIENT MULTIFAMILY HOUSING UNITS

AUTHORS: Frederick Paige & Philip Agee, *Virginia Tech*; Dong Zhao, *Michigan State*; & Andrew McCoy, *Virginia Tech*
SPEAKERS: Frederick Paige, Philip Agee, & Andrew McCoy

The purpose of this study is to better understand the impact of occupant education on energy consumption for energy efficient, affordable housing

WEDNESDAY | 1:15 PM – 2:45 PM

units. Since 2006, firms and local policies in Virginia have increasingly committed to sustainable housing principles by incentivizing green building certifications, training and construction processes. While efforts have focused on the suppliers of energy efficient homes, occupants, the source of energy consumption in buildings, have been less investigated. Technological energy efficiency improvements are often crippled by occupant behavior such as lack of understanding, improper use, over- consumption, and substandard maintenance. Previous work has studied the relationships between design, construction and energy use and also shown education to be an effective tool in reducing energy use. More work is needed to fully explore the most effective educational processes and their effects on occupant behavior. In collaboration with Housing Virginia and Viridiant, the Virginia Center for Housing Research is in phase three of a longitudinal study evaluating the performance of 15 multifamily developments at the unit-level to determine influences on the variability of energy usage by residents. Our study will inform residential energy efficiency policies for investments in education, incentives, and building components. In the most current phase of the study, we are focusing on targeted education as a solution for reducing energy consumption. In our broad sample, we found residents who had been educated about technology and energy consumption in their unit consumed 14.8% less energy. To expand on this finding we have an experimental design in progress including a 39-unit subset of our larger data set. While only a few months into the data collection, preliminary findings are promising. Residents who received a targeted education on their energy consumption are saving 25% more energy a month compared to the non-educated residents. In addition to a statistical quantitative analysis, the data we are collecting uniquely utilizes a multi-method approach through interviews and "next generation" energy monitors to reveal the appropriate occupant understanding required to optimize affordable energy efficient housing.

BUILDING SCIENCE EDUCATION: HANDS-ON LEARNING | 218

ONE BOOK/MANY TOPICS: BUT ARE THEY ENOUGH?

SPEAKER: Walter Grondzik, *Ball State University*

Through the development and distribution of a number of curriculum guides, the US Department of Energy has expressed its opinion on what an appropriate grounding in building science principles should look like. One such repository of basic principles resides in the "Building Science 101 Model Curriculum" that is part of the Building America Building Science Education Roadmap. Another, substantially independent, expression lies in the topics selected for the building science training that was an integral part of the 2017 Race to Zero student competition. Mechanical and Electrical Equipment for Buildings (12th edition / MEEB) is an 1800+ page compendium of information on building systems and assemblies—much directly related to building science. Many architecture students in North America get a fair percentage of their information about building science from MEEB as it is adopted by building systems and environmental technology course instructors. There are certainly other very influential texts (such as those by Lechner, Allen and Iano, Ching), but these are not the focus of this analysis. The objective of this presentation is to map (or cross-correlate) the essentials of USDOE-promoted building science education knowledge against the content of the 12th edition of Mechanical and Electrical Equipment for Buildings. The presentation will flag the gaps between the expected (DOE) and the delivered (MEEB) knowledge sets and provide suggestions for bridging such gaps.

EXPERIENTIAL LEARNING EXERCISES TO FURTHER UNDERSTANDING OF COMPLEX BUILDING SCIENCE PRINCIPLES

AUTHORS: Georg Reichard, *Virginia Tech*; Oluwateniola Ladipo, *Wiss Janney Elstner Associates*; Zach Gould, *Virginia Tech*
SPEAKER: Georg Reichard

In high-performing building enclosures, the reduction of heat losses can lead to higher accumulations of moisture from condensation and vapor diffusion phenomena, which in turn can lead to rot, corrosion, mold, and overall deterioration of buildings. Building construction professionals have a unique opportunity to catch design and construction errors that if unattended will lead to costly repairs down the road. New materials, frequent change orders on site, or process changes can have a lasting and expensive impact on functionality and durability of enclosure systems. A sound understanding and proficiency in building physics and its multifaceted principles can provide students with competencies to construct and promote better performing buildings in regards to durability, efficiency, health, and comfort. Teaching efforts in this area need to move beyond traditional pedagogical practices of transferring knowledge to a more stimulating and interactive approach, where educators facilitate environments for learners to gain knowledge through interactions with building components, performing independent experiments, problem-solving, and reporting on the findings gained in the process. This paper discusses the context, design, and implementation of several building physics education lab exercises, in which the interstitial condensation phenomenon in exterior wall assemblies can be evaluated. The lab activities engage students utilizing an experimental setup of a mobile cold climate chamber, a mix of exterior wall materials, and multiple temperature and humidity sensors, to investigate the occurrence and prevention of interstitial condensation. Not only observing, but also touching ice that builds up on sheathing, or fiber insulation soaked with condensate are powerful educational messages that can be delivered within the constraints of a classroom through this approach.

IMPLEMENTATION OF PROJECT BASED LEARNING IN A BUILDING SCIENCE CURRICULUM

AUTHORS: Jamie Russell, *Appalachian State*; Chelsea R. Helms, *Appalachian State*; R. Chad Everhart, *Chad Everhart Architect*; D. Jason Miller, *Appalachian State*
SPEAKER: Jamie Russell

Project based learning (PBL) fully engages students in the subject area, promotes team work, transdisciplinary collaboration, allows student teams to engage and solve community design challenges and can ultimately lead to broader student worldviews. PBL, however, comes with challenges including project definition and meaningful student assessment. The authors began the process of exploring PBL through a National Science Foundation Transformation Undergraduate Education in Science, Technology, Engineering and Mathematics (TUES) award. The program was piloted for two semesters under the TUES award and is now in its fifth semester operating as a special curricular track in parallel with the existing, traditional curricular track providing a total of 3+ years of PBL experience. The authors are currently reworking the existing program curriculum to fully integrate an PBL capstone in the senior year while maintaining a clear curricular path, creating a sound base of projects and maintaining resource limits (including space, materials, and personnel). In this paper, the authors discuss their successes and challenges in implementing PBL in an undergraduate Building Science program. Specific topics include the obstacles and challenges met during more than 7 years of both spontaneous and planned project based PBL experience.

BREAKOUT 3

WEDNESDAY | 3:00 PM – 4:30 PM

HIGH PERFORMANCE: PASSIVE HOUSE | 203

HOW PASSIVE HOUSE CAN SCALE: COST-EFFECTIVE ENERGY ENGINEERING FOR LARGER BUILDINGS

SPEAKER: Brandon Nicholson, *Nicholson Kovalchick Architects*

To deliver cost-optimized Passive House buildings we need a paradigm shift in how we approach the design and engineering of building mechanical systems. Fortunately, this shift is already underway. Learn how through a system-by-system tour of proven, low-cost engineering solutions for multifamily and commercial Passive House buildings. Passive House architecture and consulting firm, NK Architects, will share its field-tested approaches to the building systems that are so key to the energy performance and cost optimization of larger Passive House projects: from envelope design, to glazing and shading, to ventilation and heating/cooling, to elevator integration, and more. The presentation will draw on the firm's major Passive House projects in the states of Pennsylvania, Washington, and Maryland, including a 500-unit project just north of the District of Columbia.

PASSIVE BUILDING (PASSIVE HOUSE)

SPEAKER: Adam Ugliuzza, *Intertek*

Passive Building principles are important for all parties to understand that are involved in the building construction industry today. Passive House programs take a holistic approach to building design, utilizing energy efficient mechanical systems sized appropriately for a high performance building enclosure. This approach forces the design of the mechanical and building enclosure systems to be designed together to maximize energy efficiency along with durability, comfort, and indoor air quality. Passive Building design is so effective at reducing heat and cooling energy demand that domestic hot water is typically the largest energy usage for the building! It is also important to note that the majority of materials and systems used in Passive Building design and construction are commonly used on traditional residential and commercial construction projects. The key is how the materials and systems are put together that sets Passive Building apart. The presentation will include a brief history on Passive House and its development into the two main Passive House programs used in the United States today. It will dive into energy consumption comparing Passive Building design to energy usage of typical buildings across the globe, including United States, and discuss future energy needs that require energy conservation programs like Passive House to ensure that our way of life can be sustained. Passive Building design, concepts, and performance metrics will be covered as well as a summary of the Ice House Challenge, a demonstration at the capitol building in Harrisburg, PA evaluating two Ice House structures that will compare performance of Passive House and building code construction.

BUILDING ENCLOSURES: ENERGY & WINDOWS | 204

BUILDING ENVELOPE AS AN EFFECTIVE STRATEGY FOR ACHIEVING SUSTAINABLE BUILDING ENERGY EFFICIENCY

AUTHORS: Joseph Iwaro & Abraham Mwasha, *University of the West Indies, Trinidad & Tobago*
SPEAKER: Joseph Iwaro

The energy performance of building is closely linked to the energy performance of building envelope. Besides, it is important to understand the energy performance of building envelope in order to achieve building efficiency and proper building energy management. Energy-conscious buildings are becoming an important part of design helping to minimize demands on non-renewable resources while providing better natural ventilation than was previously possible. At present, new renewable energy sources such as solar, wind, wave, tidal, ocean, thermal and nuclear power are now being used to supplement fossil fuels. However, their production is still capital intensive and the wide use of fossil fuels, to some degree, has polluted the atmosphere. Besides, considering the urgency of saving the world's energy reserve. As such, the current research was undertaking to investigate and recommend effective passive strategy for achieving sustainable building energy efficiency. In order to achieve this aim, the study investigated the impact of building envelope systems such as roof and wall design solutions on the building energy efficiency through experimental approach using three building physical models attached with air-conditioning system each. Subsequently, the performance of the building envelope physical models in terms of energy consumption, cooling load, indoor temperature, indoor relative humidity, indoor comfort conditions were monitored through Lascar EasyLog USB-2-LCD data logger sensors and Multifunctional Mini Ammeter. In the results, Insulated building envelope wall and roof systems emerged as effective passive strategies for achieving sustainable building energy efficiency.

ENERGY EFFICIENT GEOMETRICAL DESIGN PARAMETERS OF WINDOWS IN RESIDENTIAL BUILDING: A COMPARISON BETWEEN HOT AND COLD CLIMATES IN THE UNITED STATES

AUTHOR: Reza Foroughi, *Penn State*
SPEAKER: Reza Foroughi

In the United States, 22% of the total primary energy consumes in residential building sector. In this sector, windows are responsible for 19% and 39% of heating and cooling loads respectively and 24% of the total building energy use in residential sector. In addition, since there is no limit for the glazing area in residential buildings, a careful attention in residential window design parameters would save significant amount of energy and subsequently reduces carbon footprint (International Residential Code, 2012). Geometrical window design parameters such as window to wall ratio (w/w), aspect ratio, and fenestration location are among the most important design factors to improve building energy performance. Finding the most proper window design parameters is always challenging for the designers and should take serious consideration from the early stage of the design process. In this study, an optimization model is developed to identify the optimum geometrical design parameters for windows. To achieve that, first, Simulated Annealing algorithm (local search algorithm) is applied and coupled with Energy Plus software. Then, a typical residential building is designed as a case study model in two different locations (hot and cold climates) to illustrate the application of the model. Finally, the result is analyzed and compared with the baseline model. The results show the amount of energy saved by optimum window design parameters and present recommendations for window designers in hot and cold climates.

WINDOWS OF OPPORTUNITY: FENESTRATION INNOVATIONS, DRIVEN BY DEMAND

SPEAKER: Bob Dudish, *Marvin Windows*

Over the last two decades, windows have evolved more quickly than perhaps any other building material, partly in response to demands for greater energy efficiency. Learn how new technologies in the design and manufacture of windows—including new framing materials, coatings, and glazings—are advancing the energy efficiency of both historic buildings and new structures. This presentation will describe new technologies that enhance windows' energy efficiency, list examples of how glazing and framing materials have evolved in response to market demand for greater energy efficiency, compare and contrast how new technologies will work in historic buildings and how they might not, and show how new window technologies can be used to help achieve specific goals and requirements for energy efficiency on large-scale projects.

DESIGN CONSIDERATIONS: POLICY & SOCIAL COMPONENTS | 205

HOUSING TECHNOLOGY AND THE CONTEMPORARY POLICY CONTEXT IN THE U.S.

AUTHORS: Carlos Martín, *Urban Institute* & Frederick Paige, *Virginia Tech*
SPEAKERS: Carlos Martín, Andrew McCoy, & Frederick Paige

A handful of monographs and program reviews shed light on the basic missions and outcomes of past federal efforts to promote housing innovation. Few of these, however, describe the industrial and policy contexts in which those efforts emerged. Even fewer delve into the programmatic operations and components—or, the policy "ingredients"—of past and current housing research and development initiatives. In this paper, the authors review the evolution of housing R&D programs since the RAND report across these two themes: 1) the policy and industrial contexts in which the programs developed; and 2) the operational makeup of the programs. The authors trace these themes across public housing technology R&D policies and programs over the last half-century. In addition to reviewing the scholarly and policy literature, the authors conducted in-depth, structured interviews with staff of current and past federal housing innovation programs. In exploring the details of the programs, the paper describes how these two themes are fundamental determinants of program success—and, in some cases, failings—and should be included as decision-making factors for future efforts.

SOCIAL HOUSING ARCHITECTURE AS A GENERATOR OF SOCIAL PRACTICES

AUTHORS: Gülcan Ay & Meltem Aksoy, *Istanbul Technical University*
SPEAKER: Gülcan Ay

Social housing and mass housing systems are applied as a solution to the problem of housing shortage that ensue from urbanization process. The housing problem that emerged with urbanization has been tried to be solved by different solutions within the scope of the social housing policies that states have produced. While some developed social housing projects for the topic succeeded, wrong policies accelerated the formation of informal settlements. In this paper, the effect of the level of user participation and the process in the social housing for low-income people was investigated through the samples and the positive and negative effects were tried to be visualized. In accordance with this purpose, some architectural examples from Turkey and the world were selected and the study being conducted on these examples such as SAAL (Serviço de Apoio Ambulatório Local) Bouça Porto(Portugal), TOKİ (Turkey), Viranşehir Su ve Toprak (Viranşehir Aqua and Earth) (Turkey), Düzce Umut Evleri (Düzce Hope Homes) (Turkey), Quinta Monroy (Chile). The examples were selected considering varied roles of actors (low-income people, the government and designers) which are included the process of social housing production.

CONTEXT-SPECIFIC CULTURAL DRIVERS & BARRIERS TO SUSTAINABLE & RESILIENT BUILDING SYSTEMS: LESSONS FROM THE HOT AND HUMID TANZANIAN COAST

SPEAKER: Esther Obonyo, *Penn State*

This identifies obstacles to, and opportunities for advancing high performance building systems using context specific cultural and other factors in the East African country of Tanzania. The authors discuss specific ways through which such factors can impede or facilitate the adoption and use of sustainable and resilient technologies in building systems. The case of sustainable earthen masonry in Tanzania is examined in detail as an example of a sustainable building technology impacted by a variety of technical and cultural factors. In addition to identifying some technical flaws that limit the update of the technology, the authors also identify some socio-cultural nuances. The paper draws lessons on context-responsive design from Swahili Architecture (a style of building along the eastern and south-eastern coasts of Africa). Selected buildings are analyzed as elements within wider socio-technical systems consisting also of knowledge, capital, labor, social practice, and cultural meaning. These cultural factors are embedded in everyday practices and routines, social norms and values, and aesthetic preferences. The analysis culminates into recommendations for a hybrid building approach that can be used to advance the structural use of earthen masonry in the hot and humid context.

WEDNESDAY | 3:00 PM – 4:30 PM

BUILDING SCIENCE EDUCATION: RACE TO ZERO + NEXT STEPS | 218

THREE COURSES/FOUR TYPOLOGIES: EXPERIENCES WITH THE 2017 RACE TO ZERO COMPETITION

AUTHORS: Tom Collins & Walter Grondzik, *Ball State University*
SPEAKERS: Tom Collins & Walter Grondzik

The Race to Zero student design competition is sponsored by the US Department of Energy. Competing teams are challenged to develop and present proposals for small residential projects that embody low energy consumption achieved through the wise design of enclosure elements and systems components. Four building typologies (competition categories) were available to the 2017 student teams: suburban single family, urban single family, attached housing, and small multifamily. Mandatory competition deliverables include a draft status report, a final report, a one-page summary sheet, and a face-to-face presentation to jurors. Optional deliverables include a poster and a physical model. Teams work on the competition for either one or two semesters/terms. The competition culminates at the National Renewable Energy Laboratory in Golden, Colorado. This paper presents experiences resulting from the involvement of four student teams from Ball State University in the 2017 Race to Zero. These four teams, involving over a dozen total students from architecture and construction management, each addressed one of the project typologies. Three faculty members were actively involved with the teams, as were several external partners. The teams benefited from a collaboration among three distinct courses—a graduate level comprehensive design studio, and two graduate electives (one focusing upon energy modeling and one upon LEED for Homes). Independent study opportunities in construction management brought a further dimension to the team's efforts and solutions. This paper describes the context of the Ball State University participation in the Race to Zero and explores the synergies that developed among the four teams, the three courses, the faculty, and the external partners. The educational benefits of participation are addressed.

2016-2017 RACE TO ZERO COMPETITION: A CASE STUDY DESIGN FOR ZERO ENERGY READY TOWNHOMES

AUTHORS: Chris Hazel, Sarah Klinetob Lowe, Tom Hanna, & Sean Copeland, *Penn State*
SPEAKERS: Chris Hazel & Sarah Klinetob Lowe

For the past four years, members of the Pennsylvania Housing Research Center (PHRC) and the Energy Efficient Housing Research Group (EEHR) at Penn State have collaborated to support student design teams for the Department of Energy (DOE) Race to Zero competition. This annual design competition challenges interdisciplinary undergraduate and graduate student teams to design an affordable, marketable, net zero energy ready home that meets the DOE Zero Energy Ready Home standard and incorporates sound building science principles. Each year of the competition, Penn State students have gone beyond baseline competition requirements to partner with a Pennsylvania-based housing organization. These partnerships have provided a real site, context, and design constraints for the students' submission and have opened the opportunities for greater community impact and industry partnerships. The 2016-2017 Penn State student team partnered with the Centre County Housing & Land Trust (CCHLT) and Ferguson Township to develop a case study design for a set of three owner-occupied townhomes within 80%-120% of the median family income in a proposed Traditional Town Development (TTD) two miles from Penn State's University Park campus. This presentation will describe the integrative design and decision making process by the team and the technical design of the townhomes presented at the April 2017 Race to Zero competition held in Golden, CO.

BUILDING SCIENCE EDUCATION: WHERE DO WE GO FROM HERE?

MODERATORS: Samuel Taylor, *Energy & Resource Efficiency* & Pat Huelman, *University of Minnesota*

Rounding out the Building Science Education track, Sam Taylor and Pat Huelman will facilitate a discussion with session participants on reflections and next steps for advancing building science education in higher education, including discussions on building science teaching resources and resource gaps

HAPPY HOUR ON THE EXHIBIT FLOOR

WEDNESDAY | 6:00 PM – 9:00 PM

Enjoy delicious food & drinks with great company! Network with conference attendees from the PHRC Housing Conference & the Residential Building Design & Construction Conference, industry exhibitors, and the next generation of housing professionals. Included in your evening are heavy hors d'oeuvres and two drinks, as well as a free tasting from Otto's, a local brewery! Thank you to our Exhibitors for sponsoring! Stop by their tables and learn more about their products and services to assist you.

PRE-REGISTRATION REQUIRED, *SEE TRACY AT THE REGISTRATION DESK BY 3:00 PM.*

Otto's Pub & Brewery

KEYNOTE

THURSDAY | 8:30 AM – 10:15 AM | ROOM 207

GLOBAL INNOVATIONS IN RESIDENTIAL BUILDING: PREFABRICATION, MODULARIZATION & AUTOMATION

PROFESSOR RYAN E. SMITH

ASSOCIATE DEAN OF RESEARCH + COMMUNITY ENGAGEMENT & DIRECTOR, *INTEGRATED TECHNOLOGY IN ARCHITECTURE CENTER (ITAC) AT UNIVERSITY OF UTAH, COLLEGE OF ARCHITECTURE + PLANNING*

Residential construction volume is up. But the labor to meet this demand is nonexistent. Furthermore, construction productivity continues to decline. One solution to meet these challenges is factory built prefabrication, modularization and automation. This presentation will review, from history to present, the residential prefabrication industry in the US – products and markets, threats and opportunities. The context thriving, mature industrialized construction cultures across the globe, including Japan, Sweden and the UK, will be also shared. Based on these international lessons learned, the presentation will propose business, product and process strategies of how the North American residential design and building industry might innovate 21st century.

Ryan E. Smith is the Associate Dean for Research and an Associate Professor in the College of Architecture + Planning at the University of Utah. Smith directs the Integrated Technology in Architecture Collaborative that works with industry to advance the design and construction sector toward innovation. He has taught, researched and consulted on the topics of prefabrication, industrialized building, modular construction, and timber modern methods of construction for 13 years. He has authored or co-authored numerous academic journal publications and the following books: Prefab Architecture (Wiley, 2011); Building Systems (Routledge, 2012); Offsite Architecture (Routledge, 2017); Leading Collaborative Architectural Practice, (Wiley, 2017); and Prefab Housing and the Future of Building (Lund & Humphries, 2017). He is a Senior Research Fellow in the Centre for Offsite Construction + Innovative Structures at Edinburgh Napier University, UK and the immediate past-Chair and founder of the National Institute of Building Sciences, Off-site Construction Council. His work has been featured in Building Design Construction Magazine, Engineering News Record, Metropolis, ArchDaily, and other popular press and professional journals. Smith is the recipient of many awards including the Modular Building Fellowship, Engineering News Record 20 under 40, and the National Institute of Building Science Member Award.

BREAKOUT 4

THURSDAY | 10:45 PM – 12:15 PM

DESIGNING FOR RESILIENCY | 203

MEASURING SUSTAINABILITY & RESILIENCE TRADEOFFS ACROSS POST-DISASTER TEMPORARY HOUSING

AUTHORS: Lauren Badeaux & Elaina J. Sutley, *University of Kansas*
SPEAKERS: Lauren Badeaux & Elaina J. Sutley

The present research began with searching for a solution to temporary housing that residents can receive quicker with an easier transition into permanent housing allowing for better overall community recovery. A framework was developed that includes three key inputs that feed into an integrated sustainability and resilience evaluation model that outputs tradeoffs between temporary housing options for a household. The three inputs include (1) the disaster scenario which describes the type of hazard, and the level of damage to the pre-disaster home, (2) a description of the particular household in need of temporary housing, and (3) the types of temporary housing options to be evaluated. The framework is exemplified through a hurricane disaster causing moderate damage to the pre-disaster homes of the households being considered. The tradeoffs for temporary housing are compared for two different households who vary significantly based on perceived social vulnerability. Common and innovative temporary housing options are considered in the examples, including manufactured homes, RAPIDO program units, shelter at home programs, and hotel stays. The integrated sustainability and resilience evaluation model measures eight quantitative qualities of the temporary housing units that collectively formulate a quality of life index. The eight qualities include adaptability, customizability, local economy promotion, health impacts, environmental impacts, financial cost, structural integrity, and hazard vulnerability. The quantities are assigned weights based on priorities and needs of the household occupying the temporary housing unit. The temporary housing option resulting with the highest quality of life index is recommended to the household.

AMPHIBIOUS HOUSE: A NOVEL FLOOD MITIGATION STRATEGY

AUTHORS: Anthony Graham & Fatemeh Orooji, *Western Kentucky University*
SPEAKER: Anthony Graham

Floods are one of the most common and destructive natural hazards worldwide. Almost 75% of all federal disaster declarations are related to flood events. Every year in the world, flooding affect millions of people. Property damage from floods is a major economic concern for federal agencies, local governments, and individual homeowners. However, because of human`s desire to live adjacent to water, houses are still being built on flood plains and other flooding-prone areas. Permanent static elevation has been a common strategy to keep homes above the water levels in flood-prone areas around the world. Permanently elevating houses creates new problems such as inconvenient access to living areas, difficult access for elderly and handicapped residents, loss of neighborhood character, and increased vulnerability of the structure to wind damage. This research developed a new concept for a flood-resilient house prototype that is capable of floating on the surface of rising floodwater and does not have to compromise its convenience and appearance for its function. This study explored an appropriate design solution for an amphibious house as an alternative flood mitigation strategy that allows the home to float on the rising floodwater without causing an increase in wind damage through identification of the amphibious design and construction key factors. The design solution included the foundation and structural sub-frame of the building, and waterproof materials.

ENHANCING THE DAMAGE PREDICTION CAPABILITY OF A TORNADO RISK ASSESSMENT TOOL

AUTHORS: David O. Prevatt, *University of Florida*; Anant Jain, *University of Florida*; & David B. Roueche, *Auburn University*
SPEAKER: Anant Jain

Researchers have quantified the damage caused by tornadoes through post-tornado damage surveys in which damage is categorized by the EF-Scale. Those data are used in estimating the damaging wind speeds of the tornado. It is possible that the major tornado damage to residential communities can be estimated through a numerical analysis if the characteristics of the tornado strength and structural resistance of a community's buildings are known. This is the premise of a stochastic analysis tool developed at the University Florida that uses a limit state approach to estimate structural damage due to tornadoes and the associated economic losses to low-rise wood-framed structures. The Engineering-based Tornado Damage Assessment (ETDA) tool is written in MATLAB and includes four modules (a Tornado Wind Field Module, a Wind Load Module, a Wind-borne Debris Module and a Structural Resistance Module), to estimate the damage (defined as engineering damage ratios) for a group of houses within the tornado path. Version 1.0 of the ETDA tool uses a single prototype house to represent the heterogeneous distribution of houses found in a typical neighbourhood. The researchers hypothesize that the accuracy of the ETDA tool may be improved by adding more building prototypes to better represent the heterogeneous distribution of structures. This research describes an approach for selecting additional prototype house models for use in the ETDA tool that can better represent the variety of typical houses impacted by a tornado. Through literature review and analysis of field data of tornado damaged houses, two additional prototypes are selected and the wind load characteristics are developed using Tokyo Polytechnic University's Wind Tunnel Database. The next step of this research is the development of the structural resistance module for the new prototype structures and then establish procedures to randomize the location and distributions of house prototypes within the existing dataset. Once the changes are complete, the version 2.0 ETDA tool will be used to conduct a sensitivity analysis to compare and evaluate the improvements in accuracy of damage ratio prediction (if any) by increasing the number of house prototypes from one to three.

HVAC DESIGN | 204

BALANCING VENTILATION & AIRTIGHTNESS IN RESIDENTIAL BUILDINGS

SPEAKERS: Sean O'Brien & Scott Bondi, *Simpson, Gumpertz & Heger*

The residential construction industry is unique in that, unlike typical commercial construction, the "design team" often consists of a loose group of contractors who each have their own engineer or architect. This is most common in single-family or small multi-unit projects, and can lead to a fragmented approach to building design where interaction between systems, etc. is not always accounted for – as opposed to commercial projects where one design professional (typically an architect) coordinates the efforts of everyone involved. In the specific case of ventilation, this can have significant performance implications for buildings. Modern energy codes continue to improve upon airtightness requirements for residential building enclosures. This can lead to problems with the ventilation strategies that designers have historically used, specifically reliance on natural ventilation through either operable windows or "incidental air leakage". This paper will discuss the areas where building enclosure and mechanical systems have an important effect on one another including air quality, air pressure control, condensation, and energy. The paper will also discuss how traditional ventilation strategies, including operable vents in fixed fenestration systems, can have unintended consequences given the changing construction styles for building enclosure systems.

A NET-ZERO ENERGY, HIGH PERFORMANCE RESIDENTIAL BUILDING TESTBED: PERFORMANCE COMPARISONS BETWEEN TWO EQUIPMENT CONFIGURATIONS

SPEAKER: Brian Dougherty, *NIST*

To facilitate research that contributes to realizing net-zero energy, high-performance residential buildings, a single-family detached home was constructed on the Gaithersburg, Maryland campus of the National Institute of Standards and Technology. The home serves as a testbed for investigating ways to improve a home's energy performance, operating efficiency, comfort, indoor air quality, on-site power generation, and effective interaction with the electrical grid. Two twelve-month monitoring periods have been completed to date using different mechanical equipment configurations. During the first period, a two-speed, air-to-air heat pump that can operate in a dedicated dehumidification mode was used to provide space cooling, space heating, and when needed, dedicated dehumidification. During the second period, the same heat pump was used but now with its dedicated dehumidification mode disabled. Instead, a whole-house dehumidifier provided supplemental dehumidification. The programmable wall thermostat and the capacity of the auxiliary resistive heating also changed between the two periods. The second wall thermostat offered different control logic and more programming flexibility. Continuous mechanical ventilation was employed during the first monitoring period that exceeded the ASHRAE Standard 62.2 minimum by 25 approximately percent. Mechanical ventilation was reduced to the ASHRAE minimum during the second period. During both monitoring periods, the same detailed occupancy and activity schedule of a typical family of four was executed. For both monitoring periods, the home generated more energy than it consumed, with the savings during the second period being higher by 1200 kWh. The dedicated dehumidification mode of the heat pump offered better performance than the whole-house dehumidifier. The combination of the lower ventilation rate and different thermostat logic for the second period resulted in comparatively less energy consumption for space cooling and heating, especially as provided by the auxiliary resistive heaters.

INTEGRATED SPACE & WATER HEATING (COMBI) SYSTEMS FOR HIGH-PERFORMANCE HOMES IN COLD CLIMATES

SPEAKER: Pat Huelman, *University of Minnesota*

High-performance, energy-efficient, and airtight building enclosures are challenging our traditional approach to mechanical systems. There is a critical need to rethink the design, sizing, and layout along with better equipment selection and specifications. The end goal are systems that provide superior comfort and convenience, robust and durable operation, and are easily maintained, repaired, or upgradeable. This paper will begin with a look at all of the key mechanical components. Then, it will focus on opportunities for simplification, integration, performance improvement, and cost reduction. An integrated space and water heating system is one potential solution that offers many advantages in high-performance houses, especially in cold climates. In today's high-performance homes there are independent mechanically-related functions, systems, appliances, and devices. In addition to heating, cooling, ventilation, and domestic hot water, there is a need to more thoughtfully address filtration, dehumidification, range ventilation, clothes drying, and make-up air. While total integration of all of these functions may not be a possible or even desirable solution, some combinations may be important for function, performance, or cost. This paper will look at the integrated (or combined) space and water heating system as a platform to address many of the other components and requirements for a high performance home. It will focus on highly-efficient, comfortable, robust, and healthy homes such as the DOE Zero Energy Ready Home.

CROSS LAMINATED TIMBER #1 | 205

BUILDING ENERGY AND HYGROTHERMAL ANALYSIS OF SINGLE FAMILY RESIDENTIAL BUILDING WITH LAMINATED TIMBER

SPEAKERS: Lewis Setter, Eric Smoorenburg & Paulo Tabares, *Colorado School of Mines*

Buildings use about 75% of the electricity generated in the United States and drive electricity peak demand in summer. Cross laminated timber (CLT) is an innovative panelized mass timber product suitable for sustainable building construction that can reduce building energy use, and potentially reduce electric cooling peak demand due to the additional thermal mass. However, up to now, most of the current CLT literature have focused in tall buildings (higher than 8 stories). Residential building energy use is very susceptible to weather, thus potentially benefitting from using CLT. This study numerically analyzes potential cost, system size, and energy savings when CLT are applying to residential building with and without variable electric rates using BEopt, a residential building energy optimization program. A typically new light frame stud construction home is compared against same house with using CLT was simulated with the same floor plan. It also compares them using different thermostat setpoints to reduce energy cost when subjected to variable rates and with the potential to use natural ventilation and night cooling. These models are analyzed in 2 climate zones based on annual energy use, peak demand and energy cost.

NUMERICAL MODEL OF CREEP BEHAVIOR FOR AXIALLY LOADED CLT PANELS

SPEAKER: Thang Dao, *University of Alabama*

Hybrid wood system of post-tensioned rocking CLT panels and traditional wood shear wall is promising structural system for residential constructions in earthquake regions. The performance of this system relies on both self-centering ability of post-tensioned rocking CLT panels and energy dissipation in light-frame wood shear walls. Specifically, the performance of post-tensioned rocking CLT panels depends on the ability to maintain the post-tensioned (PT) force in the tendon. This PT force may change over time due to the creep behavior of wood; which in turn, is a function of time and moisture content in the CLT panel. In this study, a numerical moisture content diffusion model was developed to predict the moisture content migration through CLT panel when the ambient relative humidity changes. Fick's second law and the moisture content diffusion coefficients were applied to derive the differential diffusion equation for use in a numerical model. Included was a five-element creep model to estimate the creep deformation over time under the axial load on the CLT panel with changing environment conditions. Data from a series of moisture content and creep tests under different configurations and environment conditions were used to validate the proposed moisture content diffusion and creep model. This presentation will give an update of this study on the results and applications.

FIRE PERFORMANCE OF CLT ADHESIVES IN RESIDENTIAL FLOOR APPLICATIONS

SPEAKER: Shiling Pei, *Colorado School of Mines*

Cross laminated timber (CLT), a mass-timber structural component, is well suited for use in the mid-rise residential buildings as the construction industry continues to strive for more efficient, cost-effective and sustainable buildings. However, fire safety is frequently cited as a concern when designing a CLT building due to the combustible nature of timber. In reality, the wood charring mechanics are well understood and the charring can provide a level of fire resistance that can be calculated and designed into the building. One of the questions that still remains with CLT buildings is the performance of the adhesive at high temperature. Previous research has found differences in fire performance for standard structural adhesives used today in CLT fabrication. Understanding and quantifying these differences are key to furthering the use of CLT in construction. The probability of failure will be used to quantify the risk. Preliminary findings of the probabilities of failures determined via finite elements analysis of CLT panels with various adhesives, adhesives failure models, and different fire scenarios (char rates) is presented. Based on this preliminary risk assessment, a discussion for the CLT panels used for residential floor loading case will highlighted.

PENN STATE & THE UN GLOBAL BUILDING NETWORK | 218

THE GLOBAL BUILDING NETWORK: ACHIEVING HIGH PERFORMANCE FOR EVERYONE, EVERYWHERE

SPEAKERS: Tom Richard, *Institute of Energy & the Environment* & Jim Freihaut, *Penn State*

Buildings comprise one third of the global economy, are responsible for 40% of greenhouse gas emissions, and are the places where most people spend at least 70% of their time. As the attendees of this conference know well, today we have the knowledge and technologies to simultaneously reduce building energy requirements by more than 80%, improve indoor air quality to increase occupant health and performance, and create attractive and highly functional environments for 21st century living. Exemplified by such terms as Passive House, these techniques have been proven in over 150,000 residential and commercial buildings worldwide. Recent evidence from public housing projects in Pennsylvania indicates that these goals can be accomplished at a construction cost within a few percent of conventional buildings, and perhaps equal with experience and integrated design. Last year the UN Economic Commission for Europe approved a set of Framework Principles for Building Standards that encourage a global program to adapt and adopt science-based, practical and cost-effective implementation of these principles to local climates, materials, and needs. Penn State is assembling a Global Building Network to develop the educational and research programs needed to implement this Framework, which includes governments, academic, non-profit and corporate partners working toward common goals. This session will outline initial plans for educational programs and research priorities, invite feedback and dialogue, and provide opportunities for ongoing engagement.

50 HOUSES: GLOBAL BUILDING NETWORK PASSIVE HOUSE RETROFIT PROJECT THROUGH PASSIVHAUSMAINE

SPEAKER: Naomi C.O. Beal, *passivhausMAINE*

Naomi C.O. Beal of passivhausMAINE will give an overview of progress for an ambitious retrofit project. 50 Houses, a pilot program of Global Building Initiative, will tackle the overwhelming nature of passive house level renovation through an iterative and open source process. Partners across academic disciplines, industry and design professionals work together to find long term solutions to an aging building stock.

BREAKOUT 5

ENERGY MODELING | 203

CLOSING THE POST-OCCUPANCY GAP IN ZERO ENERGY HOUSING

AUTHORS: Philip Agee, Georg Reichard, Andrew McCoy, Brian Kleiner, & Teresa Hamm, *Virginia Tech*
SPEAKER: Philip Agee

Buildings continue to have a large impact on the environment consuming 40% of U.S. energy and 70% of U.S. electricity in 2015. Buildings are complex systems, yet architecture, engineering, and construction (AEC) professionals often perform their work lacking a formal post-occupancy feedback process that informs the efficacy of zero energy performance goals when using energy simulations during design. This gap in simulated versus measured outcomes creates uncertainty in the housing industry and impedes the market transformation toward zero energy housing. The aim of this paper is to contribute to closing the post-occupancy performance gap in zero energy housing. Utilizing a descriptive and exploratory case study, researchers evaluate longitudinal evidence of 8 all-electric zero energy housing units located in the mixed-humid climate to evaluate 1) originally simulated versus measured energy performance of a senior, affordable zero energy development; 2) the impact of actual weather versus simulated standard climate on year to year energy; and 3) alternative simulation tools that could allow to better capture potential occupant impacts in zero energy housing. Preliminary findings suggest human factors have a large impact on achieving actual zero energy performance goals and energy simulation tools utilized during design may not capture the volatility of these impacts accordingly. Historically, residential buildings have been enclosure and environmental system dominated in the context of energy consumption. Aggressive, top-down enclosure and system requirements through building energy codes and federal efficiency mandates are quickly shifting loads in residential buildings away from these traditional loads toward water heating and miscellaneous electric loads (MELS). A socio-technical system (STS) model is proposed to close the post-occupancy gap and improve the operational effectiveness of zero energy housing.

IMPACT OF OCCUPANT BEHAVIOR IN DATA-DRIVEN ENERGY USE MODELING IN DIVERSE RESIDENTIAL BUILDINGS ACROSS MULTIPLE CLIMATES

AUTHORS: Huyen Do & Kristen S. Cetin, *Iowa State*
SPEAKER: Huyen Do

Data-driven, inverse modeling is often used for the estimation and prediction of energy consumption of residential buildings. Yet in contrast with commercial buildings which typically follow a more regular occupancy schedule, the occupant behavior in residential buildings can be much more varied both over time in a single home, and across different homes. This includes some homes with very regular and very irregular occupancy schedules and use patterns of the energy-consuming building systems. As a result, this can make the development of an inverse modeling method that is able to predict residential energy consumption across a diverse residential dataset challenging. In this research a modified change-point modeling method is used to fit inverse models to monthly energy use data from a diverse set of more than 1000 homes in four different cities in the U.S. located in climate zones 2A, 3A, and 5A. It was found that across the different cities of study, 3 to 28% of homes, depending on the location, do not fit the typically recommended criteria for model acceptance. Further analysis determined that between 0.2% and 12.5% of models have specific data points that do not follow the trends of the majority of the energy use data, and significantly impact model performance. To determine the reasons for unpredictable energy performance and lack of model fit, highly-granular, 1-minute and hourly interval disaggregated electricity data was then analyzed. In most of these homes with a wide variation in use, particularly during the holiday season in winter months, outlier months have significantly different occupant behavior-dependent energy end uses, such as HVAC, large appliances such as for cooking, lights, and electrical plug loads. The improved understanding of inverse model performance for residential buildings and the reasons for lack of fit and occurrence of outliers helps to drive improved inverse modeling methods to predict energy use for residential buildings.

BUILDING ENCLOSURES: QUALITY & AFFORDABILITY | 204

AN INNOVATIVE BUILDING SYSTEM FOR HIGH-PERFORMANCE AFFORDABLE HOUSING

AUTHOR: Pat Huelman, *University of Minnesota*
SPEAKER: Pat Huelman

The theory and motivation for the "perfect enclosure" are so clear and simple; place the structural elements to the interior where they will always remain warm and dry, then place the four control layers (thermal water, air, and vapor) to the exterior in a way that will be robust, durable and/or repairable. The University of Minnesota NorthernSTAR Building America Partnerships is investigating an innovative building enclosure system – including both building technology and delivery system – that fully embodies the goals of the "perfect enclosure". The project is focused on a unique "perfect wall" system that can deliver Zero Energy Ready Home performance for the affordable housing market. One of the primary drawbacks to the exterior control layer approach has been the complexity and expense. So this project is specifically investigating a new structural system that simplifies and speeds construction to save enough money to invest in high-performing exterior control layers. Ultimately the structural panel system improves construction quality while reducing both material and labor cost of the building structure. Furthermore, the system is designed to have the home dried-in and secure in 3 to 5 days. This paper with focus on cost and performance attributes for this wall system as compared to more traditional light frame construction using conventional cavity insulation and control layers. Performance comparisons will be developed through BEopt and REMRate modeling. Cost will be based on recent construction by two local not-for-profit developers and builders.

EXPERIMENTAL & NUMERICAL STUDY OF MOISTURE MOVEMENT IN SEALED ATTICS

AUTHORS: Aravind Viswanathan, *University of Florida*; David O. Prevatt, *University of Florida*; W. A. Miller & P.R. Boudreaux, *Oak Ridge National Laboratory*
SPEAKER: David O. Prevatt

Leaky ductwork in vented attics account for about 25% of energy lost in single-family residential houses per year. One way to conserve energy is to seal the underside of the wood roof sheathing and the attic vents with spray applied polyurethane foam insulation. However, in hot sealed attics, the humidity levels can reach saturating levels creating favorable conditions for moisture to condense at the underside of the sheathing. Moisture in wood should be controlled within 20% to prevent moisture related issues. This paper describes a combined experimental and numerical study of moisture and heat movement in code compliant residential houses with sealed attics in Florida. The time histories of temperature, relative humidity and moisture in the conditioned space and the attics were measured for a 12-month period in four Florida houses. The air leakage areas and salient house characteristics were recorded for use in numerical modelling. Poor workmanship in sealing the attic causes high attic air leakage resulting in poor indoor thermal comfort. The field-measurements showed less potential for condensation in all four houses and the moisture contents in wood remained well below the 20% threshold for mold formation. A numerical tool was developed to simulate the moisture movement by varying air leakage rates and occupancy habits to predict the moisture content in the wood sheathing. The results of the numerical modelling were calibrated against field-measurements; and showed good prediction accuracy. Future scope exists for the improvement of the numerical tool by accurately modelling the air change rate in the house and the attic.

RACKING TESTING FACILITY TO EVALUATE IN-PLANE PERFORMANCE OF STRUCTURAL INSULATED PANELS

AUTHORS: Ryan Solnosky, *Penn State*; Ali Memari, *Penn State*; & Paul Kremer, *Iowa State University*
SPEAKER: Ryan Solnosky

There has been a growing interest in learning about the seismic performance of Structural insulated panel (SIP) systems. In particular, an important unknown has been the ductility of SIP systems that is usually governed by panel-to-panel or panel-to-floor/foundation joints behavior. For this primary reason, which is further complicated by the variety of available methods of creating these joints, and the varied use of fasteners, SIPS are not recognized currently by building codes for areas that require designs with sufficient strength, stiffness, ductility and over-strength capacity, e.g., high seismic regions. For SIPS to be adopted by different codes and standards bodies, extensive testing is needed. Limited studies of these systems have been undertaken to compare their performance to conventional-sheathed, wood-framed walls. This paper will discuss a testing facility specially built for light frame testing under racking conditions compliant with and exceeding ASTM E 564 and E 2126 standard test method requirements. The facility permits proper evaluation of components such as SIPs to understand their behavior under in-plane racking conditions that simulate inter-story drift due to earthquakes and strong wind storms. Accurate evaluation of strength, drift and various failure modes in varied SIP configurations with the facility is also discussed.

CROSS LAMINATED TIMBER #2 | 205

CROSS LAMINATED TIMBER AS AN ALTERNATIVE FOR SINGLE FAMILY CONSTRUCTION: A COMPARATIVE COST STUDY

SPEAKER: Shiling Pei, *Colorado School of Mines*

Cross laminated timber (CLT) is a panelized engineered wood product that is gaining popularity in the United States as a structural material for massive timber buildings. CLT is shown to be cost competitive to steel and concrete in large building construction projects, but is seen as uncompetitive for smaller scale projects, especially light frame wood (LFW) residential construction. The purpose of this study is to provide a detailed comparison of the cost to construct a CLT home versus a LFW home to quantify the cost difference between both options in the single family home (SFH) market. Based on a realistic floor plan, three different designs were compared based on cost and construction timeline to determine the realistic cost differences between SFH constructions using LFW or CLT. The final results show that the CLT option results in a 21% increase in total construction cost from the LFW option. While it is difficult to justify this cost increase in Colorado, potential benefit of CLT construction against natural hazards may make a CLT house cost-effective for hurricane or tornado prone regions.

THE USE OF CROSS-LAMINATED TIMBER FOR MIXED-USE TALL WOOD BUILDINGS IN THE U.S.

AUTHOR: Shaobo Liang, *North Carolina State University*
SPEAKER: Shaobo Liang

Cross-laminated timber (CLT) is an engineered wood building system made from several layers of lumber stacked perpendicular to each other and glued together. The stability, rigidity and strength provided by this method makes CLT a sustainable option to replace concrete and steel in many building applications. CLT has been popular in Europe for over two decades and is attracting interest in the US building community, particularly in the mid to high-rise building systems. The goal of this study is to evaluate the environmental, financial and economic impacts of using CLT for a mixed-use commercial and residential tall wood building and compare impacts with traditional building materials such as concrete and steel. For this study, we will work with the architects of Framework building in Portland, OR, the winner of the USDA Tall Wood Building Competition award. The designers will also provide additional comparative designs of buildings constructed using concrete and steel for our analysis. We will use tools such as environmental life cycle assessment, financial life cycle costing and IMPLAN economic assessments to compare CLT buildings with alternative designs. This study is a unique opportunity to work with the building developers, architects and the local community in Oregon and to have a consistent and detailed study on all aspects of the different building systems. Results from this study will be incorporated into a multi-attribute decision support tool for trade-off analysis and as a means to facilitate public discussions on the benefits and costs of CLT building systems.

THURSDAY | 1:15 PM – 2:45 PM

CROSS LAMINATED TIMBER & BEETLE KILL LUMBER

SPEAKER: Eric Holt, *University of Denver*

With the upsurge of Cross Laminated Timber (CLT) in the construction market, sourcing materials and the transportation cost and logistics are part of the cost equation on every project. The Colorado front range construction market, as with every market, is looking for solutions to cut cost and increase efficiencies. The front range has a large amount of beetle kill lumber within its natural resources. Due to the nature of this resource, its location to the manufacturing plants, and the opportunities it presents, the industry is analyzing it for use in construction processes in many different market segments. This presentation discusses the opportunities for the use of beetle kill lumber for CLT and the construction industry.

COMMUNITY IMPACTS | 218

THE VALUE OF CAMPUS-BASED SOLAR DEMONSTRATION HOMES FOR STUDENTS, FACULTY, AND COMMUNITIES

AUTHORS: David Riley, Lisa Iulo, & Mahsa Safari, *Penn State*
SPEAKER: Mahsa Safari

The interaction between individuals and their homes and between members of communities includes highly impactful social, economic, and ecological interfaces. Demonstration homes have the potential to elevate sustainability strategies as systems, and offer a unique setting for learning about the impact of our day-to day decisions on the world. Efforts to design and build sustainability-focused demonstration homes are expanding across the globe. This research investigates the value of three intentionally built demonstration homes as instruments for learning and community transformation. Three case studies are presented in which residential structures were designed and built in different campus settings as demonstration homes that embody the social, economic, and ecological systems in which they are placed. Observable patterns of process design, regional decision factors, and community interaction are traced through each case to inform three archetypal strategies for sustainable demonstration homes in support of the broad and creative adoption of the living learning laboratory concept. The results of this research can help colleges and universities explore methods to provide student experiences in sustainable technologies in a way that also helps consumers gain awareness and confidence in sustainability focused technologies and practices.

PARTICIPATORY LEARNING THROUGH THE RACE TO ZERO COMPETITION

SPEAKERS: Chris Hazel & Sarah Klinetob Lowe, *Penn State*

For the past four years, members of the Pennsylvania Housing Research Center (PHRC) and the Energy Efficient Housing Research Group (EEHR) at Penn State have collaborated to support student design teams for the Department of Energy (DOE) Race to Zero competition. The annual competition requires students to design a market-rate net zero-energy ready home that responds to local context, climate, and builder knowledge/material availability. PHRC and EEHR have used the Race to Zero as a tool to educate the next generation of high-performance residential design professionals as well as a mechanism for engaging with partners in the local community. Each year, undergraduate and graduate students across multiple disciplines -- including architecture, architectural engineering, civil engineering, and energy engineering -- assemble a team to design a Zero Energy Ready Home (ZERH) to meet the needs of a local affordable housing organization. The general project process has remained consistent from year to year; however, the educational approach of the project has changed annually. Educational approaches have spanned across formal university classes, extracurricular organizations, and collaboration with industry professionals, the variations of which are based upon the specific needs of each project, the capabilities of the students involved, and available university resources. This presentation will examine the concepts, strategies, and design processes for developing and delivering the educational approach for the past four Race to Zero design competitions and the proposed educational outline for Penn State's 2017-2018 entry that partners with a new community partner, a local production builder.

GREENBUILD: UNIVERSITY-INDUSTRY COLLABORATION FOR AN AFFORDABLE, ENERGY EFFICIENT DUPLEX

SPEAKERS: Jason Grottini & Jordan Robb, *Envinity*; & Chris Hazel, *Penn State*

Since 2013, the Energy Efficient Housing Research Group, an outreach arm of the Hamer Center for Community Design, has partnered with the State College Community Land Trust to design an affordable, zero-energy ready duplex in the State College Borough. In November of 2017, ground broke at 1394 University Drive for the GreenBuild duplex. The homes, constructed by Envinity Inc, a State College-based design/build company, were researched and designed by Penn State students through the 2015 Department of Energy's Race to Zero Competition. Over the past year, Envinity–with Doug Henry and Paul Macht Architects–referenced the design documents, as well as reports assembled by EEHR, to assemble a final set of permit and construction documents for the GreenBuild homes and begin construction. This session will share the experiences of the design and decision-making process between EEHR and Envinity during the co-design and construction of the GreenBuild Duplex. It will focus on how Envinity translated the student work into construction documents; how design decisions were managed between the three stakeholders (EEHR, Envinity, and SCCLT); lessons learned from the collaboration; and how this project and process will be used for future education of students, homeowners, and design professionals.

BREAKOUT 6

THURSDAY | 3:00 PM – 4:30 PM

RESIDENTIAL BIM | 203

THE ROLE OF BIM IN DESIGNING ZERO-NET ENERGY HOMES

AUTHORS: Shahryar Habibi, *University of Ferrara, Italy* & Ali Memari, *Penn State*
SPEAKER: Shahryar Habibi

A zero-energy home is known to be capable of balancing its own energy production and consumption close to zero. Development of low-energy homes and zero-net energy houses (ZEHs) is vital to move towards energy efficiency and sustainability in the built environment. In order to achieve zero or low energy targets in homes, it is essential to use the design process that minimizes the needs for active mechanical systems. In this respect, passive design strategies and user collaboration/behavior scenarios can play a key role in achieving the objectives and targets of zero energy houses. Furthermore, building information modeling (BIM) plays a key role in advancing methods for architects and designers to communicate through a common software platform, analyze energy performance through all stages of the design and construction process, and make decisions for improving energy efficiency in the built environment. This paper reviews the literature relevant to the role of BIM to help simulating the energy performance of residential homes to more advanced levels, and in modeling the integrated design process of zero-net energy houses. The study proposes a number of potential decision-making strategies to achieve zero-net energy houses within BIM-based environment analysis process. This work also highlights key factors influencing zero-net energy houses associated with utilization of advanced building technologies.

SOFTWARE TOOL FOR AUTOMATION IN BUILDING ENERGY SIMULATION USING BUILDING INFORMATION MODELING (BIM)

AUTHORS: Ehsan Kamel, *New York Institute of Technology* & Ali Memari, *Penn State*
SPEAKER: Ehsan Kamel

Conventional building energy modeling (BEM) process for residential buildings could be time-consuming, error-prone, and requires expertise. Required parameters for energy simulation including building geometry need to be modeled in a BEM graphical user interface (GUI). Emerging capabilities such as Building Information Modeling (BIM) could contribute to automating this process. All the required information could be defined in a BIM file and used directly for energy simulation to make the whole process faster and less error-prone. This paper explains a software tool developed for automating residential building energy simulation using BIM. In addition, this tool could also contribute to providing detailed information concerning heat transfer through building envelope components such as walls, windows, roof, and floors for monitoring purposes. Tools used to develop this software capability include the modified source code of OpenStudio and EnergyPlus. A case study is used to validate the outputs of the tool using Revit to generate a BIM file, which is later converted to an Input Data File (IDF) file that includes all the required data for energy simulation to be used in modified EnergyPlus. Results are compared to the outputs from existing energy simulation tools, which will show that this tool is capable of performing automated energy simulation.

BUILDING ENCLOSURES: INNOVATIVE MATERIALS | 204

DESIGNING HIGH R-VALUE WALLS USING STONE WOOL INSULATION

SPEAKER: Antoine Habellion, ROCKWOOL

In order to meet the increasing thermal requirements in residential codes, the use of continuous exterior insulation is an effective solution. Further trends for increased energy performance designing high R-value walls requires thick exterior insulation levels to be used, adding challenges to the enclosure details in comparison to common practices. Depending on the type of insulation, different attachment methods can be used. Advanced thermal modelling research indicates that fastening the insulation using screws through the insulation to attach the cladding is more efficient over clip and girt systems. That said, there is common misconception that this can only be done with lightweight cladding types (~2.5psf or ~12.2kg/m², e.g., vinyl, metal, wood siding) with relatively small insulation thicknesses. There is further concern, although not supported though research, when using mineral wool exterior insulation as insufficiently rigid in comparison to foam products such as extruded polystyrene insulation (XPS). This presentation reviews and discusses the application methods of fastening thick layers of mineral wool exterior insulation (6"-12" (150mm – 300mm))to wood-framed walls using long screws as it relates to acceptable cladding loads, screw fastening patterns and compressive strength of the insulation. The presentation also provides recommendations for detailing around windows, doors and corners.

IMPACT OF POSITIONING PHASE CHANGE MATERIALS (PCMS) WITHIN BUILDING ENCLOSURES ON THERMAL PERFORMANCE

AUTHORS: Abdullah Abuzaid & Georg Reichard, *Virginia Tech*
SPEAKER: Abdullah Abuzaid

Utilization of phase change materials (PCMs) in building enclosures as thermal energy storage systems (TES) has become a re-appearing topic within the research community in recent years. PCMs represent an innovative solution that can contribute to the improvement of energy efficiency and thermal performance of buildings. This paper aims to present results of experimental investigations regarding the effectiveness and differences of PCM positioning within building enclosures in terms of energy performance and thermal comfort. The experiments are conducted in a laboratory setting, more specifically in an environmental test apparatus, that allows for comparative testing of interior thermal and hygrothermal performance under different exterior climate scenarios. The paper discusses the experimental setup, the employed analysis methods, and findings of effects for different PCM positions in exterior wall configurations. It explores the observed differences and discusses potential opportunities that exist in regards to reducing overall thermal losses in enclosures and improving thermal comfort in interior spaces.

PERFORMANCE EVALUATION OF WALL PANELS INCORPORATING NEW AND INNOVATIVE MATERIALS DEVELOPED WITH HIGH INSULATION PROPERTIES

AUTHORS: Xinrui Lu & Ali Memari, *Penn State*
SPEAKER: Xinrui Lu

Thermal insulation is a key factor in building design to improve energy performance and thermal comfort. There are many types of widely used insulation materials in the current market; however, even though the R-values are generally available, limited quantitative research results on the performance of such materials are available. The study presented in this paper is focused on evaluating the energy efficiency and cost competitiveness of residential wall panels incorporating both conventional and/or innovative insulation techniques. Combinations of different conventional and innovative insulation materials are also analyzed for different regions. A hygrothermal analysis was also performed to assess the condensation potential of these types of insulation materials.

CONCRETE + 3D PRINTING | 205

A BRIEF LITERATURE REVIEW OF NANOPARTICLES SUPPLEMENTATION IN CIVIL CEMENTITIOUS MATERIALS

AUTHORS: Mehrzad Zahabi, Aly Said, & Ali Memari, *Penn State*
SPEAKER: Mehrzad Zahabi

Multifunctional concrete has such applications as dwellings thermoelectric energy management, collection of solar energy, condition/damage evaluation through self- sensing, and self-healing. Nano-scale modifications through use of nanomaterials together with atomic architecture re-arrangement are necessary if reduction in dose of the conductive macro fillers are desirable in order to fine-tune the multifunctional concrete. This is one rationale behind increasing studies of nanomaterials in the past decade. In this paper, a short literature survey of several nanomaterials utilized in civil cementitious materials is presented. Nanomaterials' higher surface area may not translate to desirable macroscopic properties given their high tendency of aggregation and their intrinsic small dimensions. Further studies are needed to identify the areas these materials excel at and alterations needed plus the areas where their synthesization cost does not justify their inclusion. An extensive experimental program is being undertaken with the ultimate goal of evaluation of concrete durability, multifunctionality and mechanical properties. Additionally, in order to have a better understanding of the Mars habitats possible alternatives, geopolymers using Martian/lunar regolith simulants under simulant environmental conditions are studied.

SEAMLESS ARCHITECTURE: DESIGN & DEVELOPMENT OF FUNCTIONALLY-GRADED GREEN MATERIALS FOR BUILDING CONSTRUCTION

AUTHORS: Maryam Hojati, *Bucknell University*; Shadi Nazarian & José Duarte, *Penn State*
SPEAKERS: Maryam Hojati, Shadi Nazarian, & José Duarte

Functionally-graded materials (FGM) can be found in many natural structures such as bones, which have been studied in biomimetic research. Their varied properties, behavior, and application have been replicated in the design of synthetic materials and systems. FGMs offer promising solutions in the development of building components where multiple programmatic requirements need to be met and economy of means matter most both in the production processes as well as in performance. Conventional buildings account for almost 40% of carbon dioxide emission including energy spent to produce materials and components, and energy used to maintain and occupy them. Despite the complex mechanical joints or chemical bonds uniting materials or building components, a great amount of heat is lost through inefficient details that cannot guarantee impermeability even in presence of sufficient insulation. We need to rethink how materials/components are produced and joined. We have achieved impermeable, seamless, and progressive transition from ceramized geopolymer (GP) concrete with structural properties, to transparent glass. GP is an alternative to portland cement with multiple advantages particularly in response to the environmental concerns and sustainable practices with less embodied and operational energy. A green FGM was engineered using compositional gradients from 95% GP to 100% glass. This paper shares our observations of effective features that influence the quality and material properties of FGMs made of binary blend of GP and glass powder. These features include the influence of sintering process, GP and glass powder chemical composition, exposure conditions, and thickness of different layers. The results of our observations were used to produce a larger specimen, a 400mm column, of functionally graded composite material, made of 21 layers of binary blend of GP and glass powder.

ADDITIVE MANUFACTURING OF BUILDING PARTS: TOWARDS SEAMLESS ARCHITECTURE

AUTHORS: Flavio Craveiro, José Duarte, & Shadi Nazarian, *Penn State*
SPEAKERS: José Duarte & Shadi Nazarian

Buildings are made from thousands of components. The use of different building components or materials is often prompted by the need to respond to different functional requirements, which cannot be accomplished by one part or material alone. Whenever there are two materials or components next to one another, a joint is created and the designer or builder must design a way to construct the joint. Traditionally, a joint is created by introducing a third element or material that chemically or mechanically fastens two main components together. Depending on role of the components or their location in the building, the joint should address air-tightness, water-tightness, and load-bearing along with other multiple requirements. However, digital technology may offer the possibility of making building parts with designed functionally graded (3D printed) materials and producing parts that are made by mixing and/or uniting materials with different properties in appropriate ways, such that they respond to varying functional criteria. This paper aims to explore the use of 3D printing as a methodology to design and produce the desired composite materials for making selected building components and also to verify the possibility of designing and making a functionally graded shelter, which would create the possibility of 3D printing of the entire building.

THURSDAY | 3:00 PM – 4:30 PM

BUILDING ENCLOSURES: CONTROL LAYERS | 218

SITE QUALITY ASSURANCE PROGRAMS – HOW THIS HAS IMPROVED AIR BARRIER INSTALLATIONS

SPEAKER: John Arcidiacono, *Air Barrier Association of America*

Air leakage in buildings has become an issue that is now being focused on. The problem is you cannot see air leaks. Inspections of the installation helps and whole building testing will show how well you did but it is more important to fix the process of installation to reduce and eliminate air leaks rather than trying to correct installations after the fact. This presentation outlines a risk management approach for the installation of air barrier and water resistive barriers and address each of the players in the process, the risk they project, and steps that can be taken to reduce the risk. This presentation will explain why a site quality assurance program is especially important for the installation of air and water resistive barriers, identify the main players in the installation process, compare quality control to quality assurance, and show the difference between quality and performance.

EXTERIOR SHEATHING, WRB'S, & AB'S: MOISTURE-RELATED MATERIAL PROPERTIES AND IMPLICATIONS ON DESIGN & IN-SERVICE PERFORMANCE

SPEAKER: Danko Davidovic, *Huber Engineered Woods*

Exterior sheathing, WRB and AB are fundamental components in every building enclosure providing multiple functionalities such as structural support, control of heat, air and moisture across wall and roof assemblies. Selection and specification of these control layers greatly affects serviceability and durability of structures as well as the thermal comfort and indoor air quality of occupants. Each of these components undergoes a dynamic range of in-service conditions with regards to temperature, relative humidity and moisture contents. This study attempts to elucidate typical in-service conditions of these layers, the sensitivity of operating conditions to traditional and contemporary design approaches for specifying and locating these control layers in several typical wall and roof assemblies modeled using advanced hygrothermal simulation tools.

TOUR OF GREENBUILD DUPLEX

THURSDAY | 3:00 PM – 4:30 PM

Sign up to tour the GreenBuild Duplex, a certified Zero Energy Ready Home (ZERH) project currently under construction in State College. The homes are a collaborative project between the Energy Efficient Housing Research Group (EEHR) in the Penn State School of Architecture and the State College Community Land Trust (SCCLT), and were designed through the 2014-15 Department of Energy's Race to Zero Competition. The homes are being built by Envinity Inc. and are expected to be completed and sold by May 2018 to two owner-occupied, middle income families. Check out EEHR's GreenBuild Construction Blog at http://sites.psu.edu/eehr/greenbuild-construction-blog/ for more details.

PRE-REGISTRATION REQUIRED, *SEE SARAH OR TRACY AT THE REGISTRATION DESK.* **SPACE IS LIMITED!**

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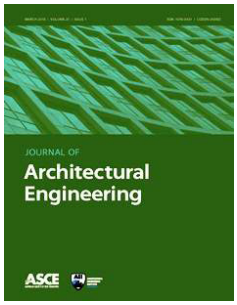

The American Society of Civil Engineers' (ASCE) Journal of Architectural Engineering (JAE) is running a Special Collection on Housing and Residential Building Construction. This peer-reviewed Special Collection covers various aspects of residential buildings, such as single- and multi-family dwellings, mid-rise and high-rise apartment buildings, dormitories, and hotels/motels, and includes technical research and development, technology transfer, case studies, and state-of-the-art review types of papers. See published papers here, *https://ascelibrary.org/page/jaeied/specialcollectionhousingandresidentialbuildingconstruction*.

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For more information, contact Dr. Ali Memari, *memari@engr.psu.edu*.

PENNSYLVANIA HOUSING RESEARCH CENTER

The Pennsylvania Housing Research Center (PHRC) serves the home building industry and the residents of Pennsylvania by improving the quality and affordability of housing. We conduct applied research, foster the development and commercialization of innovative technologies, and transfer appropriate technologies to the housing community. The PHRC is housed within the Department of Civil & Environmental Engineering at Penn State. For more information about the PHRC, check out our website, *phrc.psu.edu.*

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