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# resolve

A FOCUS ON LEHIGH ENGINEERING • VOLUME 1, 2011

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TO INFRASTRUCTURE'S BROADENING ARENA SEE PAGE 10

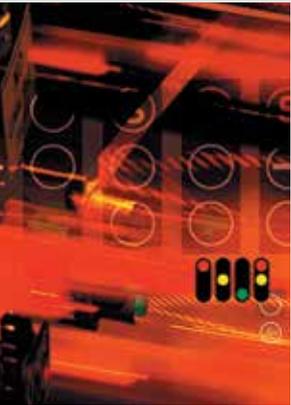
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A FOCUS ON LEHIGH ENGINEERING

VOLUME 1, 2011

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RESOLVE is published biannually by  
the P.C. Rossin College of Engineering  
and Applied Science and the Office  
of University Communications and Public  
Affairs at Lehigh University.  
[www.lehigh.edu/resolve](http://www.lehigh.edu/resolve)

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CHALLENGING GREAT MINDS...INSPIRING GREAT IMAGINATIONS

## A holistic approach to the infrastructure

Welcome to the ninth issue of *Resolve*, a magazine dedicated to research and educational innovation in the P.C. Rossin College of Engineering and Applied Science at Lehigh University.

This issue of the magazine focuses on research and education at Lehigh that support infrastructure systems. The term *infrastructure* has become synonymous with *civil infrastructure*. Yet civil infrastructure is merely one of the many inextricably linked systems that are required for society to function.

Modern infrastructure also includes the systems that generate and distribute energy, those that support transportation, communications and networking, and those that enable the provision of healthcare and essential social services. Recent events in

Japan have underscored the far-reaching influence of modern infrastructure by showing how a major disruption in one system can have a catastrophic effect on the whole.

The interconnectedness of infrastructure systems calls for multifaceted solutions. One emerging research theme at Lehigh is a smarter, greener, more sustainable approach to infrastructure. Lehigh has world-renowned capabilities not only in structural engineering and materials science, but also in energy systems, communications, advanced computing, systems engineering, and environmental science and engineering. These enable us to design and develop sustainable infrastructure systems in a holistic way.

Lehigh has historically championed comprehensive solutions to complex problems, as you will see in this issue of *Resolve*. John W. Fisher, the subject of the Q&A feature (page 8), founded

Lehigh's internationally recognized ATLSS Center a quarter-century ago in part to enable structural, materials and mechanical engineers, and computer scientists, to collaborate on fatigue-resistant structures. Electrical engineering faculty are working with systems engineers and

computer scientists to develop a "smart grid" (page 12) that saves energy while cutting carbon emissions.

Wireless systems are common to much of our infrastructure research. Geotechnical engineers and computer scientists are developing and testing

networks of sensors (page 15) that monitor groundwater contaminants, pavement cracks and other "geo-events" that affect the built infrastructure. Electrical engineers are fashioning multichannel sensors (page 13) that, when integrated with carbon nanotubes, will enable cell phones to detect chemical leaks.

***"Recent events in Japan underscore the far-reaching influence of modern infrastructure by showing how a disruption in one system can affect the whole."*** —S. David Wu

Meanwhile, in the area of digital communications, electrical engineers are developing erasure codes (page 16) that make digital data storage less redundant and more energy-efficient.

Infrastructure research at Lehigh is also emphasized in innovative educational programs. Our professional master's program in structural engineering (page 22) leverages strong partnerships with major architectural and construc-



tion firms to train next-generation leaders in advanced infrastructure systems. Immersed in issues at the cutting-edge of the field, students gain technical experience in project management and operations. The success of our early graduates in this program attests to the need for interdisciplinary thinking.

I hope you enjoy this issue of *Resolve*. Please drop me a note to share your thoughts and comments.

A handwritten signature in black ink, appearing to read "David Wu".

S. David Wu, Dean and Iacocca Professor  
P.C. Rossin College of Engineering and  
Applied Science  
david.wu@lehigh.edu



## A fish sheds light on cardiovascular disease

*Berger studies the development of the embryo in the tiny zebrafish, whose heart is similar to a human's.*

The heart, one of the first organs to develop in a human embryo, begins forming about a month after conception. Problems occurring during its development can lead to numerous diseases in adults. One of the more common is aortic stenosis, which narrows or blocks the aortic valve opening, making it difficult for the heart to pump blood into the aorta, the body's largest artery.

The cause of cardiovascular disease is unknown, but Bryan Berger believes his research group has found a clue in the embryonic development of a tiny tropical freshwater fish native to India's Ganges River.

The zebrafish lays eggs with clear shells that become translucent embryos. Its heart has much in common with a human's – both pump oxygenated blood around the body, and both consist of chambers with valves that ensure blood flows in the right direction.

"We have shown that a family of G-protein coupled receptors [GPCRs] and associated co-receptors are vital to embryonic cardiovascular development in zebrafish," says Berger, an assistant professor of

chemical engineering and member of Lehigh's bioengineering program.

One co-receptor, a transmembrane protein located in the cell's endoplasmic reticulum, interacts directly with a GPCR, allowing it to be transported to the cell surface, where it activates a cascade of biological signals that affect the formation and function of the heart.

The production of this GPCR and co-receptor can be inhibited by a morpholino, an RNA-like molecule. The morpholino interacts with, or "knocks down," the messenger RNA that encodes for the GPCR and co-receptor.

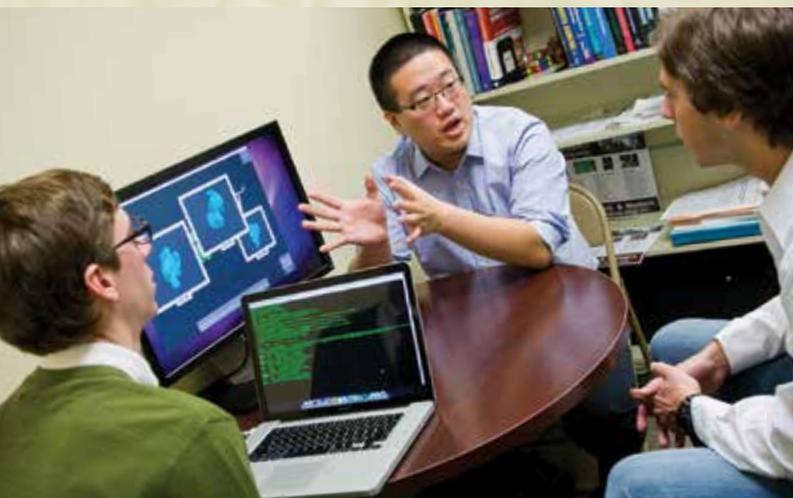
"Injecting the zebrafish embryo with morpholino during the early stages of development almost always leads to the development of an embryo with a heart defect," says Berger. "Our project is in its preliminary stages, but this result is rather exciting, as it suggests these co-receptors may play a critical role in the development and maintenance of a healthy heart throughout adulthood."

Berger is working with James Wu, a cardiovascular surgeon at

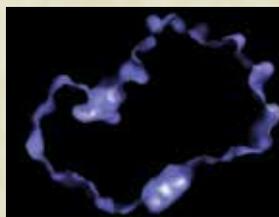
Lehigh Valley Hospital, to determine the amount of corresponding GPCR expressed in human tissue samples collected from patients who have undergone aortic valve replacement surgery. 



## Software automates the analysis of protein cavities



Almost every biological process that occurs in the human body depends on the interaction of proteins with other molecules. To learn how the human body functions at a molecular level, structural biologists have determined the atomic structure of tens of thousands of proteins.



*Seniors David Stolfo and Frank Kriete help Chen analyze the cavity shapes that affect a protein's ability to bind with molecules.*

The active sites for many interactions between proteins and other molecules are often located within a cavity on the protein surface. The shape of a cavity enables proteins to selectively bind the molecules with which they interact while avoiding those they should avoid.

Precisely evolved structural and chemical complementarity enables a diversity of molecular signaling pathways to operate effectively without interfering with each other. For the same reasons, specially designed

## Predicting the 3-D structure of proteins

**A protein chain gains unique properties when it folds into a 3-D configuration. Several serious diseases have been linked to protein misfolding.**

One of the grand challenges in computational biology is to be able to predict the three-dimensional structure of a protein molecule from a known sequence of amino acids. Developing new numerical models to simulate the protein-folding process and predict the resulting protein structure is a research goal being pursued by Jeetain Mittal.

Proteins play a central role in the structure and functioning of all living cells. All enzymes are proteins, as are many structural tissues such as muscles and the collagen found in skin, bone and tendons. Proteins are manufactured within the cell cytoplasm on ribosomes, which are bead-like structures associated with messenger RNA. Each polymeric protein chain is generated by linking a large number of amino acids together in a specific order.

The atoms in the polymer chain do not remain stationary but are in constant motion. Their range of motion is restricted by interactions with neighboring atoms and by the amount of

free space that is available. Within a few milliseconds, a protein chain folds into a specific 3-D configuration that gives the protein its unique properties. When a protein folds incorrectly, however, things can go wrong. In the past few decades, many diseases, including Alzheimer's, cystic fibrosis and several cancers, have been

linked to protein misfolding.

X-ray crystallography and other investigative techniques have revealed that protein chains fold primarily into two different types of structure: an alpha ( $\alpha$ )-helix, in which the chain turns around itself to form a right-handed coil or spiral that is stabilized by hydrogen bonding, and a beta ( $\beta$ )-sheet, in which the chain folds back on itself.

Simulating the folding of an entire protein molecule, which in some cases

can contain more than 300 amino acids, is impossible even for today's most powerful computers. Scientists, therefore, focus their efforts on small globular proteins and smaller segments of longer proteins.

"Many of the current computational models tend to favor the formation of  $\alpha$ -helices," says Mittal, an assistant professor of chemical engineering. "The known propensity of a particular protein sequence to form a specific structure tends to determine the type of model that is used and, therefore, cannot be predictive."

By simply modifying the part of the force field that represents the torsional stiffness (or twisting behavior) of the chemical bonds in the polymer chain, Mittal, in a collaboration with Robert Best from the University of Cambridge in England, has been able to use the same model, a modified version of the Amber ff03 force field, to predict the structure

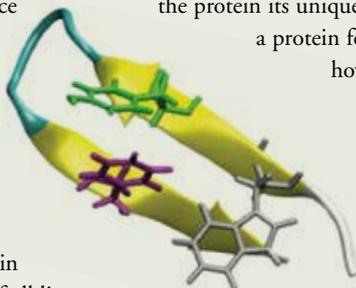
**Mittal and Best have achieved a breakthrough in protein-folding simulation that could shed light on protein-folding mechanisms.**

of four mini-proteins: the GB1 hairpin (containing 16 amino acids) known to form a  $\beta$ -sheet, the Trp cage (containing 20 amino acids) known to form an  $\alpha$ -helix, the Villin HP35 (containing 35 amino acids) known to form  $\alpha$ -helices, and the Pin WW domain (containing 37 amino acids) known to form  $\beta$ -sheets.

"This is the first time that the same model has been used to accurately predict these structures," says Mittal. The achievement, he adds, represents a major step forward in protein-folding simulation and could lead to a much better understanding of protein-folding mechanisms and why proteins sometimes misfold.

The researchers utilize the computational capabilities of the Biowulf PC/Linux cluster at the National Institutes of Health in Bethesda, Maryland. 

*Folded structures of the GB1 hairpin (beta-sheet, top) and Trp cage (alpha-helix and 3-10 helix, bottom).*

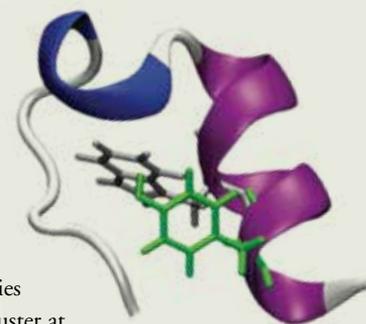


molecules capable of blocking a particular protein cavity are often used as drugs to combat disease by preventing unwanted interactions. Designing these molecules is a core effort in the pharmaceutical industry.

Brian Chen, assistant professor of computer science and engineering, is developing software that uses solid volumetric representations of protein cavities. His approach enables an automated deconstructive analysis of the similarities and variations in cavity shape that affect selective binding.

In a paper published recently in *PLOS Computational Biology*, Chen and coauthor Barry Honig of Columbia University showed that this software could isolate the amino acids and cavity regions that drive differences in binding preferences among serine proteases, a well-studied family of digestive proteins. The two researchers also demonstrated the success of their software with START domains, an important family of lipid transporters.

"This is just a very early proof of concept," says Chen. "Hopefully, this technology will help us understand the causes of preferential binding in a wider range of molecular interactions and one day improve the efficiency of drug design." 



## Imaging the spot of UV light produced by a “bow tie” nano-antenna

*The intense light measures less than 70nm in diameter, far below the resolution of an optical microscope set by the diffraction limit.*

Chip-scale ultraviolet light sources that can be used to detect small concentrations of chemical and biological agents could prove invaluable to the medical

microscope (NSOM), an instrument whose design is closely related to the better-known scanning tunneling and atomic force microscopes. An NSOM works by scanning a small aperture over an object. Only light can pass through this aperture, thus the size of the aperture governs the resolution of the image.

“In order to obtain UV images, we had to modify the optics in our near-field optical microscope,” says Dierolf, a member of Lehigh’s Center for Optical Technologies. “Our group is the first to directly image the UV optical field that passes through a bow tie nano-antenna.”

The antenna itself consists of two triangular pieces of aluminum, approximately 200nm in length and 185nm wide, arranged apex-to-apex with a small gap

(about 50nm) between them. It was fabricated by first depositing a thin layer of aluminum onto a fused silica. A high-precision focused ion beam of gallium ions was used to create the bow tie structure.

*“In order to obtain UV images, we had to modify the optics in our nearfield optical microscope.”* —Volkmar Dierolf

The tiny spot of light is produced when the bow tie structure is back illuminated with a UV laser so the beam passes through the substrate first. The transmitted light has both near-field and far-field components.

The far-field component can travel through space in an unconfined manner and is the “normal” light that can

be detected in a conventional light microscope. The near-field component, which is focused into a small but intense spot, is confined to the first few nanometers of surface. In order to image this tiny spot, the NSOM aperture has to be positioned and then scanned at a fixed height of just 10nm above the sample.

“The two triangles operate like an antenna to confine strong electromagnetic fields in the gap,” says Dierolf.

The antenna’s ability to produce a strong field is due to the incident UV light inducing a collective oscillation, or wave, of the free electrons in the aluminum – a surface plasmon. “The strength of the optical field is governed by the degree of resonance of the plasmonic wave,” says Dierolf. “This is governed by the length of the triangles in the bow tie.”

To demonstrate this, graduate students Liangcheng Zhou (who recently accepted a post-doctoral position at Princeton University) and Qiaoqiang Gan (now an assistant professor at SUNY Buffalo) fabricated a series of antennas having different triangle lengths ranging from 300nm to 650nm and positioned them next to each other so they could be imaged under identical illumination conditions. The highest intensities were found for 300nm and 500nm, which corresponded with their theoretical predictions.

“Direct measurement of the optical field near the nano-antenna contributes to a better understanding of the

underlying physics of these nanoscale antennas, which is crucial for advancing studies of sub-wavelength optics,” says Dierolf. “It has potential applications in photolithography, tip-enhanced Raman spectroscopy, single molecule imaging and nanoparticle trapping.”

The project is funded by NSF. 

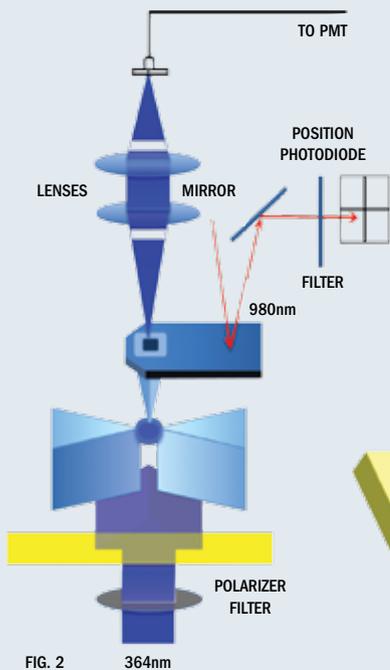


FIG. 2 364nm

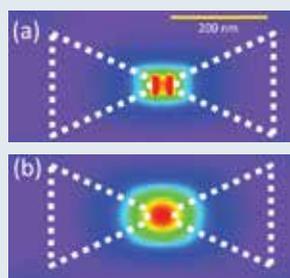


FIG. 3

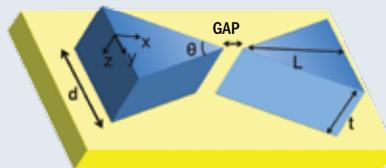


FIG. 1

*Fig. 1 The bow tie antenna, its two triangles separated by a 50nm gap, is fabricated on aluminum by a high-precision focused gallium-ion beam. Fig. 2 The UV nearfield optical microscope. Fig. 3 The intense light speck, with predicted (a) and measured (b) result, is seen when the bow tie is back-illuminated by a UV laser.*

industry. Such light sources rely on nanoscale concentrations of light.

Under the direction of Volkmar Dierolf, professor of physics in the College of Arts and Sciences, and Filbert Bartoli, professor of electrical and computer engineering, a Lehigh research team has manufactured a tiny bow tie-shaped antenna that can produce an intense spot of UV light measuring less than 70 nanometers in diameter, far below the resolution of a microscope set by the diffraction limit.

The resolution of conventional optical microscopes is limited by the wavelength of the incident radiation. Imaging a 70nm speck of light is no trivial matter. It can be achieved only with a near-field scanning optical

## New roles for two common materials

*The goal is to improve the strength and mechanical stability of alumina while promoting the orderly distribution of pores on its surface.*

Aluminum-oxide, or alumina, is hard, is resistant to corrosion and abrasion and is, for a ceramic, a good conductor of heat. It is used in spark plugs and cutting tools, hip replacements and water filters, toothpaste and prefinished wood flooring.

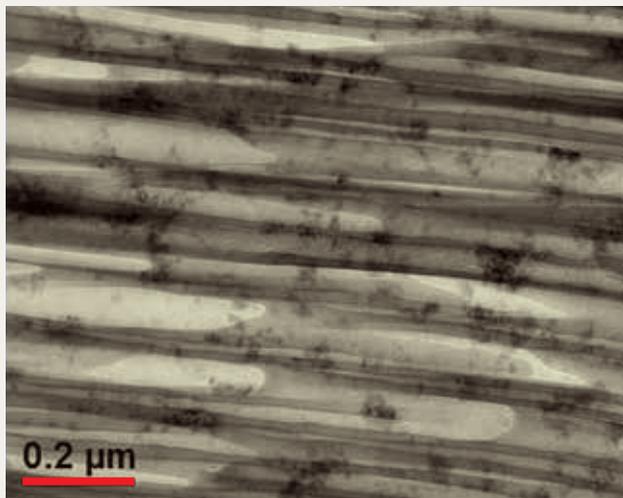
Researchers in Lehigh's Institute of Metal Forming (IMF) are attempting to equip one type of alumina for a new role – the production of a more-efficient kidney dialysis filter.

Alejandro Toro, Wojciech Misiolek, Kylan McQuaig and William Van Geertruyden studied the structure of anodic alumina with an aberration-corrected transmission electron microscope (TEM) that resolves specimens to 0.1nm. They also performed diffraction analyses with conventional TEM to learn how groups of atoms form the crystal structure. They published their results in the *Journal of Materials Science*.

Alumina is amorphous in the samples fabricated by the IMF anodization process. Under proper heat treatment, it becomes crystalline

and acquires an orderly structure. Toro and Misiolek used TEM to determine how heat treatment affects the chemical structure and crystallography of anodic alumina. They were able to improve the ceramic's strength and mechanical stability and promote the orderly distribution of pores on its surface.

The project follows the development by Misiolek and Van Geertruyden of a ceramic dialysis filter whose nanopores correspond more closely with the nano-sized toxins in the body's blood than do the larger pores in conventional polymeric dialysis filters. This gives it the potential to remove toxins more quickly and



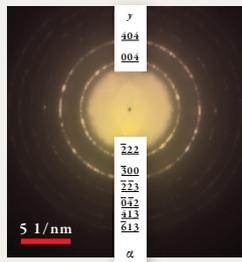
efficiently from the blood and shorten the length of a dialysis session.

Misiolek is IMF director and Loewy Chair of materials forming and processing. Toro, professor of materials science and engineering at the National University of Colombia in Medellin, recently concluded a Loewy professorship at Lehigh. McQuaig, the university's first Loewy graduate fellow, earned his M.S. in 2010.

In a separate collaboration with General Motors, Misiolek and Toro used TEM to determine the structure and mechanical stability of a magnesium alloy containing zinc and cesium.

"Magnesium is even lighter than aluminum," says Misiolek. "The hope is that it can make cars lighter, more fuel-efficient, cleaner and easier to handle. This alloy improves magnesium's ability to deform without compromising its strength and its ability to bear loads.

"This is especially important to auto manufacturers. The parts of a car are geometrically complex and require a material that can deform to create the right shape and thickness." 



*TEM illuminates the poorly understood crystalline phases formed from anodic alumina.*

*DuPont's specialty is the welding metallurgy of nickel-based alloys used in power plants.*

## A material concern for energy

From solar, wind and nuclear to coal, oil and natural gas, says John DuPont, the solutions to the world's growing demand for energy share a common requirement – a sound understanding of the principles that underlie the joining of materials.

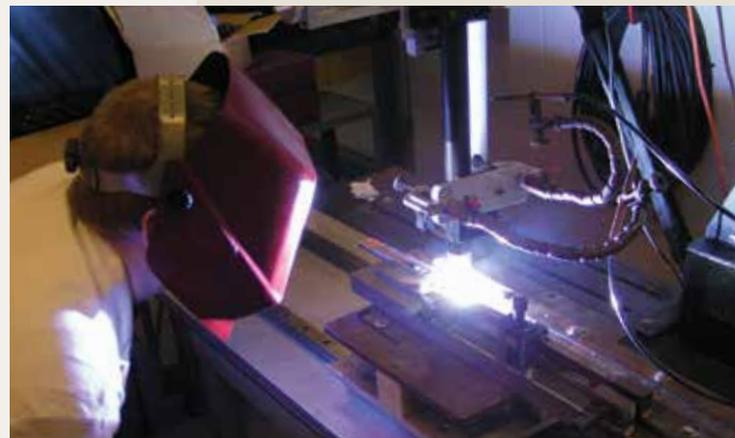
The steel towers in windmill farms are welded, as are the pipelines carrying gas and oil. The boilers in coal-fired power plants require welding expertise, as do lithium-ion car batteries, offshore oil rigs and nuclear power plants.

DuPont, professor of materials science and engineering, recently helped create the Center for Integrative Materials Joining Science for Energy Applications. The NSF-funded Industry-University Cooperative Research Center seeks to extend the service lifetime of welds in existing energy infrastructure and to increase the efficiency of advanced welding materials used in new infrastructure.

The center is a collaboration involving four universities (lead school Ohio State, Lehigh, Wisconsin-Madison and the Colorado School of Mines), three national laboratories (Los Alamos, Oak Ridge and Idaho), NASA and 16 industrial companies.

Improved welding materials and technologies are needed, says DuPont, because new power plants are designed to operate at higher temperatures and under greater pressure. These factors enable plants to run more efficiently but impose greater demands on welded joints.

"A weld is like a weak link. Its performance influences the performance of the overall material. So when we develop new welding materials, we have to minimize the adverse effect that joining can have on material performance." 



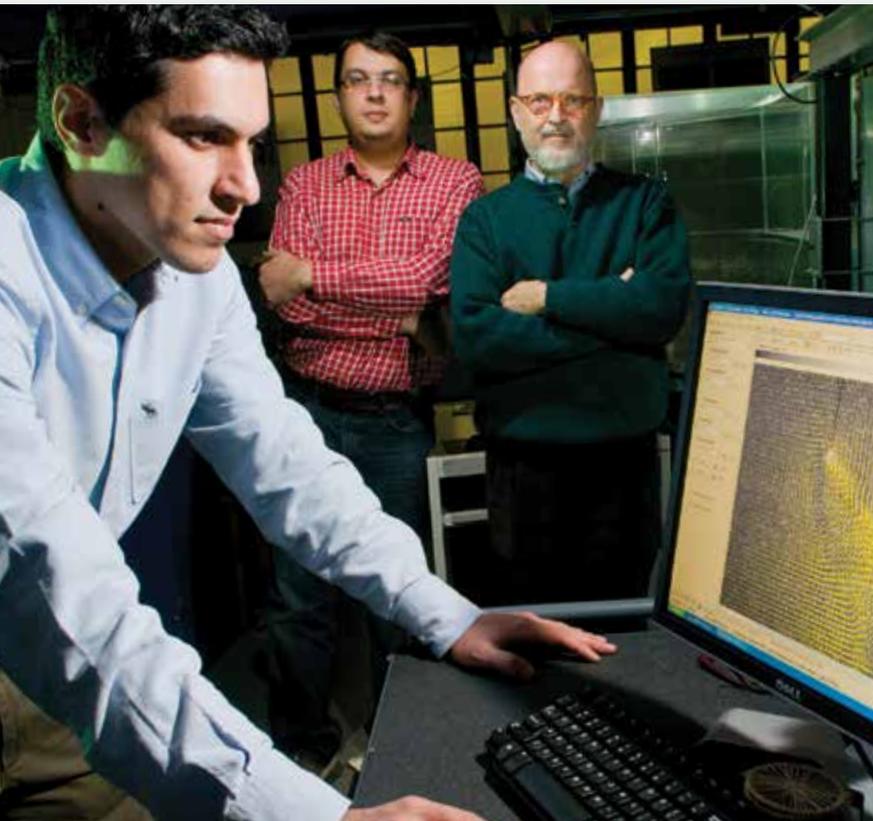
## Multidimensional laser images of flow patterns on beating wings

Not everything that flies, says Donald Rockwell, employs the same type of wing motion.

A large bird has a well-recognized motion, while the small wings of insects beat much faster. The wings of hovering insects create an almost figure-eight type of pattern. And the flow patterns of both birds and insects are much more sophisticated than those of aircraft.

Rockwell, the Paul B. Reinhold Professor of mechanical engineering and mechanics, uses lasers to illuminate the complex physics of fluid flows – from the breaking of ocean waves against oil derricks to the flow of blood from a catheter.

*Rockwell's group constructs 3-D images of vortices created by two types of wing motions.*



One of the most fascinating phenomena he studies is the flow patterns generated by beating insect wings.

“Fruit flies and dragonflies have

incredible maneuvering ability,” says Rockwell. “If we understand the kinds of vortices formed by their wing motions, we can optimize the flight of micro-aerial and other manmade vehicles.”

In Lehigh’s Fluids Research Laboratory, Rockwell’s group was the first to quantitatively image basic vortex patterns using laser-based imaging techniques and image processing.

“We are now constructing 3-D images of vortices for two classes of wing motion,” says Rockwell. “The first is characterized by a sudden increase in the angle of the attack of the wing. The second is a rotating motion of the wing.

“When a wing rotates, the fluid is exposed to centripetal and Coriolis accelerations, which do not occur if the wing flapping is in a straight line.”

To see vortices in 3-D, Rockwell’s group conducts two types of experiments: stereo imaging and sectional imaging. For the latter, they seek to look at a cross-section of the flow pattern on one plane. Laser imaging enables the group to stack the images on

many planes, using a technique called phase referencing, and thereby construct a 3-D image of the flow field above and on the wing.

“The flow patterns generated by insect wings are not steady,” says Rockwell. “You’re not looking at the same 3-D velocity at all times. It’s necessary to track wing motion, 3-D velocity and changing patterns of velocity over time.



“With sectional imaging, we use one laser sheet and scan it to different locations. By successively moving the laser to different positions, it is possible to acquire a large number of slices of the flow. Simultaneously, we reference this image

acquisition to the position of the wing. We tell the computer to take an image at, say, an angle of 80 degrees. This process can be repeated at different angles of wing rotation to determine the time history of the volume [3-D] flow pattern. We’ve just developed a stereo version of this technique, which will provide further insight.”

Rockwell also studies shallow flows, especially the flow of water past cavities in rivers and tidal zones. Spur dikes prevent erosion and create a cavity flow. Pollutants entering this cavity will eventually find their way back to the main river or tide. How fast this occurs depends on the vortex being formed near the entrance to the cavity.

“We need to understand what controls vortex formation in order to figure out how fast pollutants are entering the river,” he says.

Rockwell has advised 34 Ph.D. students at Lehigh. His research has been funded for decades by the Air Force Office of Scientific Research, the Office of Naval Research and NSF.

Last summer, *Experiments in Fluids* dedicated an entire issue – 28 refereed articles and more than 350 pages – to Rockwell for his leadership as the journal’s editor-in-chief and his contributions to the field of fluid mechanics. ①

## A more perfect 'back to the future'

The perpetual motion of molecules, says Yujie Ding, makes air a turbulent medium that undermines efforts to achieve clear long-distance imaging.

"When you send a beam of light through a turbulent medium," says Ding, professor of electrical and computer engineering, "the returning beam is no longer coherent. The phase of the light wave becomes random and this causes the image you see to be blurred."

Improving the quality of images is critical for astronomers scanning the skies and for engineers and scientists taking advantage of remote sensing.

To overcome the negative effects of turbulent media, scientists have tried to exploit a third-order nonlinear medium. The goal is to achieve a time-reversed returning beam, or phase conjugate beam, with its phase variation and propagation direction exactly opposite to those of the incoming beam. But wave mixing in a third-order nonlinear medium, says Ding, is an inefficient process.

Scientists have also tried to take advantage of the photorefractive effect. However, phase conjugation based on such an effect, says Ding, is too slow to effectively recover or correct blurred images.

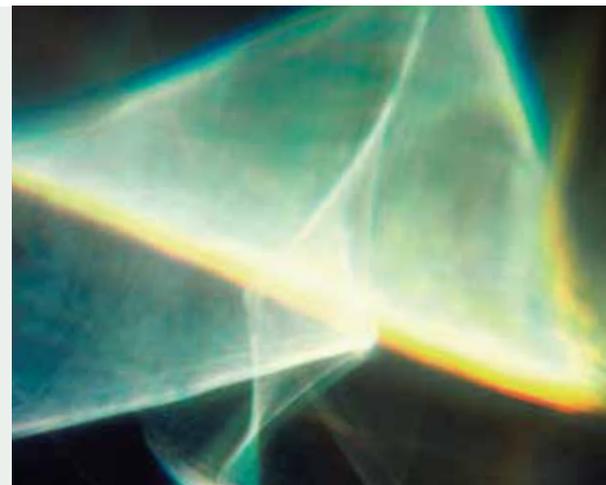
Ding is experimenting with a second-order nonlinear medium that he believes much more efficiently reverses the phase variation of the incoming light wave through phase conjugation.

"A phase-conjugated returning wave

**"We have experimental results that demonstrate a phase conjugation using second-order nonlinearities. This has not been done before."** —Yujie Ding

is a time reversal of the incoming wave," says Ding. "It's like going back to the future. If the returning wave recovers the phase of the incoming wave before it enters the turbulent medium, the present meets the past in an almost instantaneous process. The recovery of the original wave results in no distortion in the image that you see.

"Using second-order nonlinearities to achieve phase conjugation in the absence



*Ding's goal is to overcome the distortion that results when a light beam returns from turbulent media.*

of the photorefractive effect has not been done before. We have experimental results that demonstrate phase conjugation using second-order nonlinearities. We're trying to improve the efficiency of the process."

Ding will present his findings at CLEO 2011, the Conference on Lasers and Electro-Optics in Baltimore, in May. His work is supported by the Air Force Office of Scientific Research. 

## Streamlining the scheduling of OR procedures

Operating rooms account for 40 percent of a hospital's total revenue but run at only 69 percent of capacity, according to the Health Care Financial Management Association.

Most hospitals book a fixed amount of time for an operation, determine the number that can be performed in a day and assign each a starting time. If an operation runs late, it delays the starting time for each subsequent surgery.

Camilo Mancilla, a Ph.D. student, hopes to improve OR utilization with algorithms that account for the unpredictable durations of operations. He creates a sample of random times (or scenarios) for each procedure. By running a huge number of possible scenarios, the program eventually finds an optimal solution that accounts for randomness.

Improving OR utilization also requires determining the optimal order for surgeries. Common sense, says Robert Storer, professor of industrial and systems engineering, dictates scheduling a surgery of known duration before one whose

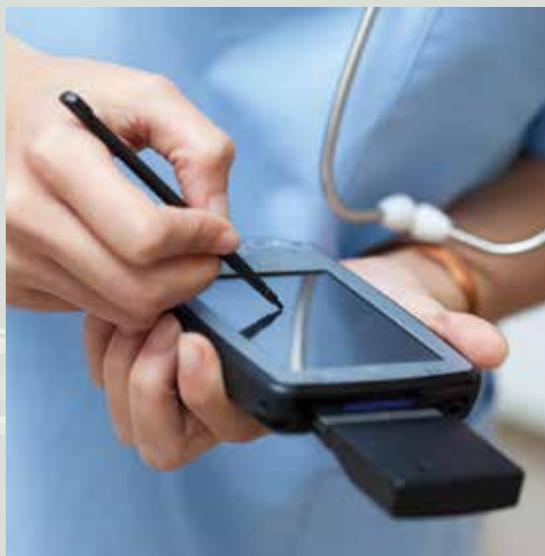
length is harder to predict. But the problem becomes more complicated when determining the best sequence for 10 operations rather than two.

Some studies have examined the stochastic optimization of starting times for a given sequence of operations, but few have investigated the effect of changing the sequence. This requires an enormous amount of computing time.

Mancilla has developed a heuristic solution based on Benders' decomposition, a technique that eliminates whole sets of poor sequences. His method reduces from days to minutes the computing time required to optimize a 10-operation-a-day schedule over a sample of 100 scenarios.

Mancilla and Storer have also developed a model for one surgeon performing procedures in two parallel ORs.

"In this case, there are two types of wasted time: when the OR is idle and staff is waiting for a surgeon or patient to arrive, and when a surgeon is waiting for the OR to be set up," says Storer. "We estimate there would be about 60 percent less wasted time using our scheme rather than the current method." 



# A NEW PERSPECTIVE ON DESIGN



## BUILDING A BRIDGE FROM THE LAB TO THE REAL WORLD

John W. Fisher, one of the world's preeminent bridge engineers, is a pioneering expert on fatigue and its effects on welded and bolted connections in steel structures. In a career spanning six decades, he has investigated many noted structural failures, including the collapse of the World Trade Center and the I-35W bridge in Minneapolis. The recipient of numerous honors, including election to the National Academy of Engineering, Fisher has been praised for improving health, safety and the economy while advancing the art of bridge engineering and design codes. Fisher is the founder of Lehigh's world-renowned ATLSS (Advanced Technology for Large Structural Systems) Center.

**Q: What are the main qualities necessary to be a good researcher?**

**A:** Ambition, creativity, patience and dedication to what you enjoy doing. And the desire to work with young people.

**Q: After serving in the 4th U.S. Army Engineer Combat Battalion, you earned a B.S. from Washington University in St. Louis in 1956 and an M.S. from Lehigh in 1958. What led you then to your lifelong interest in steel bridges?**

**A:** I worked three years as an assistant bridge research engineer with the AASHO (now the American Association of State Highway and Transportation Officials) Road Test. We studied bridges and pavements and conducted a lot of statistically designed experiments whose results are still a primary source of data for the highway design codes in our country and much of the world.

As assistant bridge engineer, I observed bridges and the impact of truck loads on bridges. That's where I got exposed to the concept of experiment design and to the fact that cracks could develop at welded details. When I returned to Lehigh as a Ph.D. student in 1961, I was the only person among faculty and students who had worked with computers, so I was asked to teach the first course in computers.

**Q: How did your research career take shape at Lehigh?**

**A:** Initially I worked on high strength bolted connections for my Ph.D. studies. In 1967, I started my first major project, the effect of weldments on the fatigue strength of steel bridges, funded by the National Cooperative Highway Research Program (NCHRP). The project had five or six phases, and it lasted into the mid-1980s.

At that time, there were many assumptions about what factors were critical to the ability



*Good researchers, says John Fisher, extrapolate only from a reliable base of knowledge.*

This changed the whole perspective on fatigue design. It also explained why, in the 1970s, we began seeing the first signs of fatigue cracking in bridges that had been designed and built after World War II for the interstate highway system. It turned out these designs were based on erroneous assumptions.

You have to be careful where your knowledge is and how you extrapolate. I think that's one of the crucial things with any researcher.

**Q:** *You were the founding director of Lehigh's ATSS Center when it was established as an NSF Engineering Research Center in 1986. What was the impetus for its creation?*

**A:** We wanted the capability to test full-size elements and specimens so we could assess size effects on building systems subjected to earthquakes and bridges subjected to loads from trucks and trains.

Also, I'm an avid supporter of the interdisciplinary approach. ATSS provided the opportunity to put several minds to work on the same problem from different perspectives. This is a good experience for students. It gives them new tools to understand problems.

**Q:** *You were part of a team of ATSS researchers that investigated the damage to steel buildings caused by the 1994 Northridge-Los Angeles Earthquake. What was your conclusion?*

**A:** Because of the dynamic loads of the earthquake, a large number of relatively new buildings developed fractures at welded joints at beam-to-column connections. Many of these structures were rendered unusable even though you could not see the fracture at first because the building had not collapsed or was not tilting.

In retrospect, our knowledge base was limited. The assumptions underlying structural designs relied, again, on tests conducted on small specimens rather than full-scale joints. That earthquake generated a huge amount of studies on scale effects, material effects, welding and the quality of welds. None of these had been adequately studied. We're still trying today to develop structural systems that are better able to resist dynamic loads.

**Q:** *You served on the national commission that investigated the collapse of the World Trade Center after the Sept. 11, 2001, terrorist attacks. What did you conclude?*

**A:** Both buildings were subjected to a massive

impact, which they were able to resist. But the impacts disabled the fire-suppressant systems, and fires destroyed enough depth in the structures to create the instability that caused them to collapse. Never before in the history of the world had large structures been subjected to so many fires at the same time, all of them simultaneously set because of the impact of the fuel tanks.

**Q:** *You've campaigned for more research to prevent structural failures and the resulting repair and litigation costs. Have your warnings been heeded?*

**A:** Unfortunately, our society is content to respond to disasters. There are insufficient studies to ensure long-term serviceability and proper quality control. This doesn't get the attention it should. I have not seen this change much. I'm not sure it ever will.

**Q:** *You have received almost every award in your field. Which have been the most notable?*

**A:** The Fritz Medal is among the top (the award is given by five international engineering professional societies; winners have included Thomas Edison and Alexander Graham Bell). Being the first academic to be named *Engineering News Record* magazine's Construction Man of the Year. Also the Outstanding Projects and Leaders (OPAL) Award from the American Society of Civil Engineers for lifetime achievement in education.

**Q:** *What is your teaching philosophy?*

**A:** I try to give students freedom in the way they approach a problem. I often take them into the field so they can see what's happening and why. My students and I learn a lot working together. I can attribute part of my success to the fact that I have had good students.

**Q:** *How do we educate the next generation of engineers? What are we not doing that we should be?*

**A:** I see too much reliance on models and computers. To understand the basic behavior of structures, you have to get your hands dirty. We need to promote hands-on experience and experimental work or there will be many more failures.

We also have to convince the country of the need for talented engineers. Engineering is the application of science to solve problems. More people would enjoy engineering if they understood this. 

of structures to resist fatigue (repeated stresses). Also, many bridge engineers thought contemporary designs would prevent fatigue cracking in bridges. But those design codes then were largely based on tests done on small specimens.

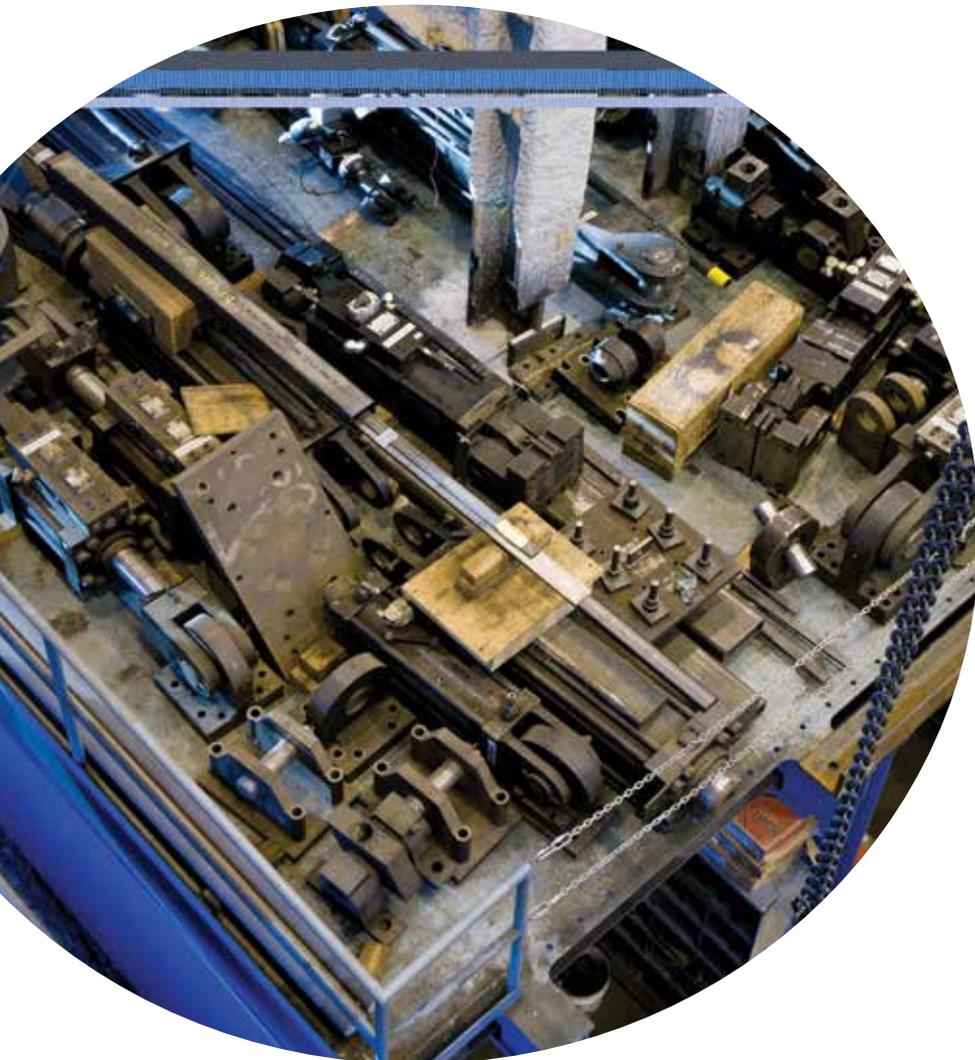
We conducted statistically designed experiments and found there was only one critical stress condition — the stress cycle. I was the first to propose this and I was opposed by a lot of bridge engineers. But our findings resulted in the adoption, in the U.S. and much of the rest of the world, of comprehensive specifications for designing steel structures, particularly bridges, for fatigue resistance.

**Q:** *What else did you learn from the NCHRP project?*

**A:** When we initiated the project, it was generally assumed that 2 million cycles was the fatigue limit, that if a structural detail withstood that many cycles, it would not fail at, say, 5 or 10 million cycles. But we tested specimens until they failed and discovered that the fatigue limit was different for different details. In some cases the limit was 20 million cycles, not 2 million.

# THE EXPANDING STATE OF THE INFRASTRUCTURE

Researchers apply a layer of sophistication to a “system of systems”



Few words have taken on as much baggage in recent history as *infrastructure*.

For more than two decades, *infrastructure* has kept questionable company, appearing with adjectives like *crumbling* and *aging*, *substandard* and *neglected*.

It has been linked to tragedies like Hurricane Katrina (2005), the Los Angeles-Northridge Earthquake (1994) and the recent crisis at Japan's earthquake- and tsunami-battered Fukushima nuclear power plant.

Politicians of all stripes have catalogued the decline of America's public works and facilities and have pegged the cost of meaningful overhaul at \$1 trillion or more.

Lehigh researchers who study the infrastructure are hardly oblivious to its shortcomings – many have sounded the warnings that helped bring the topic to the forefront of the public imagination.

But today, these researchers are focusing on the potential of infrastructure. They are working on advances in smart systems, software and sensors that will make it possible to allocate resources more efficiently and build more durable structures. They envision a day when infrastructure will be sustainable, engineered for a longer lifecycle and able to withstand extreme events without major damage.

When that day arrives, *infrastructure* will keep company with words like *intelligent*, *personal autonomy* and *environmentally friendly*. Technology will enable people to assume more responsibility for the resources they consume while affording greater protection against hackers, failures and down time.

*Infrastructure* is a broad term, encompassing the range of physical structures and services – levees and wastewater treatment plants, highways and airports, power grids and wireless networks, even schools and hospitals – that enable a society to function.

In the past two years, Lehigh's engineering researchers have carved out strategic areas of focus in new areas such as the smart grid while enhancing their traditional expertise in the civil infrastructure and power generation. Their approach is governed by a philosophy that regards the infrastructure as a system of systems that are integrated and interdependent.

The following pages explore a few infrastructure research projects at Lehigh.

## SAVING LIVES, PRESERVING COMMUNITY

Lehigh's structural engineers took a step toward the goal of sustainable infrastructure recently with a successful experiment on the world's largest earthquake shake table.

The test verified the superior performance of a reinforced concrete building system containing earthquake-resisting technology developed at Lehigh's ATLSS (Advanced Technology for Large Structural Systems) Center.

Sustainable infrastructure, says ATLSS director Richard Sause, protects lives while enabling building and transportation facilities to remain operational after an earthquake. In the process, it preserves the social and economic value of the community.

"Think of San Francisco," says Sause. "What will happen when the next big earthquake hits? Twenty years ago, the question was, 'Can we build structures that protect the lives of people?'"

"Today, the question is, 'Where are people going to live if there's extensive damage to the infrastructure?' What will happen if one-third or more of the people and businesses have to leave?"

The ATLSS technology is a self-centering system with reinforced concrete wall panels designed to "rock" during an earthquake. After shaking concludes, post-tensioned steel strands act like a rubber band to pull the building back to its original position.

The shake table test was conducted at the Hyogo Earthquake Engineering Research Center, or E-Defense Center, in Japan. Lehigh researchers joined peers from the Network for Earthquake Engineering Simulation in the U.S. and the National Research Institute for Earth Science and Disaster Prevention in Japan. The project was led by E-Defense researchers and funded by the Japanese government.

Researchers built two full-scale models of a reinforced-concrete four-story building – one with the ATLSS system and one with conventional reinforced concrete. The shake table simulated the 1995 Kobe Earthquake.

"The self-centering post-tensioned concrete wall system [sustained] very little damage under very strong earthquake ground motions," Sause and

Wesley Keller, a Ph.D. candidate, reported.

"We think that type of performance should be expected. By contrast, the conventional reinforced concrete in the adjacent building was badly damaged."

Self-centering post-tensioned concrete walls are made by casting panels of reinforced concrete and then feeding steel cables through pre-existing hollow ducts in the panels. When the panels are in place, the cables are stretched and then anchored at the top and bottom of the wall, which clamps the panels together.

Lehigh researchers have found that by using "unbonded" post-tensioned steel, concrete walls can be designed to perform well under strong ground shaking. By not bonding the steel to the surrounding concrete, says Sause, deformations in the steel are distributed over a relatively long length rather than concentrated in a small critical region. Strain levels in the steel are thus significantly decreased during earthquake loading.

**Lehigh's structural engineers took a step toward the goal of sustainable infrastructure recently with a successful experiment on the world's largest earthquake shake table.**

"An unbonded post-tensioned structure remains nearly elastic during earthquake shaking. As a result, it returns to its original shape after the earthquake without the need for costly repairs," says Sause.

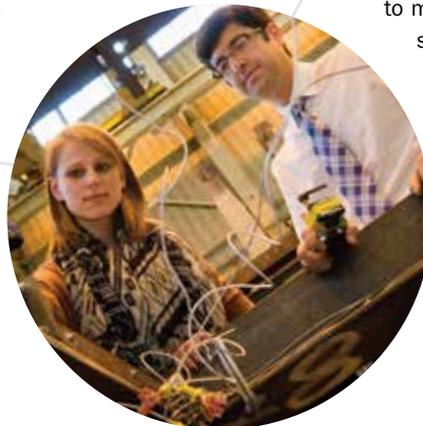
## IN THE EVENT OF EARTHQUAKES, GREATER RESILIENCE

In another project, ATLSS researchers are evaluating the potential for magnetorheological (MR) dampers to minimize seismic damage to structures. They study the dampers using hybrid simulation, which integrates two types of data – data generated by numerical models of structural components that are well understood and can be modeled analytically and data collected simultaneously from lab experiments on components that are not well understood.

MR dampers, say Sause and James Ricles, professors of structural engineering, improve the resilience of a multi-story steel-framed structure to earthquakes by



*The E-Defense shake table (above) confirmed the superior performance of earthquake-resisting technology developed at Lehigh's ATLSS Center (left).*



*Shamim Pakzad (right) and graduate student Liz Labuz develop wireless sensor networks to measure a bridge's response to ambient vibrations.*

minimizing its drift and vibration during a seismic event.

During an earthquake, says Ricles, floors in a high-rise can drift laterally, damaging beams and columns and pipes and wires. A building that looks sturdy can still be deemed unsafe to use and can cost more to repair than to be demolished and rebuilt.

Hybrid simulation, says Sause, increases the amount of information researchers can gather from an experiment.

“Hybrid simulation allows us to evaluate the performance of very large buildings under the dynamic loading of an earthquake in real time and also to compare designs,” says Sause. “Such data would be too expensive to collect from physical experiments alone.”

***The building, which was rendered unusable by the Northridge Earthquake, would not have had to be condemned if it had been fitted with MR dampers.***

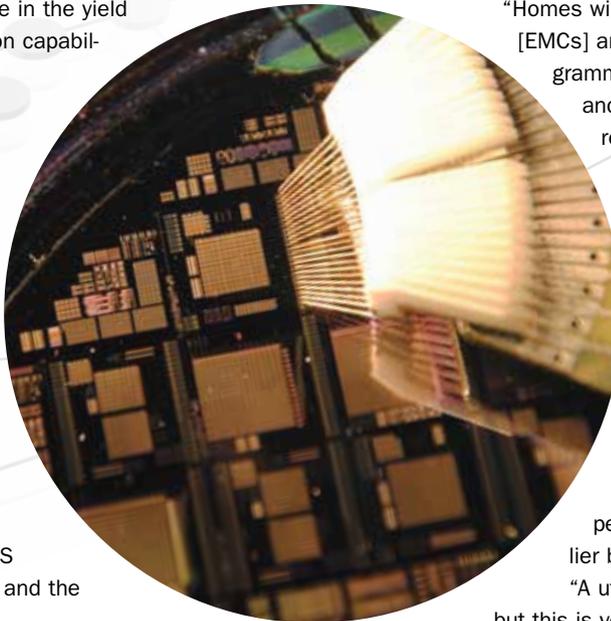
Sause and Ricles evaluated the benefit of using MR dampers by performing hybrid simulations of a nine-story building subjected to conditions equivalent to those of the Northridge Earthquake. The actual building was condemned after the earthquake.

“MR dampers are unique,” says Ricles. “Their properties can be controlled by varying an applied electrical current. The fluid inside the damper contains iron particles, which form linear chains that align with the induced magnetic field when a current is applied.

“This alignment increases the viscosity of the fluid and restricts its ability to move through the orifices of the damper. The result is a change in the yield strength and energy dissipation capability of the fluid.”

“The dampers significantly reduce the vibration and drift of the structure,” says Yunbyeong Chae, a Ph.D. student. The building that was rendered unusable by the Northridge Earthquake, he adds, would not have had to be condemned if it had been fitted with MR dampers.

The test was performed at the NEES Real-Time Multi-Directional Earthquake Simulation Facility in the ATLSS Center, with funding from NSF and the state of Pennsylvania.



## FOR THE GRID, AN INTELLIGENT INTERFACE

No part of America's infrastructure, says Rick Blum, is more overdue for a fresh coat of intelligent systems than the electrical grid that generates, transmits and distributes power to more than 300 million people.

Blum, professor of electrical and computer engineering, is one of a cluster of Lehigh researchers studying the smart grid. The group also includes Shalinee Kishore, associate professor of electrical and computer engineering; Lawrence Snyder, associate professor of industrial and systems engineering; and Liang Cheng, associate professor of computer science and engineering. The group formed a year ago when engineering faculty, meeting with experts from industry, government and national labs, determined that Lehigh's expertise in systems engineering was ideally suited to help overhaul the grid.

“The electrical grid,” says Blum, “needs to be able to respond to demand and to control distribution in real time. We have to figure out when consumers need power, how much they need and how much power is being generated at a given time by a given plant.

“The smart grid will increase energy efficiency and decrease carbon emissions. It will integrate renewable energy sources like wind and solar. Because power generated by these sources is variable, the prices charged for power must become variable as well.”

Information architecture overlaying the smart grid, says Kishore, will more efficiently match supply with demand.

“The smart grid will send information on real-time prices directly to consumers, allowing them to make decisions regarding the purchase of power,” she says.

“Homes will have energy management controllers [EMCs] and smart meters. Your EMC will be programmed to know your power usage patterns and preferences. It will look at prices in real time and make decisions for you.”

Communication between EMCs and the grid, says Kishore, will enable consumers to use power when it is priced most cheaply.

Communication among EMCs will allow car batteries to be charged and dishwashers to be run on a schedule that spreads out demand for power.

This leveling effect, says Snyder, will help power companies avoid costly periods of peak demand and even costlier brownouts and blackouts.

“A utility always tries to meet peak demand, but this is very expensive,” says Snyder. “The peak

usually lasts a short period of time. But a utility has to maintain expensive equipment – usually older, more polluting equipment – to be able to turn on power as needed no matter what.”

Kishore and Snyder are developing mathematical models that optimize communication among EMCs and between EMCs and the grid. The model, says Snyder, is similar to a CSMA (carrier sense multiple access) protocol that enables a node in a network of sensors to transmit information only when it detects that other nodes in the network are idle.

“Let’s say your EMC wants to run the air conditioner, dishwasher and clothes dryer,” says Snyder, who is developing an optimization algorithm for the model. “It asks the other EMCs in the network, ‘Do I have enough power?’ They might respond, ‘No, you have to delay one of your tasks.’”

“This is like rationing, but it’s structured so that users never really feel it.”

Without communication among each other, says Kishore, too many EMCs might schedule tasks during periods of low power demand, distorting usage and pricing patterns. Kishore and Snyder have run tests showing that this distortion would actually cause a greater spike in peak demand. To avoid this, a smart grid would act in concert with EMCs to manage the number of power-driven tasks performed at various times during the day. It would implement its decisions to achieve fairness without infringing on customers’ privacy.

“Pricing is just one mechanism to achieve efficiency,” says Kishore. “Communication is also essential. Our scheme shows you can develop coordinator-based communications protocols that allow the leveling of peak usage.”

## THE CELL PHONE USER AS CHEMICAL DETECTIVE

In the not-too-distant future, says Milto Hatalis, the ubiquitous cell phone will acquire a new, silent function.

Fitted with arrays of gas sensors, it will monitor the air for leaks of toxic chemicals.

In fact, says Hatalis, professor of electrical and computer engineering, groups of cell phones will serve as dynamic, wireless networks of chemical sensors – first for police and other first responders and later for average phone users.

“What we see,” says Hatalis, “is the day when every cell phone will be a mobile chemical lab detecting and analyzing harmful chemicals. The phones will send data to a central location, which will correlate data to achieve a realistic picture of a regional environment.”

None of this will come to fruition until sensors can be integrated cheaply into cell phones.



Hatalis’ group is working with NASA to make multi-channel sensors that will be integrated with carbon-nanotube (CNT) sensing materials. The CNTs will be functionalized to absorb certain chemicals selectively. This will cause changes in their electrical resistance that signify gases have been detected.

One goal is to increase the number of sensors that can be fitted into a phone and to ensure their accurate performance.

“As the number of sensors increases,” says Hatalis, “it becomes impractical to wire each sensor directly to the circuit that measures the change in electrical resistance.”

“We’ve developed an array of 64 sensors that requires only 16 wires. We’re exploring a device with 256 channels and 24 wires. Our goal is to have arrays of thousands of sensors that can be read with just a few input-output wires.”

“By reducing the number of wires and utilizing glass substrates, we’ll end up with a device that is smaller, cheaper and much easier to integrate into a cell phone.”

## TAKING THE STING OUT OF EXPLOSIONS

Terrorist attacks have motivated engineers to design structures that withstand explosions without collapsing while also minimizing danger from flying debris.

Clay Naito, associate professor of structural engineering, has worked six years with the Air Force Research Laboratory and Portland Cement Association to assess the blast resistance of precast concrete panels. His group conducts full-scale blast tests to evaluate the resistance to explosions of standard wall panel construction techniques. The goal is to design the panels more accurately and efficiently.

*Precast concrete sandwich panels reinforced with wire and insulating foam, says Clay Naito, help buildings withstand detonations. Facing page: Multi-channel sensors integrated with CNTs enable cell phones to sense chemicals.*

Wall panels are typically designed to resist loads from handling, construction, wind pressure, thermal expansion and shrinkage, and from floors and roofs. Flexural (bending) resistance is also a concern.

During an explosion, a wall sustains a pressure increase of up to 28,000 pounds per square foot, which falls to a negative pressure, creating suction on the panel, before returning to ambient conditions. All of this happens in less than a 20<sup>th</sup> of a second.

Even a small explosion can cause a pressure increase 20 times greater than the maximum static load a panel is designed to support. Inertial and flexural resistance, says Naito, help a structure withstand a blast.

In an NSF project, Naito is attempting to improve the flexural performance of precast concrete sandwich panels by using reinforcement strategies that combine bonded and unbonded wire strands with an internal layer of insulating foam.

“An analytical study is under way to determine the most effective arrangement of bonded to unbonded strands,” says Naito.

Under close-proximity detonations, the pressure of the initial impact generates a compression wave that penetrates the thick-

ness of the panel and reflects off an interior face as a tension wave. If this wave exceeds the tensile capacity of the concrete, fragments break off, or spall. If the spall depth exceeds half the thickness of the panel, a breach typically occurs.

“The propagation of the compression wave is reduced by the presence of low-density foam insulation,” says Naito. “We plan to study this effect and assess the potential for supplemental reinforcing materials such as carbon fibers, nylon and other synthetic fibers to improve the tensile strength of the concrete layers.”

Naito also collaborates with Auburn University. Blast testing is carried out at the Tyndall Air Force Base in Florida.

## TREATING BRIDGES AS A SYSTEM

The ambient vibrations caused by wind, river flow and car traffic are not the most dramatic loads a bridge sustains, says Shamim Pakzad, assistant professor of structural engineering. Forced vibrations from large trucks and earthquakes cause the most significant stresses.

But an assessment of ambient vibrations can paint a revealing portrait of a bridge’s structural health and enable engineers to evaluate more precisely the effect of an extreme event.

Pakzad and his students use networks of wireless sensors to study three truss bridges near Lehigh. On the Northampton Street Bridge connecting Easton, Pa., to Phillipsburg, N.J., the students installed 28 sensor units. In one day, they collected 3 million data points, or more than 100,000 information bits per sensor.

The sensors record ground vibrations to the bridge’s foundation as well as response vibrations by beams, columns and bridge deck. The baseline data will help engineers detect damage caused over the long term by truck traffic or over the shorter term by an extreme event.

The three bridges, says Pakzad, function as a system whose performance affects the social and economic life of eastern Pennsylvania.

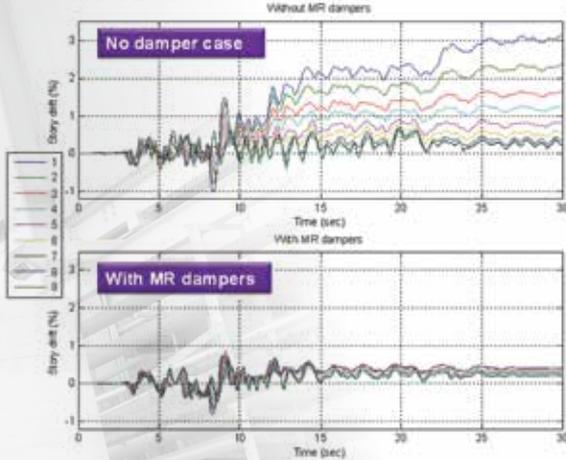
“If one bridge is taken out of service, its traffic has to be taken up by other bridges in the region. This increases the risk to the other bridges and requires us to look at the behavior of the overall system.

“Instead of looking at one bridge and evaluating its prognosis, you look at all the bridges as a system. A decision about one affects the others.”

Pakzad recently helped lead a team that installed 64 wireless sensor units on San Francisco’s Golden Gate Bridge. The units worked as effectively as conventional wired sensors at a fraction of the cost.

Each wired unit on the Golden Gate cost thousands of dollars, says Pakzad. Each prototype installed by his group cost \$200. Mass production and new design could cut that to \$10. 

MR DAMPER GRAPH



*Magnetorheological (MR) dampers significantly reduce the vibration and drift of a structure during an earthquake, say ATLSS researchers.*



## Practicing preventive forensics in the hidden infrastructure

Just beneath the topsoil, says Sibel Pamukcu, the layer of the earth's surface known as the subsurface, or subsoil, plays a vital but poorly understood role in the health of society's civil infrastructure.

As the topsoil sustains the earth's rich tapestry of plant life, the subsurface provides the foundation for buildings, bridges and roads; for tunnels, pipelines and embankments – in short, for every manmade structure placed in or on the ground.

Pamukcu, professor of geotechnical engineering, leads an interdisciplinary team of researchers attempting to shed light on the densely packed clay and sand that make up the subsurface.

The group is developing networks of wireless sensors and installing them in strategic locations underground to monitor pipeline leaks, mudslides, pavement cracks and other “geo-events” that affect the performance of the infrastructure.

“The health of the civil infrastructure depends on events in the subsurface,” says Pamukcu, who works with Liang Cheng, associate professor of computer science and engineering, and Muhannad Suleiman, assistant professor of geotechnical engineering.

“We can see structures above the ground. We can examine a bridge and look for signs of deterioration. But we can't see the subsurface or the hidden infrastructure of tunnels, embankments, levees, and bridge and highway foundations.

“Often this infrastructure is not monitored until a catastrophe occurs. So sensors have to be our remote eyes.”

In a project funded by NSF, Pamukcu, Cheng and Suleiman load transceivers, or breadboards, with sensors that are programmed to detect moisture, heat, soil movement, electrical conductivity and other characteristics of the subsurface. Changes in these characteristics, says Pamukcu, alter the way the transceivers transmit electromagnetic waves.

“We are trying to determine whether changes in the transmission of the electromagnetic waves are occurring because of the presence of liquid in the soil or because of compaction or loosening of the soil. These phenomena can be early warning signs of contaminant intrusion, the onset of a progressive slide or other events that normally appear to happen suddenly.

“Our goal is to be able to pinpoint the location of a likely event and to take precautions or preventive measures – to do forensic work – before the event occurs.”

Subsurface wireless sensor networks are not yet used to monitor the hidden infrastructure, says Pamukcu. She and her collaborators and their graduate students have installed and tested networks of transceivers in the soil on Lehigh's campus and are building a room-size soil box in a laboratory. Their aim is to learn how the electromagnetic wave signal is affected by the distance between transceivers and by the depth at which the transceivers are placed in the soil.

“We have been able to place our transceivers six feet underground and still get good transmission,” says Pamukcu. “We have also been



DOUGLAS BENEDECT

*The research team of Muhannad Suleiman, Sibel Pamukcu, and Liang Cheng (top, center) and graduate students Ehsan Ghazanfari and Suk-Un Yoon (bottom) places wireless sensor networks beneath the soil to monitor geo-events.*

able to show clearly in the lab that the transmission rate and signal both change drastically during a geo-event. And our system can identify and detect the location of injected fluid.

“The transceivers transmit well over short distances. Now we need to increase the distance of transmission and the battery life of the sensors. We need to stretch the envelope.”

Pamukcu's group is developing mathematical models and comparing their results with data from physical experiments. The next step is to install a wireless network of transceivers in a new structure or in an existing structure that is being rebuilt.

“Our goal is to provide long-term monitoring options for a structure, its subsurface and its vicinity as well,” says Pamukcu. “This will be an online system.”

# SIMPLE LOGIC FOR SMART DATA PROTECTION

PARITY CHECKS COULD MEET THE EXPLODING DEMAND FOR DIGITAL STORAGE.

People who want to make the digital revolution more energy efficient, says Tiffany Jing Li, might benefit from a visit to the U.S. Library of Congress.

The world's largest library has assembled 29 million books and periodicals, 15 million recordings and photographs, and 5 million maps in its 210-year history.

If that sounds impressive, says Li, consider this: The world today generates an equivalent amount of new digital information every 15 minutes.

Whether the videos, photos and tunes taking their place in cyberspace are as worthy of preservation as congressional tomes is a matter of conjecture.

But there is little doubt, says Li, an associate professor of electrical and computer engineering, that the explosion of digital data is exacting a steep energy price tag.

inconsequential amount of heat, says Li. But when hundreds or thousands join forces to back up data at a bank, corporation or military base, cooling is essential. In 2006, the U.S. burned through 61 billion kilowatt-hours, at a cost of \$4.5 billion, to power and cool data centers. The U.S. Environmental Protection Agency predicts consumption will double by 2011.

Much of that energy, says Li, goes to provide redundant data protection.

"If one disk fails, you need to replace it and restore the data from its duplication. If a second disk fails during the restoration, you need a third disk with the data backed up and protected. Replicating in triplicate enables you to support two concurrent failures.

"All three disks have to be operating simultaneously – collecting and filing

ness, you can cut costs significantly."

Government and industry have sought to make data centers more efficient by arranging servers more optimally, improving air flow and developing better lighting and cooling systems.

Li, who has an EAGER (Early Concept Grants for Exploratory Research) grant from NSF's Office of Cyberinfrastructure, proposes to cut energy consumption in data centers by making data storage itself more efficient. She designs erasure codes that restore lost data when storage disks fail, thus reducing the need for heavily redundant replacement schemes.

An efficient erasure code, says Li, enables one storage disk to protect multiple disks of data with parity checks that rely on a simple logical operation known as the "exclusive or" (XOR), or "modulo-2 addition." Data is stored as a binary sequence. A parity check adds the sequences for a and b, rounding sums to 0 for even numbers and 1 for odd numbers.

"If you know any two numbers, you can derive the missing number," says Li. For example, using a parity check, a c disk can protect disk a and disk b through bit-by-bit XOR operation.

"The c disk is equal to a modulo-2 plus b. It is a function of both. If the

TIFFANY JING LI'S ERASURE CODES PROMISE TO **REDUCE THE NEED** FOR HEAVILY REDUNDANT DATA REPLACEMENT SCHEMES.

"The proliferation of information has created an exponential demand for digital storage," says Li. "This requires the availability of massive data centers that are becoming notorious energy hogs."

A PC or laptop by itself generates an

data, incorporating updates, using energy. So when you measure energy usage, you are always multiplying by at least three.

"If you can reduce your storage disks without sacrificing reliability or robust-

a disk fails, you subtract b from c to retrieve and restore the content of a. If the b disk fails, you do the reverse. If the c disk fails, you recompute using data from a and b. A single parity disk thus simultaneously backs up two data disks.

While the idea sounds attractive, erasure codes are difficult to design, implement and verify in large-scale data storage systems, says Li.

“In case of data changes, you have to recalculate the related parity checks. With one-for-one replication, it’s easy to verify whether or not you’ve correctly backed up or restored data.

“Erasure codes must be designed just right. The optimal code has to be computationally simple. It has to provide maximum protection against erasures with a minimal number of parity checks.

“In the end, it’s not just a storage network but also a computing network that is needed.”

An optimal erasure code, says Li, is like a hypothetical situation in which a person is given five keys to open three locked doors.

“If you lose two of the keys,” she says, “the remaining three will still open all three doors. It doesn’t matter which keys you lose.

“The same is true when you back up three disks of original data with two parity check disks such that any one disk can replace any other. With an optimal code consisting of a + b + c plus f + g, you can derive the data on two failed disks as long as three remain. Any added disk can replace any original disk, but the bits have to work harder.”

The 3 + 2 replacement scheme can be expanded to 5 + 2, 7 + 2 and beyond, says Li.

“Our goal is to design optimal erasure coding schemes that are robust, simple and space-efficient and can replace the replication method of storing data.”

Li draws an analogy to baseball.

While today’s specialized relief pitchers might be called on to face just one batter, a Babe Ruth able to strike out the side and then hit the game-winning homer is a superior model for the versatility required of bits of data in an erasure code backup scheme.

Li and her students have successfully designed optimal k + 2 erasure codes for any integer k and for odd values of k. These codes have the smallest possible computational complexity promised by theory. Li’s group has performed theoretical analyses and run computer

simulations and will work with data centers to check the codes against real-world failure frequencies and protection requirements.

“Each data center is different. You have to observe it for years, and you have to provide protection for all possible contingencies.

“We’re investigating the possibility and efficiency of a layered approach, with codes of different erasure-correcting capabilities coexisting in the same center to provide local, regional and global protection.”

**A PARITY CHECK ON ENERGY USE:** The Library of Congress needed 210 years to amass the quantity of information that the world today generates digitally every 15 minutes. Parity checks, says Tiffany Jing Li, allow one storage disk to protect multiple disks of data, thus easing energy consumption at data storage centers.

**A PROLIFERATION OF INFORMATION**

210 YEAR HISTORY

\*EVERY 15 MINUTES



**DATA STORAGE CENTERS ARE ENERGY HOGS**

\*A COST OF 4.5 BILLION

EPA PREDICTS CONSUMPTION WILL

**61 BILLION KILOWATTS DOUBLE**

2006 UNITED STATES DATA CENTER \*WHEN YOU MEASURE ENERGY USAGE, YOU ARE ALWAYS MULTIPLYING BY AT LEAST THREE

BY 2011

AN OPTIMAL SOLUTION



**k + 2**  
ERASURE CODE





# The new art of shipbuilding

## A “SERIAL INVENTOR” BUILDS A HYBRID VESSEL TO STUDY THE COMPLEXITIES OF SLAMMING.

The custom dates back to the Vikings and maybe the ancient Greeks: As a new ship embarks on its first voyage, members of the crew break a bottle of wine – more recently champagne – over its bow to ensure good fortune.

The venerable tradition came to Lehigh last fall when a 29-foot speedboat made of stainless steel and composite materials was unveiled and formally named *The Numerette* by Lehigh President Alice Gast.

Under a crystal blue sky, in front of the lawn and flagpole on Lehigh’s Asa Packer Campus, a crowd of 150 engineering students and faculty and staff members raised glasses of sparkling cider to toast the new craft.

The crowd soon swelled with passers-by – other Lehigh students, a few school children and landscape workers – who were attracted by the craft’s gleaming orange and white colors and its gently beveled exterior.

*The Numerette* – the English pronunciation of the name resembles how the words “number one” are said in Swedish – is the product of more than a decade of design, testing, mathematical modeling and construction.

Its inventor, Joachim Grenestedt, professor of mechanical engineering

*“A hybrid material enables us to take advantage of the qualities of both steel and composites. The combination is greater than the sum of its parts.”*

—Joachim Grenestedt

and mechanics and director of Lehigh’s Composites Lab, believes the craft is the largest to date made with panels of a composite sandwich material bonded to a frame of stainless steel.

The new vessel has embarked on a twofold mission. It will serve as a portable research lab to investigate the destructive but little-understood phenomenon of “slamming,” which occurs when a ship belly-flops rhythmically against oncoming waves. And it will seek to show that a steel-composite hybrid construction can be applied to large ships to make them lighter, stronger, stealthier and more fuel-efficient.

“We believe a steel-composite hybrid may be the optimal way to construct a larger vessel, such as a frigate or a destroyer,” says Grenestedt. “Cruise ships, lightweight blast-resistant buildings and bridges in earthquake-prone areas are other potential applications.

“The hybrid construction enables us to take advantage of the particular qualities of both the steel and the composites. The combination is greater than the sum of its parts.”

### **A STRATEGIC HARMONY**

The properties of the carbon and glass fibers in the composite panels of *The Numerette*, says Grenestedt, complement those of stainless steel.

The materials are nonmagnetic, which enables a ship to pass over explosive mines without triggering them. Composites provide strength, resistance to fatigue (repeated stresses) and other environmental impacts, and insulation. They lack stiffness,



*The Numerette will serve as a lab to study the effects of slamming. Its hybrid construction, Grenestedt believes, can make larger vessels lighter, stronger and more fuel-efficient.*



*Grenestedt and The Numerette (right, below). Alice Gast (right, above) unveils the new vessel while Bill Maroun (above, standing) meets with Brian Kaplun '06. Maroun and Grenestedt designed a mono-ski and bucket seat to let Kaplun glide down the slopes.*

*“We’ve made every single panel on the bottom of the boat differently so we can determine which construction works best for slamming.”*

—Robert Thodal, *graduate student*

but they are lightweight and can be molded easily into complex shapes or made very flat to help a ship avoid radar detection. The 50 sandwich panels on *The Numerette* have a lightweight foam core and two composite skins for strength and lightness.

Stainless steel is heavier and more ductile than composites, and it provides the stiffness necessary for a ship’s hull.

Grenestedt played a role in the structural design and materials testing of the *Visby*, a 239-foot-long Swedish stealth corvette (small warship) that fits 20 people and was the largest carbon-fiber vessel ever built when it was launched in 2000.

“For a ship like the *Visby*, carbon fiber is a great choice,” says Grenestedt. “But to get to the scale of, say, a destroyer, a steel-composite hybrid

concept has a lot of advantages.”

The main challenge in working with a steel-composite hybrid, he says, is joining the two materials.

“It’s challenging to join steel and composites because each has a very different stiffness. Steel can be strained on the order of 0.2 percent, while a composite, at such low strains, is not making much of a contribution. Composites need to be strained extensively. The challenge is to allow them to do this without overstraining the steel. We have developed very special joints in order to accomplish this.”

The group that designed and built *The Numerette*, which also included six graduate students as well as engineering technician William Maroun, performed finite-element analyses and conducted extensive stress and loading tests in Lehigh’s ATLSS (Advanced Technology for Large Structural Systems) Center on everything from small coupon specimens up to a 16-ton fatigue-loaded specimen representing a ship hull section. The large specimen survived 100,000 fatigue cycles at loads 20 percent greater than those for which they were designed without damage to the composite materials or the bonded joints.

“We learned very much from this test, in particular the importance of the joint details,” says Grenestedt.

### SHINING A LIGHT ON SLAMMING

Next to explosions and bomb attacks, slamming – the harsh and steady slapping of waves against a hull – imposes the highest forces on a water vessel. Slamming, along with associated vertical accelerations, is also one of the main causes of injury to sailors, especially those on high-speed boats.

*The Numerette* is equipped with 123 strain gages, and prepared for 160 pressure sensors, to measure

the effects of slamming on its composite panels and steel skeleton. In an effort to gather more information, Grenestedt's group has given each panel on the bottom of the boat a different construction, varying the strength, stiffness and mass.

"Slamming lasts a few milliseconds," says Robert Thodal, a graduate student in the group. "It is very dynamic, very quick and quite hard to measure.

"Each of our sensors is sampled 50,000 times per second. When a wave hits the boat, we will be able to determine what happens to each panel transversely and longitudinally, how each panel bends, and how the wave moves across the hull.

"We've made all the bottom panels differently so that we can compare their performances to determine which construction works best for slamming."

In addition to the sensors, *The Numerette* contains sophisticated instruments for data acquisition and analysis. Computers and electronic equipment are mounted in water- and shockproof boxes attached to the steel frame. (All the attached features – battery, engine, fire extinguisher and more – are fixed to the frame firmly enough to withstand 23 G's of acceleration.) A video screen shows in real time how the bottom panels are deforming.

"Our goal," says Grenestedt, "is to gain a better understanding of slamming and eventually work this into design codes that will lead to lighter and stronger boats and ships, both military and civil."

### A HO-HUM ON THE FIRST RUN

Besides Thodal, other graduate students who have worked on *The Numerette* include Jian Lv, Scott Shirey, Drew Truxel, Brett Snowden and Jack Reany. The Office of Naval

Research has funded the project since Grenestedt began studying steel-composite hybrid hulls a decade ago.

The maiden voyage of *The Numerette* took place on Pennsylvania's Lake Beltzville and lasted two hours. In subsequent tests, the boat reached speeds approaching 60 mph.

"We were surprised the boat performed so well," says Grenestedt. "We started at a slow speed, did a lot of turns at different rates and then slowly increased speed. The testing of any new vehicle requires slow and careful envelope expansion.

"I had envisioned a white-knuckle experience. The adrenaline was pumping when we started out, but after an hour of intense testing, it became almost boring. We have so far found no bad behavior in the boat."

Grenestedt calls the Composites Lab a "rare find" in a university setting.

"Seldom are large structures designed, analyzed, built and tested in a single lab. This gives students a broad educational experience while requiring 'out-of-the-box thinking.' In the end, students acquire solid engineering skills that enable them to hit the ground running."

At the unveiling of *The Numerette*

last fall, S. David Wu, dean of the engineering college, noted that Grenestedt incorporates composite materials into much of his life. He owns and flies a two-seat airplane made of composites. A beam supporting the deck of his house is made of carbon fibers. Last year, at Utah's Bonneville Speedway, Grenestedt set the U.S. land speed record for 125-cc gasoline engines in an enclosed streamliner motorcycle that he designed and built from composite materials.

And Grenestedt's students have caught the fever – they are building an all-composite land yacht and aiming to break the land-sailing speed record.

"You are a serial inventor," Wu said to Grenestedt. "You are no stranger to new innovations, all of them offered at high speeds." 

*The Numerette has 123 strain gages and is prepared for 160 pressure sensors. One goal, says Grenestedt (below), is to develop design codes based on a better understanding of slamming.*





# NOT FOR THE FAINT OF HEART

*One goal of the program is to prepare students like Dale Statler and Michelle Tillotson to design skyscrapers and other superstructures at the cutting edge of the structural engineering profession.*

**The intensive, 10-month M.Eng. program in structural engineering prepares graduates for professional practice.**

It's one thing to run a computer simulation to predict the failure load for a beam, column or other structural component.

It's quite another to apply more than 100,000 pounds of force to a reinforced concrete beam and watch it slowly crack and then, with one loud bang, collapse into a pile of rubble.

Students working toward a master's of engineering in structural engineering at Lehigh get to do both. The intensive, 10-month master's of engineering (M.Eng.) program starts in the summer with the Structural Behavior Laboratory, where students conduct destructive tests to determine how structures behave.

These experiments lay the groundwork for

the program's centerpiece, the Group Design Project, in which students work in small groups to design a major structure. They use the actual architectural drawings of a structure that has already been built, but they start from scratch, reviewing structural codes, investigating and choosing structural systems, and presenting their final designs.

Students compare building systems, such as steel staggered truss, composite steel beams, precast concrete and post-tensioned concrete two-way flat plate. They also learn about the many complexities that go into building a structure. For example, when engineers build a parking garage out of structural steel, they must add protective coatings to the steel because salt and other residue brought in by cars can cause the metal to corrode.

In the Group Design Project, which runs the course of the M.Eng. program, the students periodically present their designs to professors and engineering professionals, including some who work for the very firm that built the original structure. During these presentations, they field questions from experienced engineers and defend their findings.

"I believe the most beneficial part of the program was the design project," says Janelle Hemnitz, an alumna of the program who now works for Alfred Benesch & Company in Allentown, Pa.

"The project was much more in-depth than any assignment I had as an undergraduate. We learned how different structural systems work together, and we used the same references we would be using later in our professional careers, such as various codes and computer software for analysis.

"We also learned the importance of communication, not only between group members, but also with outside parties."

In fact, every aspect of the M.Eng. program, which enrolled its first class in 2008 and now has 26 students, is designed to prepare students for successful careers as practicing engineers. The program emphasizes practical knowledge and design experience over theoretical research.

"I chose the M.Eng. program rather than the M.S. program because I wanted

a design-based program," says Christopher Buente, a graduate of the program's first class who now works for Wiss, Janney, Elstner Associates, Inc. in New Jersey.

"The M.Eng. program is also condensed into one year. I was anxious to get out into the workforce so the one-year degree was perfect."

The program is directed by Jennifer Gross, a professor of practice with

Thornton Tomasetti and other advisory board companies host students for externships during breaks between semesters. Students shadow engineers, assist on projects and make professional connections.

"I had a wonderful experience at Wiss, Janney, Elstner Associates, Inc., which specializes in forensic engineering," says Michelle Tillotson, who will graduate from

*The most beneficial part of the program was the design project. We learned how different structural systems work together and we learned the importance of communication.* —Janelle Hemnitz

12 years of industry experience. As a professional engineer, Gross has worked on such projects as the convention center and hotel complex at Gaylord National Harbor in Oxon Hill, Md.; The Borgata Hotel Casino and Spa in Atlantic City, N.J.; and Seuss Landing at Universal Studios, Islands of Adventure in Orlando, Fla.

"Becoming a professor seemed like an exciting way to work with students and teach them what I know," Gross says. "This program is geared toward the practical applications of engineering. Everything the students are learning about, I have done."

Students in the program use the world-renowned structural testing facilities in Lehigh's Fritz Engineering Laboratory and ATLSS (Advanced Technology for Large Structural Systems) Center. They also have a dedicated computer lab equipped with the same software that practicing engineers use.

An executive advisory board composed of representatives from leading engineering firms and partners makes sure that the curriculum meets industry needs. Advisory board members also interact with students, critiquing the group design project, giving guest presentations and supporting scholarships.

"We help advise the M.Eng. program because it gives us the opportunity to provide input as to what a practicing engineering company looks for in a graduating student," says Daniel A. Cuoco, P.E., president and chief executive officer of Thornton Tomasetti.

the program in May. "I was able to visit the site of a garage collapse. My experience showed me the benefits of getting my master's degree and reaffirmed my passion for structural engineering."

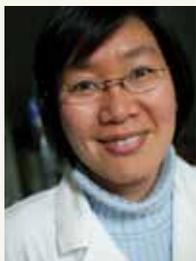
The most prestigious engineering firms generally consider a master's degree to be the entry-level degree for practicing structural engineers. Lehigh's M.Eng. program gives students the experience and knowledge they need in a short period of time so they are prepared to enter the workforce quickly.

Even in a tight economy that has hit the construction industry especially hard, most of the program's graduates have found jobs. They have gone into bridge or building design, forensic engineering and construction management. One alumnus works in the aerospace industry, and another does structural analysis for submarines.

The Class of 2011 looks forward to the same success.

"This program has allowed me to conduct the full structural design of a complicated project using the tools and techniques actually employed in industry," says Dale Statler, who will complete the program in May.

"I believe that my exposure to advanced course work in structural analysis and design, combined with the practical design experience, will make me a much more competitive job applicant and a far more capable structural engineer." 



*Cheng's device could bring modern medicine to remote regions of the world. Besides microfluidics, it has required a knowledge of manufacturing and processing.*

## Going with the tiniest of flows

The modern age offers abundant opportunities to a person with an interest in medicine, an aptitude for science and mathematics – and a willingness to venture well outside one's comfort zone.

Growing up in China's Hubei Province, Xuanhong Cheng dreamed of becoming a doctor. In high school, she learned to appreciate the analytical way engineers view the world.

College enabled Cheng to explore several fields. She earned a B.S. in biology from Wuhan University and then an M.S. in electrical engineering and a Ph.D. in biomedical engineering from the University of Washington.

As a research scientist at Harvard Medical School, and now as an assistant

Developing ideas into products that benefit people, says Cheng, involves more than design, fabrication and testing. It can also require fluency in product development and knowledge of other cultures.

Cheng's main project is a hand-held device that monitors the progress of HIV by measuring the concentration of lymphocytes, a type of white blood cell, that possess a CD4 receptor. In the lab, that typically requires a dozen steps and must be done in a large machine. Cheng's goal is to do the test in four steps on the portable device and eventually on a chip. That way, patients can have their blood analyzed without having to live near a lab.

The device is based on microfluidics, or the precise manipulation of fluids at the microscale. After cycling a fingerprick of blood through tiny pouches and capillaries, the device separates

CD4 cells from other blood components. Then a reagent counts the CD4 cells by reading their electrical signals.

"A microfluidics device like this can eliminate the need for assays that require large amounts of bloods," says Cheng. "And an assay on such a small scale can be done much more quickly."

Cheng's group has made progress – after overcoming obstacles.

"At first, I thought making the device

would be easy," says Cheng. "Then, working in the lab, I realized it would involve manufacturing and processing, as well as materials science, chemistry and biology.

"Product development requires a different set of skills. What kind of plastic is most biocompatible? What about cost? How do you mold a plastic channel tens of microns in height so that fluid does not get trapped in a 90-degree turn and cause a high background signal?

"And how do you functionalize a plastic surface with an antibody? When it comes to putting a protein onto the geometry of our device, there's very little expertise."

Cheng's group is working with a company to commercialize the device. In late 2009, she and four other researchers made a fact-finding trip to Africa, where the incidence of HIV and AIDS, especially among children, is especially high.

"We spent five days in Kenya visiting clinics and hospitals," says Cheng. "The purpose of the trip was to learn about infectious disease diagnosis and find out what kind of facilities Africa has.

"You can't successfully design a product without knowing the setting in which it's going to be used. The setting in Africa is very poor. Sometimes clinics don't have electric power, which means our system has to be robust and cheap."

The group had hoped to begin field-testing its device in Africa before the end of 2010, but technical problems forced a postponement until later in 2011.

"Our device is not yet mature enough," says Cheng. "When it is, we will go back to Africa to set up a clinical trial."

It may take several more years before the device reaches the market, says Cheng, but the wait is worth it.

"I chose this field because my work could have a faster impact. It's exciting to know that the ideas my students and I are working on might one day become products that help someone else." **1**

*"You can't design a product without knowing where it's going to be used. In Africa, our system will have to be robust." —Xuanhong Cheng*

professor of materials science and engineering at Lehigh, Cheng has blended the diverse elements of her academic background with more recently acquired capabilities.

She has worked the past five years, with doctors, scientists and engineers, on small medical devices that automate the diagnosis of disease and promise to bring modern medicine to remote regions of the world.

KATE HOUL



Lehigh's contributions to society's critical infrastructure are many and varied. Here are a few examples:

## Transportation/Logistics

JAMES WARD PACKARD 1884 introduced a number of innovations, including the modern steering wheel and, years later, the first production 12-cylinder engine ...

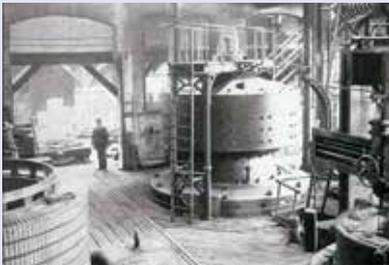
EDUARDO B. FOWLER 1908 helped build Cuba's Havana Harbor and Santiago de Cuba Harbor and all of the bridges on the Carretera Central highway, which runs the entire length of the island nation ... **Ai-ting "Tobey" Yu '49 Ph.D.** played a large role in converting the Great Lakes into an efficient waterway for coal and ore shipping, including modern, self-loading ships.



## Energy/Electricity

The research of **Lewis B. Stillwell** 1885 led the Niagara power plant to introduce in 1895 the "Stillwell regulator" to keep from producing more power than necessary ... In 1966, **WILMER WILBERN '52** developed the world's first application of closed-loop computer control to the operation of large electric smelting furnaces ... **PAUL CAMUTI '83** is leading Siemens' approach to smart-grid technologies as president of its smart-grid research division. Many Lehigh alumni have assumed CEO roles across the utility sector, including

**LEWIS HAY '77** of NextEra Energy, **ANNE MURTLOW '82** of Indianapolis Power & Light, **BILL HECHT '64 '70G** of PPL (ret.) and **J. BARRY MITCHELL '70** of ComEdison (ret.).



## Industrial Safety

**Bill Maloney '80** helped develop and execute the plan to rescue 33 trapped Chilean miners in October 2010 – two months ahead of initial projections ... **PHILIP DRINKER '17G**, one of the most influential

industrial hygienists in the field's history, invented the iron lung and protective gas masks, developed standards for industrial air quality, and helped launch Harvard's School of Public Health.

## Information/Computer Technology

**Clarence Hogan '71 Ph.D.** is a pioneer in microwave and semiconductor technology, and worked under Nobel Prize laureate inventor of the transistor, Bill Shockley ... **KEVIN KENNEDY '77** is CEO of telecom giant JDS Uniphase and has served as a U.S. Congressional Fellow on Science, Space and Technology ... **STEVE CHANG '78G** formed Trend Micro with the mission of developing antivirus software for personal computers and business networks ... **GEORGE KLEDARAS '87** is a leader in developing financial software for instantaneous global trading.



To learn more about the achievements of Lehigh engineers, visit the Lehigh Engineering Heritage Initiative at

[www.lehigh.edu/heritage](http://www.lehigh.edu/heritage)

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## A NEW PERSPECTIVE ON DESIGN

Engineers, says John W. Fisher, should learn early to tie experiments in the lab with experience in the field. In a career spanning six decades, Fisher has earned global renown for advancing the art of infrastructure engineering and design while investigating many of the world's noted structural failures.

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