Cold-formed steel rebuilds earthquake-resistant architecture

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This full-scale cold-formed steel building withstood strong earthquake forces in a recent shake table test in Buffalo, NY. Credit: Kara Peterman, Johns Hopkins University

Academia and industry are collaborating in a new effort to engineer earthquake-ready buildings. The effort based at Johns Hopkins University aims to design and test a single structure primarily built from cold-formed steel, a material that has boomed in structural engineering projects over the last 25 years.

With funding from the National Science Foundation, JHU engineering professor Benjamin Schafer helped bring together a team composed of industry professionals, professors, graduate students and the occasional high school or undergraduate student yearning for research experience to conduct experimental and computational seismic research on cold-formed steel components.

The first industry standards and codes for cold-formed steel were written in 1946 and are mostly based on empirical data, in many cases lacking underlying theory. When engineers attempt to make a building earthquake-resistant, they use specific structural components, appropriately called details, to absorb earthquake forces and help direct some of those forces back to the ground.

That works, but when an earthquake hits, the entire building reacts, not just the sections containing details. Even though academic research has lead to improvements to the original building codes over the decades, there is much to be learned about the entire system of a cold-formed steel building as it responds to an earthquake.

"When you have a big knowledge gap, you have a danger gap," says Schafer. To fill the gap, he and his collaborators are testing and analyzing individual components of a cold-formed steel structure, and taking what they learn about each piece to design a full-scale building that will undergo three stages of shake table tests. The tests will occur in 2013 at the NSF Network for Earthquake Engineering Simulation (NEES) site at the University of Buffalo in New York and are part of NEES's broader research efforts.

Cold-formed steel in the lab

Cold-formed steel is lightweight and shines like aluminum because it possesses a galvanized coating. Kara Peterman, a third-year Ph.D. student on the project, describes it as "steel that is rolled by a long string of machines into a thin sheet, then bent like origami into a desired shape."

With every shape change, each made at room temperature (hence the name cold-formed), the properties of the piece change, improving the qualities of the steel. Small tweaks have the potential to increase the steel strength, making one component more efficient than it was before. For example, when an 8-foot tall sheet of steel is converted into a u-shape with two 90-degree bends, it becomes a stud that can withstand ten thousand pounds of loading. The beam could carry five Volkswagen Beetles - each about two thousand pounds - yet it is light enough for Peterman to lift.

Peterman has been working with a second graduate student, Peng Liu, to assess how individual cold-formed steel components bear loads. She has tested components such as beam-columns and local connections in the JHU lab, and this past summer, she tested wall-to-floor connections. Liu, a visiting Northeastern University Ph.D. student from China, has been conducting experiments on shear walls, which are specifically made to resist lateral forces. He completed his testing in a facility at the University of North Texas. Liu also analyzes and interprets the raw data that his experiments have yielded.

Peterman and Liu relay very specific information to Jiazhen Leng, a Ph.D. student at JHU, who can then code a highly detailed building model, component by component, using OpenSees - open-source building analysis software. With the 3-D model in place, he has the ability to perform various analytics. In turn, his analytical data informs predictions for more experimental work, particularly the 2013 full-scale test. The work the graduate students perform comes full circle, linking them together.

The big blue baby

In the bowels of Latrobe Hall, the civil engineering building on the JHU campus, dwells the Big Blue Baby, also known as the multi-axis structural testing rig. Schafer's research group, which designed the machine, is proud of the fact that there is only one other like it in the United States (at the University of Minnesota, also part of the NEES network.) The body is made of hot-rolled steel and the brain is a computer, which drives a hydraulic pump. The system sits in the center of the cramped lab, where black electrical wires snake along the ground toward other, smaller systems. Rows of walls, made in-house, lean against the back of the room, with stacks of sheathing and steel at the front.

"Compared to the NEES facilities, our room is tiny," admits Peterman. "But, we've gotten a lot out of this lab - great results, great publications, and great changes to the codes."

Experiments are large-scale tests of small components, because it's almost impossible to scale down every behavior. The Big Blue Baby can hold a standard wall in its belly and apply loads using hydraulic actuators, which look like thick, black tentacles. What makes this machine unique is its ability to perform combined loading. The punch can come straight down, twist from two different sides, or apply stress from several directions at once.

Most structures experience varying loads from multiple directions, so the Big Blue Baby simulates real-world engineering situations. The most common type of load is called the axial load, weight that comes directly down on a wall due to gravity - think furniture or snow. There are red emergency buttons around the rig, just in case the thirty thousand pound Baby decides to throw a tantrum and it must be taken offline.

The 2013 Shake Table Tests

Robert Madsen, Senior Project Engineer at Devco Engineering, Inc., is the primary link between the researchers and industry. Leading up to the

2013 large-scale tests, there is a meeting every three months between the academics and a larger industry advisory board for updates from both sides. Madsen provided the constructible design for the 2013 NEES building that the graduate students have been characterizing on a component level.

The plan is to construct a two-story building, 50 feet by 23 feet, inside the colossal NEES Buffalo lab. The building will sit upon dual shake tables that will be linked. The Buffalo building will undergo shake table tests in three major stages: the first will be as a steel skeleton; the second stage will include only walls and other structural components that engineers currently rely upon; and the third stage is a complete structure built to standard and ready to be inhabited.

Cue Narutoshi Nakata, co-principle investigator from JHU, brings his expertise in shake-table testing and performance evaluation. To attain meaningful and useful results, Nakata must determine the right number of sensors on the table, their locations, and what they will measure. He must also decide what type of ground motion the table will produce, such as fast versus slow, and the number of scenarios to enact. Based on Leng's 3-D model and analytical tests, Nakata creates the mathematical models of earthquakes that the shake table will generate, and will eventually analyze how the structure dynamically reacts. One of the scenarios is a reproduction of the 1994 Northridge earthquake - as a well-recorded, historical Los Angeles earthquake with a magnitude of 6.7, it is widely used for simulation experiments.

Immediate Impact

Schafer has involved high school and undergraduate students in the project to provide them with hands-on experience quite early in their careers. High school students often come from Baltimore Polytechnic Institute, a Baltimore City public school, which offers a research practicum course that allows those enrolled to volunteer at the JHU lab a couple hours per week. The latest volunteer was from Garrison Forest High School, a private all-girls school in Owings Mills, Md., which required the student to complete a specific research project she could present at the end of the semester. With Peterman's guidance, the student had the opportunity to explore connection testing variables.

The team also tries to get younger college students involved, because research is usually not an opportunity they have until they are juniors and seniors. After passing a trial period to prove their interest, two undergraduate students participated this past summer: one who just finished his freshman year, the other her sophomore year.

The bigger picture

Although the east coast is not often on the news for earthquakes, Schafer explains that, "Earthquakes are a matter of return period, not a matter of where you live. They come more quickly in California, but if you design a building and you expect it to exist for 20, 50, or 100 years, you'll go into the codes and you'll see almost anywhere you are in the U.S., you're going to need to design for earthquakes."

Schafer remains driven to impact fundamental knowledge and change U.S. practice. "If an engineer knew how the whole system responded," he adds, "instead of just one little bit, then they would be able to design the whole building to be earthquake ready."

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