MIT CONCRETE SUSTAINABILITY HUB

CSHub Annual Report

An Overview of CSHub Research and Activities in 2020

February 2021

The Great Dome seen from across the Charles River in Boston.

2020: A Year in Review

At CSHub, we parse unpredictability. Whether it's variations in wind loads, fluctuations in prices, or the moment a structure might fail, we seek to master uncertainties. But even our familiarity with the outlier couldn't have prepared us for 2020.

With little warning, both the familiar—our regular Monday seminars—and even the remarkable—our attendance at CONEXPO-Con/AGG—were interrupted. We found our research halted, lab space off-limits, and meetings canceled. Several CSHub personnel were even forced to race back from Nevada as gathering restrictions materialized at home.

And yet, these drastic interruptions inspired new forms of collaboration, engagement, and achievement. Over the subsequent year, researchers published in high-impact journals, had their work covered in major national news outlets, all while sustaining a busy presentation schedule and a public webinar series with record attendance.

This is not to say adaptation came easily. We had had to supplement a familiar roster of connections with an array of new technologies and shifted schedules. Separated from one another, each of us came face to face with the kinds of disruptions we regularly try to anticipate and mitigate. In that sense, it's been a painful lesson in the very importance of our work.

Though the current crisis is far from over, we hope you can reflect with us on an eventful, if harrowing, year. It's taught us a lot. We've strived to live up to our values, reach out to one another, and, against the odds, achieve. As we enter 2021, one thing has become clear; we're still mastering uncertainty—but it seems we're learning to handle it too.

Jeremy Gregory
Executive Director
The MIT Concrete Sustainability Hub

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By the Numbers

Research

9 Research Briefs

3 Topic Summaries

10 Peer-reviewed Journal Papers

Audiovisual

6 Webinars

3 Explainer Videos

24,000 Total YouTube Views

Presentations

33 Presentations

4000+ Attendees

Highlights include CONEXPO-CON/AGG and the Net Zero Schools Summit

Media Coverage

9 Appearances in National News Outlets

1 Feature Story in *The New York Times*

2 Podcasts, including WNYC's *Science Friday*

Embodied Carbon

Conductive cement samples doped with nanocarbon black particles.

What will it take to reduce the impacts of the world's most consumed construction material? This question has increasingly occupied the minds of policymakers, engineers and architects–as well as researchers at the MIT CSHub. In 2020, we sought to dramatically expand our research on this topic and generate vibrant conversations in the process. To do this, we chose to start from the ground up.

A Solid Foundation

In March, the principal investigators collaborated to produce an *MIT News* piece that sketched out the essentials of concrete. The piece, "Explained: Cement vs. concrete — their differences, and opportunities for sustainability," was a part of *MIT News*'s long running "Explained" series on fundamental topics. Just as with our research, the piece examined concrete at all scales.

It started by introducing the materials used to manufacture cement, then detailed the intricacies of the hydration reaction, before finally outlining how the optimization of mixes—as well as concrete's innate properties—can dictate performance and sustainability. In addition to technical innovation, they stressed collaboration. "Change doesn't have to happen based on just technology," Jeremy Gregory noted. "It can also happen by how we work together toward common objectives."

Concrete Roadmaps

So then, what exactly would such change look like? During 2020, CSHub researchers plotted a future in which low-carbon concrete technologies are abundant.

In his August research brief, CSHub postdoc Ehsan Vahidi, now the John N. Butler Endowed Professor in Extractive Metallurgy at the University of Nevada Reno, presented an ambitious scenario that could drastically cut the emissions of the U.S. buildings sector. He found that if several mitigation solutions such as grid decarbonization, the implementation of the latest building codes, and the use of low carbon binders in concrete it would be possible to nearly halve the U.S.'s construction emissions between 2016 and 2050.

Hessam AzariJafari, a CSHub postdoc, has also been working on modeling the climate change impacts of concrete over time with a focus on pavements. His recent paper, "Carbon uptake of concrete in the US pavement network," estimated the cumulative carbon uptake of U.S. pavements over 30 years due to carbonation, a natural process of CO_2 sequestration that occurs in concrete.

By developing a model of the entire U.S. pavement network, AzariJafari created a high-fidelity estimation of carbon uptake: he found that if all end-of-life requirements were met, carbonation could offset around 5% of the emissions generated from the cement used in pavements. As he explains in a recent MIT News piece, these savings suggest that carbonation in pavements is—at least currently—a more cost-effective form of carbon uptake than artificial carbon capture and sequestration.

In collaboration with The French National Centre for Scientific Research (CNRS), CSHub-affiliated researchers have also begun to explore a future in which concrete possesses multifunctionality. By incorporating nanocarbon black particles into cement mixtures, CSHub-affiliated postdocs Nancy Soliman and Nicolas Chanut have found that the material can conduct electricity.

When they ran a relatively low voltage through their samples, the duo discovered that they could generate heat due to what's known as the Joule effect. Their findings, published in a paper in *Physical Review Materials*, present a first-order model that they hope could encourage the scale-up of the technology for use in an array of applications—from deicing runways and roads to enabling radiative slab heating in buildings.

Tall Ambitions. Low Emissions.

As the embodied impacts of concrete receive increasing attention, CSHub has become a trusted source of information for policymakers, journalists, and other academics.

Over the course of 2020, both *The Wall Street Journal* and *The New York Times* ran articles that took stock of various new concrete technologies, such as bioconcrete, carbon-dioxide injection, and concrene (a mixture of concrete with the addition of graphene). In both articles, they included comments from Jeremy Gregory on concrete's use and the mindset needed to decarbonize its production.

Gregory also had the chance to speak on WNYC's *Science Friday* with the renowned science journalist Ira Flatow for a roundtable on sustainable construction with other experts. "On a per unit weight basis, concrete has a low impact," said Gregory during the discussion. "But since we make

CSHub Executive Director Jeremy Gregory at the Net Zero Schools Summit at Yale University.

MIT Climate Portal

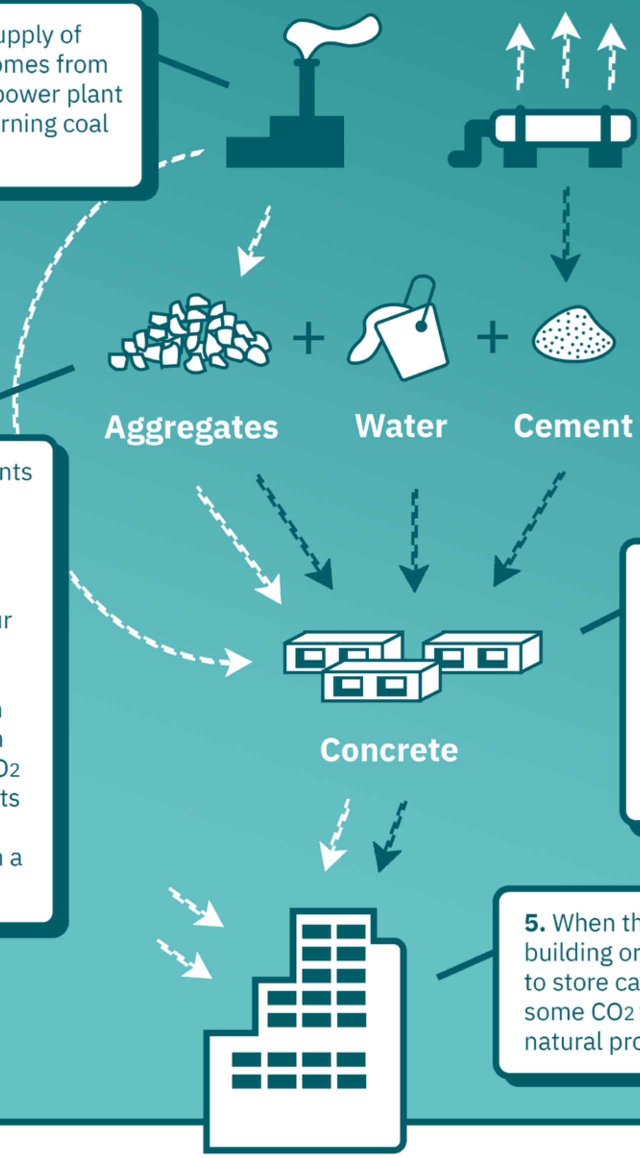
Carbon-negative concrete

We're not there yet, but in the right circumstances, the production of concrete could actually store more CO_2 than it releases into the atmosphere.

This graphic shows a carbon-negative process for making concrete. White arrows represent the movement of carbon as it is used, emitted or absorbed, while blue arrows represent the flow of other materials.

1. First you need a supply of CO_2. Most likely, it comes from carbon capture at a power plant or industrial plant burning coal or natural gas.

2. You also need cement, which is made at high temperatures in a kiln. The process releases CO_2, which can be captured to replace the need for CO_2 from another industrial source.



3. The key ingredients of concrete are "aggregates" (like sand and gravel), water, and cement. One way to use your supply of CO_2 is by turning it into aggregates through "mineralization." In this process, the CO_2 reacts with elements like calcium or magnesium to form a solid.

4. Once the cement, water and aggregates are mixed, the concrete has to be slowly "cured" to become more durable and prevent cracking. A second way to use your CO_2 is to inject it in the curing process, which provides added strength.

5. When the concrete hardens in a finished building or road, there is one last opportunity to store carbon. Concrete structures absorb some CO_2 from the surrounding air in a natural process called "carbonation."

Concrete is carbon-negative when it stores more carbon than was emitted in its production. In the best case, all the CO_2 emissions along the way are captured, mineralized, and become ingredients in the finished concrete, either as aggregates or in the curing process.

Opposite Page: In December 2020, CSHub collaborated with the MIT Climate Portal to explain the steps involved in producing low-carbon concrete. The result was this infographic and a brief article on the topic.

so much of it, we should look at it as an opportunity to lower CO_2 emissions."

During several conferences, Gregory also engaged in other discussions on embodied carbon with prominent thinkers in the worlds of architecture and engineering. In January, he spoke at the Net Zero Schools Summit at Yale University. There, he explained carbon uptake in concrete and even presented the audience with data on how much CO_2 Yale's famed Rudolph Hall had absorbed since its construction. That summer, he also contributed to the Boston Society of Architecture's Embodied Carbon 101 series. His panel, which focused on reducing the embodied carbon of building structures, included engineers from Le Messurier and Studio NYL.

CSHub has also hosted its own discussions on embodied carbon through our public webinar series, which, this year, attained record levels of engagement. Our most popular webinar, "The Role of Concrete in Life Cycle Greenhouse Gas Emission Reductions," attracted around 190 attendees in total. Among those that registered included members from notable organizations such as The Ohio State University, the New York State Department of Transportation, and the University of Cambridge. That was just our first webinar on embodied carbon that year. We also hosted "Lowering the Embodied Environmental Impacts of Cement and Concrete," which attracted more than 150 registrants and has accumulated more than 1,000 views on YouTube.

Our 2021 webinar series has continued to focus on embodied carbon as well as break attendance records. On February 11, we hosted "Challenges and Opportunities of Using Environmental Product Declarations (EPDs) in Environmental Performance Comparisons of Concrete." The webinar had 200 attendees—a new high. Some of those in attendance included members of the Colorado Department of Transportation, the Port Authority of New York and New Jersey, and The Pennsylvania State University.

In January, we also released a topic summary on optimizing EPDs and sustainable procurement policies along with an MIT Climate Portal explainer on concrete. In the works are briefs on greenhouse gas (GHG) reduction strategies for concrete and a video summarizing concrete's embodied impact. So, we have a busy year ahead in terms of embodied carbon. Stay tuned.

Pavements

CSHub research assistant Meshkat Botshekan has been heavily involved in developing Carbin.

Building the best infrastructure requires the right perspectives. Our pavements research takes a life cycle approach, anticipating uncertainties and fluctuations to offer policymakers the tools to think—and succeed—in the long term. 2020 represented a milestone in our pavements work. We developed and promoted cutting-edge technologies, like the Carbin app, while expanding on past life cycle analysis and network asset management research.

Carbin Captures

One of the most striking developments in our pavements research has been Carbin. Launched in early 2019, Carbin is a navigation app based on CSHub research that enables users to crowdsource road quality and its impact on fuel consumption as they drive. All data Carbin users gather is anonymously mapped on the app's homepage, fixmyroad.us.

By the end of 2020, the fixmyroad.us map had become speckled with nearly half a million miles of data from thousands of users residing in more than three dozen countries. This reach is fitting: Carbin is, in fact, a product of both local and international collaboration. In addition to input from the nearby University of Massachusetts Dartmouth, the app's development relied heavily on the work of researchers from Birzeit University in the West Bank and the American University of Beirut.

Over the past year, Carbin has done more than collect data—it's also captured the attention of the public. In January of 2020, it was profiled in *The New York Times*. The piece included photos of all of the CSHub and UMass Dartmouth researchers involved. Soon after the article, the Carbin team traveled to Las Vegas as a part of the CONEXPO-CON/AGG Tech Experience. Their exhibit at the Tech Experience featured an interactive time-lapse of the app's data collection over several months in multiple U.S. metro areas. Though they had to leave prematurely due to the impending pandemic, the Carbin team still had time to give presentations on their work and where they were headed next.

It turns out, that that next step was peer-review. Over the subsequent year, the Carbin team would publish two papers in peer-reviewed journals detailing the framework of their approach. The first, in the University of Cambridge Press's *Data-centric Engineering*, validated the model's roughness measurements while the second, in *The Proceedings of the Royal Society*, demonstrated how the Carbin model could infer vehicle types.

Now that they've sharpened Carbin's capacities, the team hopes to incorporate a more sophisticated, interactive data visualization feature into the fixmyroad.us website. They also aim to incorporate past CSHub network asset management research into the app. With highly accurate data and proven pavement management tools at their fingertips, departments of transportation could plan and improve their networks in an unparalleled way.

A Competitive Edge

Since 2016, we've studied the competition between paving industries, examining how changes in market share could alter material prices and paving costs across the country. In 2020, CSHub Ph.D. candidate Fengdi Guo spearheaded further investigations into this topic.

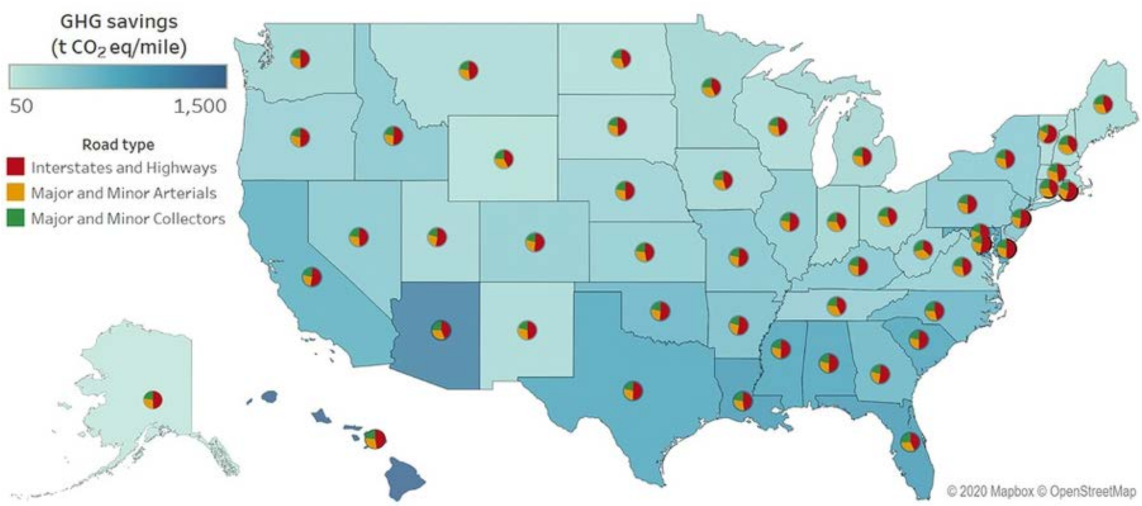
Based on past competition research, he helped develop a calculator that could estimate—at any given market share, paving budget, or material price—how much the quantities and prices of paving materials could change for any DOT in the country due to inter-industry competition. The calculator's results, detailed in a topic summary, indicate that a moderate increase in competition could lower the unit costs of asphalt and concrete by around 5% and 20%, respectively.

In a subsequent research brief, Guo zeroed in on inter-industry competition in Missouri while also applying his past work on network asset management. His goal was to determine the benefits of incorporating competition into the budget allocation process using a model he had outlined in a *Transportation Research C* paper earlier that year.

The results of his analysis, in which competition helped to determine the segment-level treatment actions, found that an increase in competition would lower road roughness by 11% and greenhouse gas emissions by 8% on Missouri's high-trafficked roads.

Stiff Pavements, Strong Roads

Our research has long found that pavement condition, surface qualities, and structure, all contribute to the fuel consumption of vehicles—a phenomenon called pavement-vehicle interaction



The map above shows the potential reductions in overall greenhouse gas emissions from the transportation sector as a consequence of stiffening pavements nationwide. The data derives from research that appeared in the *Transportation Research Record*.

(PVI). So, what would these effects of PVI look like across the United States?

In a paper published in the *Transportation Research Record*, CSHub researchers Hessam Azari-Jafari, Jeremy Gregory, and Randolph Kirchain tackled this question. Using a model of the U.S. pavement network, they found that the introduction of stiffer pavements across the nation, either through the addition of synthetic fibers or the use of concrete, could significantly mitigate PVI from deflection—enough to offset 0.5% of U.S. transportation emissions over 50 years.

The findings garnered attention in *TechCrunch* and the *MIT Technology Review* and led to a brief interview in *Scientific American*'s *60-Second Science* podcast. "Usually when it comes to reducing emissions in the transportation sector, [we think about] changing policies related to vehicles or driving behavior, which involves millions and millions of people," Gregory explained on the podcast, "as opposed to the way we design and maintain our pavements, [which involves only] thousands of people working at transportation agencies."

CSHub pavements research also appeared in *The Hill*. As Congress weighed investments in infrastructure in the spring of 2020, Jeremy Gregory detailed what such investments might look like in an op-ed. By applying CShub research and analyzing the outcomes of the American Recovery and Reinvestment Act of 2009, he explained what Congress could do to make the nation's next great infrastructure investment as sustainable as possible. "Rather than spending expediently and repetitively," he wrote, "there needs to be prudent investment in solutions that give us the best long-term performance."

Cool Paving

To the average driver, the reflectivity of a pavement may seem immaterial. But for those engaged in urban and transportation planning, even this superficial property is essential. That's because pavements are so abundant that their reflectivity, also known as albedo, exerts a significant climate change impact—and in more ways than one.

2020 was an enlightening year for our investigations into pavement albedo. In March, CSHub researchers published, "An integrated model for quantifying the impacts of pavement albedo and urban morphology on building energy demand," in *Energy and Buildings*. Their paper presented the results of a model that found that increasing pavement albedo in Boston's neighborhoods would reduce CO_2 emissions by more than 91 thousand tons over 50 years.

The findings of this paper were some of many included in our November topic summary on reflective pavements. Starting with the basics of pavement albedo, the summary explains the array of available reflective pavements as well as their numerous benefits. Reasserting past findings, CSHub researchers noted that the implementation of reflective pavements nationwide could lower air temperatures by more than 2.5 °F and reduce the frequency of heatwaves by 41% across all U.S. urban areas.

Those interested in a succinct synopsis of these findings can read the *MIT News* 3 Questions interview featuring Hessam AzariJafari, who has led much of our work on reflective pavements. In it, he breaks down the net benefits of reflective pavements by placing them in their context.

"On highways…the surface roughness and structural properties of a pavement contribute to a greater proportion of that pavement's life cycle emissions" he explains, "Therefore, it is important to consider all elements of a life cycle when municipalities and transportation authorities decide on [reflective pavements]."

Such a finding is a reminder of the importance of life cycle analysis when designing any form of infrastructure. No matter what subjects we approach, life cycle perspectives imbue every aspect of our work. As you'll see in the next section of our report, our buildings research is no exception.

Buildings

Between 2016 and 2050, the U.S. will build the equivalent of New York City 20 times over. Such an immense undertaking will require not just new techniques and perspectives, it must invariably respond to pressing challenges like inequity and climate change. Our buildings and resilience research aims to make this sustainable, equitable transformation possible. Using tools like life cycle analysis, we investigate how to make structures stand the tests of time, disaster, and rapid transition.

Building for Life

When it comes to mitigating climate change, a building's construction is just the beginning. That's because the use phase can generate most of a structure's emissions. Minimizing use phase emissions means maximizing efficiency—something passive house designs do especially well.

CSHub postdoc Jasmina Burek has studied these increasingly popular designs to examine not just their climate change mitigation benefits, but also their feasibility. Though they use a fraction of the energy of their conventional counterparts due to improved insulation, design, and layout, their construction has traditionally been considered carbon-intensive and expensive. Her work, however, suggests that that may no longer be the case.

In her research brief, "Affordability of Passive Houses and Zero-Energy Buildings," she presents the results of an investigation into the life cycle costs and emissions of various building designs in the San Francisco Bay Area. Her model, which ran thousands of simulations over a 50-year analysis period, found that passive homes would not only have lower life cycle emissions, but lower median embodied emissions and costs as well. Though there's more work to be done, her findings suggest that these cutting-edge designs could slash emissions at a far more reasonable price.

Passive houses, however, will likely comprise only a fraction of new construction. To meet climate targets, architects and engineers will need

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the tools to examine and minimize the impacts of all new buildings. CSHub research assistant Jingyi Liu has been working on a streamlined tool that could guide sustainable construction. Her progress was presented in her February research brief. In it, she explains how her new tool could embed seamlessly into existing CAD software and allow designers to conduct LCAs early on in the design phase—which is when they can have the greatest impact.

Resilient Communities

A similar life cycle mindset has driven CSHub's resilience research. Over the past decade, we've calculated the lifetime costs of construction in hazard-prone regions like South Florida and New Orleans. Just as with emissions, we've found that the use phase is critical: it can compose a majority of a structure's costs in areas where disasters tend to strike.

Jeremy Gregory provided a succinct summary of these findings in a brief video released in September 2020—during the middle of what was an unprecedented hurricane season. Accompanied by a series of animations, he discusses the rising costs associated with hurricanes as well as the greater benefits of mitigation. In a city like New Orleans, resilient retrofits could mitigate enough storm damage to pay off within a few years, he explains. Of course, achieving a more resilient nation will require change. Not only will stronger building codes need implementation, he argues, but the nation as a whole must experience a perspective shift: America can't afford not to invest in resilience.

CSHub research assistant Bensu Manav has spent the last two years quantifying just how greatly resilience can benefit communities. The key to her approach is city texture, which is a measure of neighborhood disorder.

Rather than studying structures individually, she places them in their context, using city texture to capture how the position and orientation of buildings may amplify a hurricane's winds and, therefore, the damage they could sustain. Her investigations into the hazard-prone region of coastal Florida have yielded striking results.

She found that without incorporating city texture into loss estimations, residents of Florida's adjacent Sarasota and Lee counties would, on average, experience damages of around 5% of their home's value during a 95-percentile storm. But when she incorporated texture, those same figures rose to around 10% for Sarasota County and 15% for Lee County. The upshot? The city

CSHub researchers have spent the last year studying how the arrangements of structures—also known as city texture—may influence windloads and hurricane losses. Much of their work has focused on Florida.

Credit: Johnny Milano/The New York Times/Redux texture model captured damages that conventional models failed to predict—damages for which many might not be prepared.

While more research is needed to apply this approach to other hazard-prone regions, it represents a novel and efficient analytical tool that could offer vulnerable communities a faster means of predicting the full extent of hurricane damage.

Robust Buildings

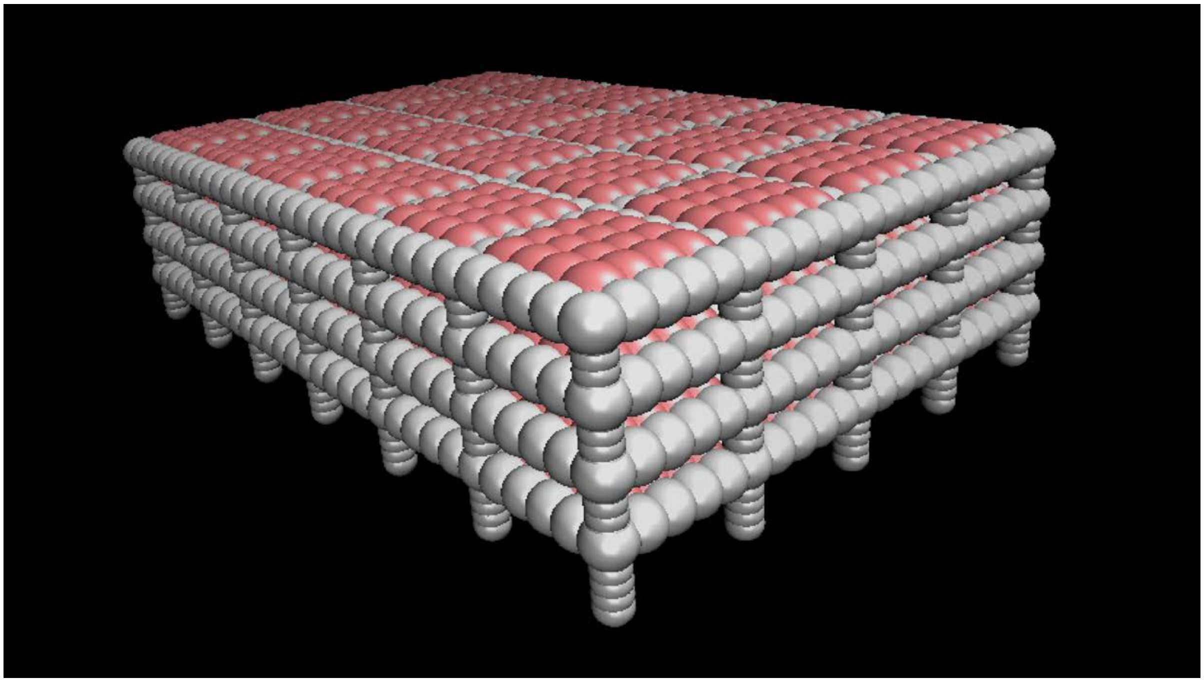
Assessing a building's resilience, however, requires investigation at all scales. Talal Mulla, a CSHub research assistant, has sought to bridge two scales, those of the building and the component, to generate fragility curves. Vital to resilience assessment, fragility curves represent the likelihood of damage a structure will experience at any load level. To generate curves for a whole structure, engineers have either created curves for each component individually or treated the building as a single unit, incorporating its many components together into one curve.

Mulla has instead combined these two approaches. The method he has developed can generate fragility curves for a whole structure without the need to explicitly generate curves for each component. The result, described in his November 2020 research brief, could be a faster but equally accurate technique.

Though much of CSHub's resilience assessments address hazards like hurricanes, researchers have begun to investigate other forms of hazards, namely, fires. The choice is a timely one. During summer 2020, the devastating consequences of wildfires were seared into the public eye by dramatic photos taken in San Francisco, Portland, and other western cities. Kostas Keremidis, a research assistant at CSHub, has led our investigations into fire resilience, aiming to give fire-prone communities the tools to better predict and mitigate losses.

The conceptual key to his work is the atom. Inspired by molecular dynamics, he simulates the behavior of an entire structure as an ensemble of atoms. Keremidis has used this approach, known as molecular dynamics-based resilience assessment, to model spalling and charring, which are both common forms of fire damage. What makes his approach unique is its consideration of building components in their context of the building geometry—something current building codes fail to do.

His July research brief applied this new approach by simulating fire in two designs based on



Inspired by molecular dynamics, CSHub research assistant Kostas Keremidis models buildings as an ensemble of atoms. Though unconventional, such an approach has allowed him to predict building failure far more quickly than with traditional methods such as Finite Elements.

a Department of Energy reference building: one of reinforced concrete and one of wood beams, concrete columns, and steel connections. After running his simulations, he found a surprising discrepancy. While IBC codes would suggest the designs would have fire-resistance ratings of 90 minutes, his models suggested otherwise. Instead, the concrete design failed at 80 minutes and the wood design at 20 minutes. These findings suggest that a systems-scale analysis may help building codes better respond to the rise in fire hazards seen in recent years.

The year ahead has presented new opportunities for CSHub's resilience efforts. Elli Vartziotis, a Ph.D. candidate, is adapting the city texture model to assess flood risks—not just wind loads. She aims to provide cities with an efficient alternative to flood maps, which tend to be both time- and resource-intensive to generate. Bensu Manav, in collaboration with two MIT undergrads, Liz Yugov and Mikayla Britsch, has begun to expand her city texture resilience assessment tool. Eventually, the trio hopes to create an interactive dashboard that displays wind risks and the cost benefits of mitigation.

In Closing: 2021 and Beyond

So, it's been a hard but productive year—a year of contradictions. As we grappled with emerging crises and anticipated future ones, we experienced difficult lessons and were presented with numerous opportunities. But to view 2021 as the beginning of a new chapter would be misplaced.

The world is still in the grips of the COVID-19 pandemic; anomalous weather has wreaked havoc on the nation's unprepared energy infrastructure; hurricane and wildfire seasons are just around the corner; climate change remains an omnipresent threat.

In essence, crises will continue to occur. To predict and manage them will require constant vigilance and the right tools rather than complacency. In 2020, and well into the future, resilience and long-term thinking must dictate decision making and evolve to match a rapidly changing world.

Over the past year, we've witnessed a corresponding evolution in our research. We've expanded its scope, building the figurative infrastructure for what's to come—whether that's decarbonizing the buildings sector, revitalizing the nation's roads, or minimizing embodied carbon.

It's been a project long in the making. Since our founding in 2009, we've advanced interdisciplinary research into concrete and infrastructure science, engineering, and economics to achieve durable and sustainable homes, buildings, and infrastructure in ever more demanding environments.

Now that we have entered our 12th year, we remain committed to this mission. And as the world learned firsthand during 2020, it's one worth fighting for.

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