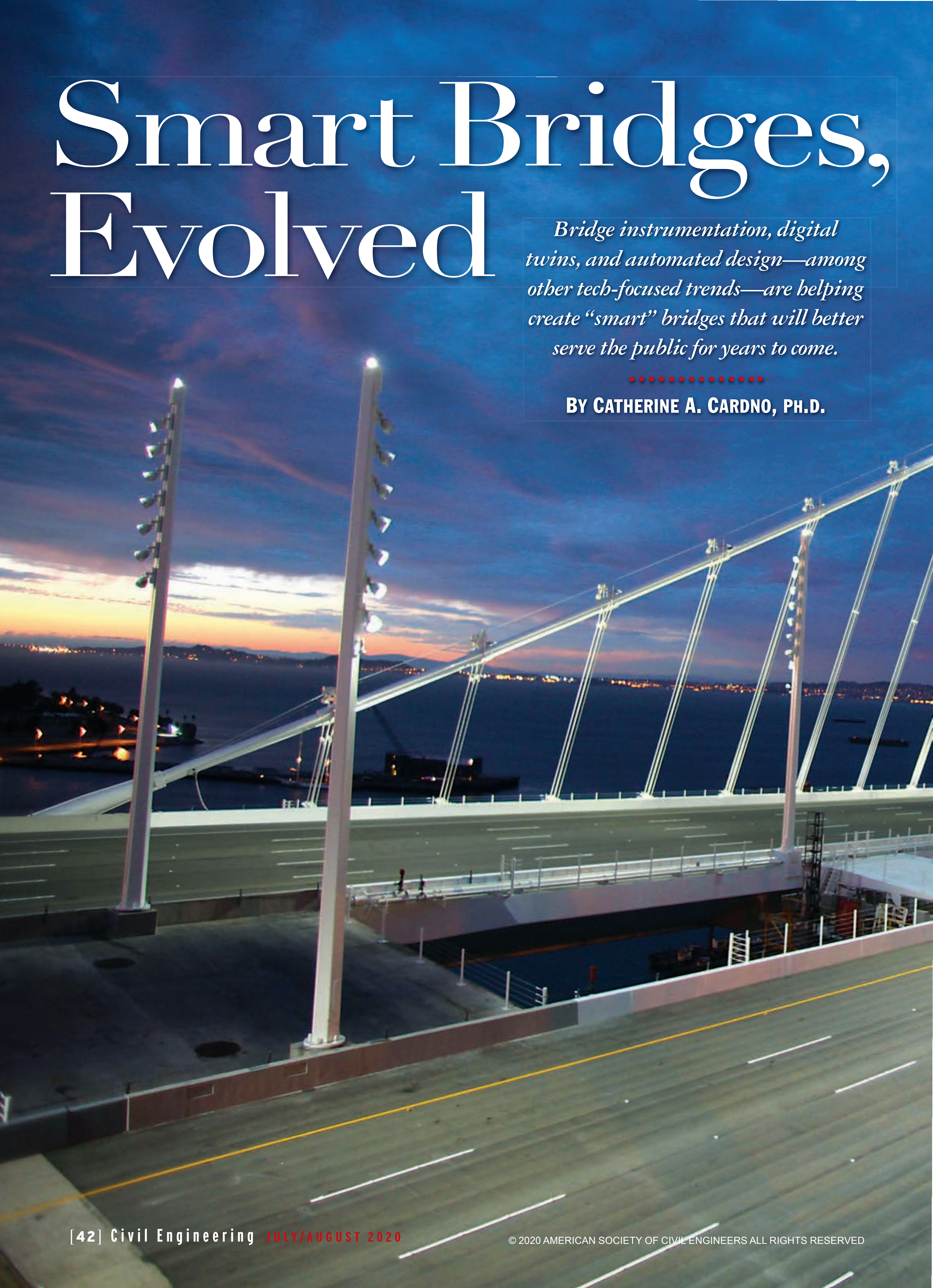
# Smart Bridges, Evolved

*Bridge instrumentation, digital twins, and automated design—among other tech-focused trends—are helping create "smart" bridges that will better serve the public for years to come.*

**By Catherine A. Cardno, Ph.D.**



The east span of the San Francisco–Oakland Bay Bridge will be part of a three-year project that will provide researchers and Caltrans with real-time data about the seismic response of five bridges in California.

PHOTOGRAPH BY MARTIN CHANDRAWINATA, COURTESY OF METROPOLITAN TRANSPORTATION COMMISSION

WHAT EXACTLY IS considered a "smart" bridge these days? Is it an instrumented bridge in which sensors continually collect data about behavior? Is it a bridge that can communicate with connected vehicles? Is it a bridge that collects data that can be turned into revenue streams?

It is all this and more.

At its most fundamental level, a smart bridge is a technology-enabled bridge—be it in its design, its operation, or its life—that includes digital elements that help keep it performing at its optimum level. Whether it uses a network of sensors that monitor health and performance during normal use or extreme events or a digital twin that can predict critical failures while the damage can still be fixed as minor repairs, a smart bridge features an interface between the physical and the digital. And researchers are pushing the boundaries of just what a smart bridge can be. Some, for example, are using digital technology to create flexible designs so a bridge's capacity can be increased over the years if future traffic demands require; others are using automated designs that can be completed within minutes rather than weeks.

"Whether it's smart cities, smart transport, or smart bridges, fundamentally it's the same thing," says Mark Enzer, the chief technical officer at global engineering and management firm Mott MacDonald. "'Smart' is where we bring physical and digital together and we get something that is more than either physical or digital alone."

"HISTORICALLY, smart bridges started with a desire to better understand how bridges were deteriorating," explains Jerome P. Lynch, Ph.D., M.ASCE, who is a professor in and the Donald Malloure Chair of the Department of Civil and Environmental Engineering at the University of Michigan as well as a professor in the university's Department of Electrical Engineering and Computer Science. "I think we understand qualitatively how bridges behave, and we've done a lot of experimental testing in the lab to inform our codes. But once those bridges are built and they are in operation, what is the in situ deterioration that is happening in those bridges?

"I think that is where the field recognized—maybe twenty, thirty years ago—that our knowledge base wasn't as large as we would like. So we started to deploy sensors."

At first, mostly long-span bridges, such as cable-stayed and suspension bridges—particularly those in seismic or typhoon-prone areas around the world—were instrumented with sensors, Lynch explains. These sensors were focused on providing information for owners so that they could determine when a bridge needed to be closed because of unsafe movements caused by extreme events.

Many smart bridges exist overseas, particularly in China, Japan, and South Korea, explains B. F. Spencer, Ph.D, P.E., F.ASCE, the Nathan M. & Anne M. Newmark Endowed Chair in Civil Engineering and the director of the Smart Structures Technology Laboratory at the University of Illinois at Urbana-Champaign.

China has established a structural health-monitoring code, Spencer explains, and construction and instrumentation there have exploded in recent years. One-third of the world's longest suspension bridges and 70 percent of its longest cable-stayed bridges are in China. And the world's largest deployment to date of wireless sensors was on the 2nd Jindo Bridge in South Korea, which is one of two 1,588 ft

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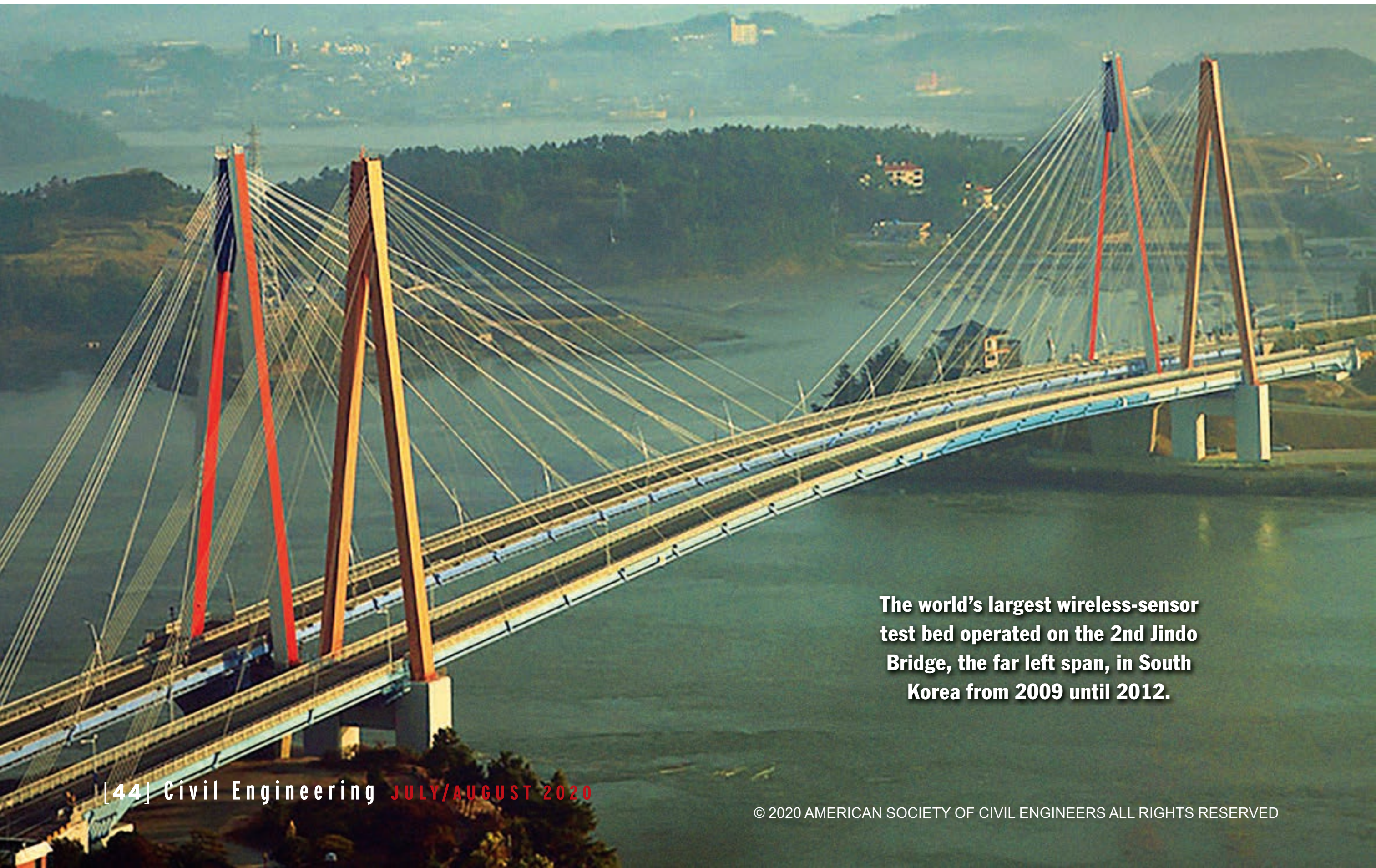

The world's largest wireless-sensor test bed operated on the 2nd Jindo Bridge, the far left span, in South Korea from 2009 until 2012.

More than four dozen sensors are being operated on the vertical lift span of the Memorial Bridge in Portsmouth, New Hampshire.

PHOTOGRAPH COURTESY OF LIVING BRIDGE PROJECT

long cable-stayed bridges connecting Jindo Island with the Korean Peninsula. This test bed monitoring system, initially installed in 2009 and expanded in 2010, was operated continuously until 2012 and included 113 wireless sensor nodes providing 669 channels of sensor data, according to Spencer.

With the decreasing costs of sensors and the expansion of analytical capabilities, sensor technology is now being used on smaller and smaller bridges, according to Lynch. "Today we're actually seeing some instrumentation of small, short-span bridges, which represent a large fraction of our bridge inventory in the United States," he says. In turn, the use of the sensors has evolved from a focus on extreme events to asset management under regular service conditions. Sensors frequently gather information on vehicle and weather-related loading conditions and the causality between loads, operational environments, and deterioration, he explains.

ONE EXAMPLE of this is the Memorial Bridge in Portsmouth, New Hampshire. Researchers at the University of New Hampshire in Durham, working with the National Science Foundation, the Federal Highway Administration, and the New Hampshire Department of Transportation, are operating more than four dozen sensors on the 1,201 ft long vertical lift bridge that connects Portsmouth to the town of Kittery, Maine, across the Piscataqua River. (See "UNH Unveils 'Living Laboratory' on Portsmouth Crossing," *Civil Engineering*, January 2020, pages 32–33.) The engineers hope that the Memorial Bridge's "laboratory," which includes bridge sensors as well as in-water sensors that monitor a power-generating tidal turbine, will further the conversation among civil engineers about the importance of developing smart, sustainable bridges, says Erin Santini Bell, Ph.D., P.E., a professor in and the chair of the Department of Civil and Environmental Engineering at the University of New Hampshire.

If a new bridge is built to be smart, as the Memorial Bridge was, the data it collects can be invaluable because they can provide baseline information about its performance right from the beginning and inform future bridge designs elsewhere, Bell says. However, it does provide yet another item on the bridge that has to be maintained.

This means that it is crucial that every sensor that is placed on a bridge has a specific job. "It should be on there for a very specific reason, [because] you're answering a question or you're concerned about a long-term behavior," Bell says. "Every dollar has to be strategically spent." With shrinking state department of transportation staff numbers and budgets and the retirement of a generation of workers who are most intimately familiar with the bridges they have worked on for decades, it is becoming ever more important for smart bridges to be able to self-monitor and self-report issues in this way, according to Bell.

One of the most significant benefits of health-monitoring sensors is their maintenance cost savings, according to Khalid M. Mosalam, Ph.D., P.E., the Taisei Professor of Civil Engineering and the director of the Pacific Earthquake Engineering Research Center at the University of California, Berkeley. As more bridges are instrumented, "this will be a huge transformation from maintenance on a schedule to maintenance on demand," he says.

With early notification of issues, repairs can potentially be managed in one evening before they turn into major issues that might require a two-week closure window, says Lee Lentz, P.E.,

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a mechanical engineering project manager for moveable bridges in the Mechanicsburg, Pennsylvania, office of Modjeski and Masters, a bridge design and engineering firm.

But overcollection of data can also be an issue. "One of the Achilles' heels of these smart bridges is that sometimes they just collect so much data that nobody even wants to be bothered with it anymore, because so much of it is meaningless," says David Barrett, P.E., a senior mechanical engineer in the Mechanicsburg office of Modjeski and Masters. Developing automated algorithms that can sift through that collected data is crucial, especially in pinpointing a bridge's deterioration and its remaining reliable life. "But no two bridges or future bridges are exactly the same, so there are a lot of judgment calls on trying to use data [to better understand] similar structures," he says.

For this reason, human assessment of sensor data will always be important. "There can be wild goose chases that are created by, literally, a rogue spider that happens to fog the view of a sensor," Lentz says.

Or, for example, a bit of corrosion on the bridge under a gauge can make it seem as though the whole bridge is at risk. "We regularly hear from bridge owners [that] the data say their bridge is about to fall down, but as it turns out, the [bridges] were suffering from corrosion underneath the gauge," Barrett says. "We respond [by saying], 'You know, if those readings were true, the bridge would have collapsed. So, something else is going on.'"

Ioannis Brilakis, Ph.D., M.ASCE, the Laing O'Rourke Reader in Construction Engineering in the Department of Engineering at the University of Cambridge in the United Kingdom, cautions that the cost of instrumentation for maintenance alone might not be the best option for the vast majority of bridges. Instead, deploying mobile sensing systems such as radar, lidar, or other technologies for biannual inspections could offer the same benefits as sensor solutions at a lower cost and would produce less data congestion.

Engineers must think long-term and compare the expected life span of a bridge to the life span of the sensors that might be installed on it as well as the process it takes to install them, Brilakis says. "A huge challenge in smart infrastructure [is that] the life cycle of the asset is so much longer than the life cycle of the sensor," he says. "The sensor will maybe last you two to five years. And if it lasts even five years, it's going to be technologically obsolete.

"[If] you have a bridge that's there to last a hundred, a hundred and fifty years, theoretically, over its lifetime, that bridge should go through thirty different generations of sensors."

HOWEVER, there are uses for bridge instrumentation outside of health monitoring that can be important and lucrative. An emerging trend in smart bridges is the use of sensors to communicate with autonomous and connected vehicles, according to Spencer. Seamless communication among smart bridges, smart highways, and smart cars is necessary to realize the vision of autonomous vehicles and reduce traffic congestion as well as vehicle-related pollution, he says.

"With the emergence of smart- and connected-vehicle technologies, the very forefront of the smart bridge field is now thinking beyond just asset management," Lynch says. Just one example of this is using a sensor to detect black ice on a bridge surface and communicate that fact directly to oncoming cars. "So those sensors now have a safety role as much as they may have a role in understanding the behavior of the structure," Lynch says.

Asset-management data gathered by smart bridge technologies could also be used to manage use by overloaded trucks. Typically, permits that allow overloaded trucks to pass over bridges are granted for specific time windows to avoid other heavy traffic that is expected at certain times on the bridge, Bell explains. "But some of the research we're seeing [shows that] it should be a temperature window [that is used] on some of the bridges," she says. Higher temperatures increase stresses on bridges, she explains, so temperature data could be used to limit the crossing of overloaded vehicles to certain temperature bands and redirect traffic to other routes as necessary.

Data collected by smart bridges can also redefine what is considered "good condition" when a bridge that was built and operated via a public–private partnership is ultimately returned to its public owner after the lease ends. These leases typically specify that bridges must be in good condition when they are handed off to the public owners, Lynch explains. With sensor data, "good" could be quantitatively—and therefore much more accurately—determined by smart bridge technologies, he says.

The data gathered by smart bridges can also be sold, generating new revenue streams for owners, according to Lynch. "We can now start to measure things like how much load is coming on the bridge, what kind of loads," he says. "That is very valuable data that may have value to other parties that would be willing to buy that data or subscribe to that data." For example, load data could be analyzed as if the bridge were a large truck scale to provide "unique and special insight" into how local economies are doing based on the amount of freight that is arriving or departing. "We all recognize that there is a very pronounced funding gap in this country for infrastructure," Lynch says. "Our field should be thinking about new ways to generate revenue besides gas taxes to help fund that infrastructure. And data can open those opportunities."

And this monetization of data means that smart bridges can pay for themselves, he adds. "There is a lot of hesitation of bridge owners thinking the cost of the technology is too large, and they don't have a clear [understanding] of that return on investment," he says. "But today I would say there is tremendous return now shown for what you can use that data for."

BRIDGE DATA can also improve future designs. "There is a real benefit to the profession in understanding performance, particularly on the durability side of infrastructure," Lynch says. "Data can help our codes be more thoughtful about the long-term durability of our bridges, leading to better codes that would make our structures more resilient and more robust to long-term deterioration."

Seismic monitoring is a key example. Researchers at the University of California, Berkeley are partnering with the California Department of Transportation (Caltrans) to develop

**Data was collected from a concrete bridge near Cambridge, England, United Kingdom, *top*, and a laser scanner was used to generate its point cloud, *center*. The point cloud was then used to create a geometric digital twin, *bottom*.**

IMAGES COURTESY OF RUODAN LU AND IOANNIS BRILAKIS, UNIVERSITY OF CAMBRIDGE

a program known as the Bridge Rapid Assessment Center for Extreme Events (BRACE2) to help inform the seismic design of bridges. The program will run for the next three years and provide real-time assessments during seismic events from five Caltrans bridges in the San Francisco Bay Area.

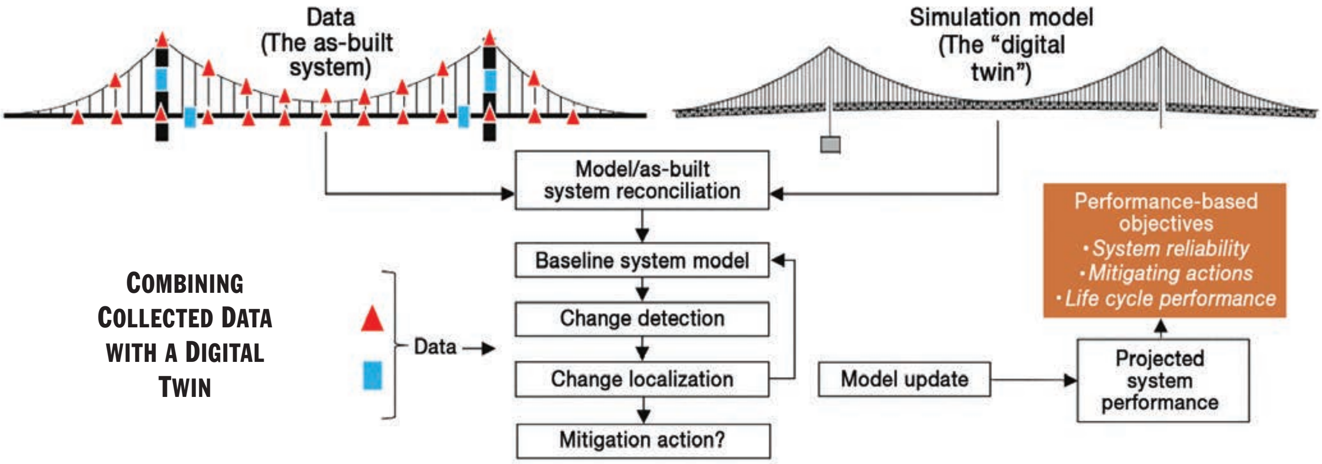
The following five bridges were identified for the first phase of the project:

- the self-anchored suspension portion of the new 1.93 mi long east span of the San Francisco–Oakland Bay Bridge
- the double-suspension, two-deck, 1.95 mi long west span of the San Francisco–Oakland Bay Bridge, which connects to the east span via a tunnel through Yerba Buena Island in the San Francisco Bay
- the westbound Carquinez Bridge, a 0.66 mi long suspension bridge that extends across the Carquinez Strait, which connects the tidal estuaries of the San Pablo Bay and the Suisun Bay, located to the northeast of the San Francisco Bay
- the Benicia–Martinez Bridge, comprising a 1.2 mi long deck-truss segment and a 1.7 mi long lightweight-concrete segmental structure that crosses the Carquinez Strait to the west of Suisun Bay
- the Dumbarton Bridge, a 1.63 mi long girder bridge that is the southernmost of the highway bridges that cross the San Francisco Bay and which connects Fremont and Menlo Park

California has been ahead of the smart bridge curve in part because of the work of the California Strong Motion Instrumentation Program (CSMIP), according to Mosalam. This program, part of California's Geological Survey, was established in 1972 and obtains earthquake data for the engineering and scientific communities. The program not only acquired data about bridge motion, it also processed, stored, and offered the data to the community for interpretation, Mosalam says. It is a unique approach that could serve as a model for all sensor data collected from today's smart bridges and structures, he says.

Despite the current explosion of data being made available from bridge sensors, to fully understand the big picture of a bridge's behavior, he says, "It is not enough to think of only what is called single modality," that is, using data from one type of sensor. "You have to consider a fusion of data from different kinds of sensors and heavily rely on tools from artificial intelligence, such as machine-, deep-, and reinforcement-learning techniques."

This, in turn, will help develop digital twins—that is, exact digital models that can change over time just like the real-life versions—that can be analyzed to better understand a physical bridge's behaviors under service conditions and extreme events. BRACE2 is developing digital twins of the five bridges in its program. Existing and new sensors will be used to develop efficient computational models that will be continually updated as the sensors collect data. The researchers will compare the arriving data about the bridge's actual movements and performance to what their digital model is predicting and "back calculate" so that the digital model reflects real-world conditions. "By




**COMBINING COLLECTED DATA WITH A DIGITAL TWIN**

doing that rapidly and continuously, with more data coupled with artificial intelligence capabilities and more cycles of refinement of the digital twin, we hope that such digital models eventually become as accurate as the instrumented physical structure itself," Mosalam says.

As a concept, digital twins are extremely useful for managing assets throughout their life cycles, according to Mott MacDonald's Enzer, who is also the head of the National Digital Twin program at Cambridge's Centre for Digital Built Britain. The National Digital Twin program is dedicated to creating an ecosystem of interconnected digital twins to explore whether connecting them via secure data sharing will enable better decisions and outcomes, Enzer explains. While digital twins are new to infrastructure, they have been used for years in aerospace, manufacturing, and vehicle racing, he says.

The connection, via data, between the digital and physical assets is the defining characteristic of digital twins, Enzer says. The digital twin can be used to optimize operational and maintenance decisions as well as investment and planning decisions for the physical asset.

"Bridges are one part of a larger system," Mosalam adds. "Transportation network[ing] and asset management require significant knowledge of intra- and interdependencies between these parts. The digital twin[ning of] the entire network will be essential for understanding, adapting, and even controlling future complex systems such as transportation networks."

Digital twins are also invaluable for understanding the data that are generated by bridge inspections over decades, Brilakis says. "I need to have a digital copy so that if I'm doing any kind of instrumentation or monitoring or remote sensing, I can bring that data back into the digital model and compare it against the geometry so that I can make sense of the numbers," he explains. "Even for basic manual inspection, a crack is a crack. But if I know where the crack is on a member, then I can very quickly tell you, 'Oh, that is a flexural crack.' Or, 'That is a shear crack.' Simply from the position of the crack in [relation] to the member." And the twin is capturing everything down to potential cracks on the nuts and bolts of the bridge itself, he says.

But—much like with sensors—knowing in advance what purpose the digital twin is meant to serve is key, Enzer is quick to point out. "As soon as we know what purpose we're using it for, that can help us to understand what data we need to go look for, what kind of analysis we need, whether that's physics-based models or some kind of simulation or optimization engine," he explains. "Then instead of just doing the twin because we can, we're doing the twin because it drives a specific benefit."

"The message that we are trying to give to owners is that we are now moving into a world whereby when you order the contractor to build the physical asset, you are only doing half the job," Brilakis says. "Just as the owners have specs for the physical asset, they should create specs for the digital asset, [and] then make it part of the same job for the contractor to deliver both.

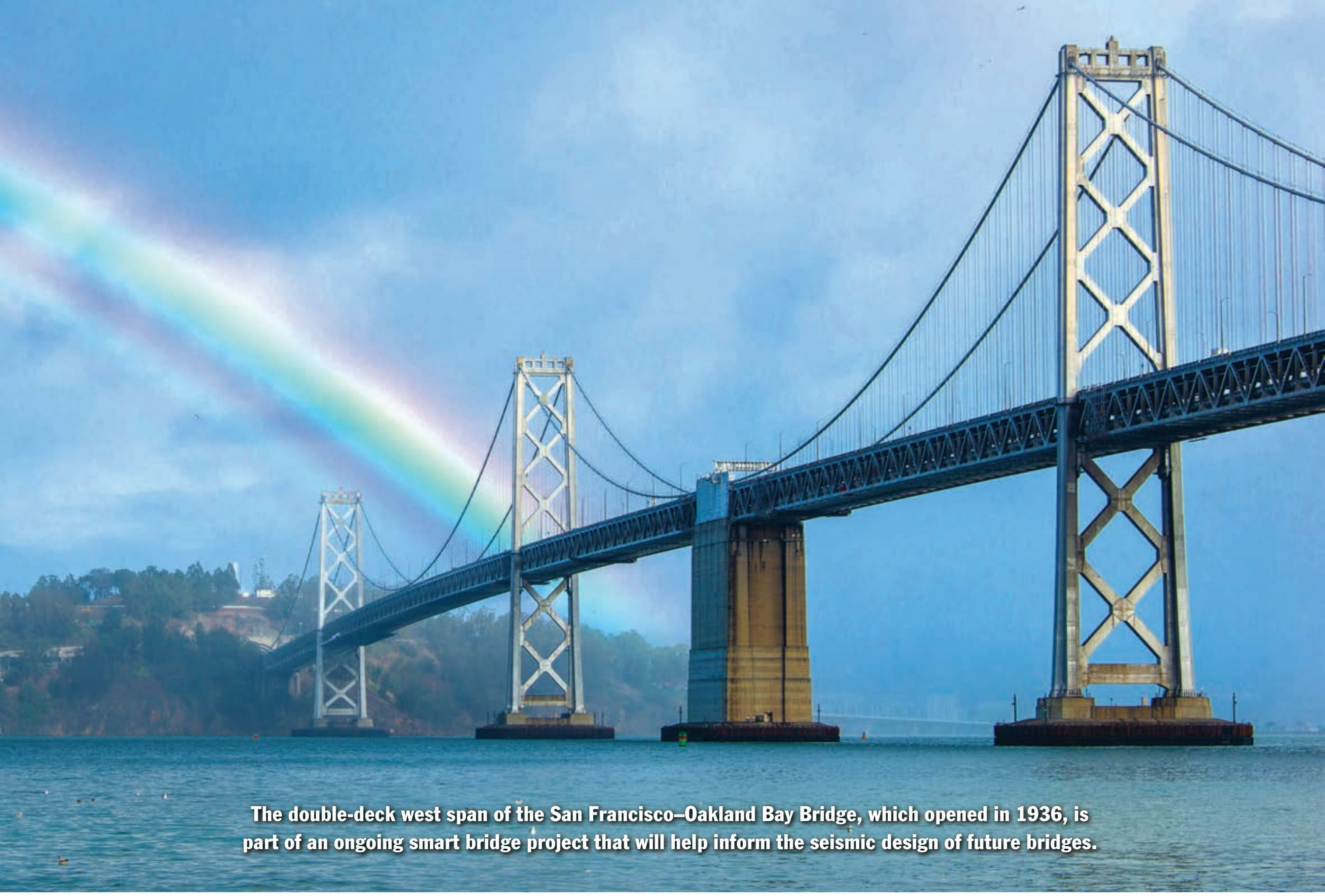
"Once you have a good-quality digital twin of your asset, then it is cost-effective every time you do that biannual inspection to keep it up to date," Brilakis adds. And because the digital twin keeps a record of when the new data come in, it is possible to easily view the bridge's condition at any point in time.

SMART BRIDGES have rich histories. "We've been talking about smart infrastructure for decades, honestly," says Brilakis, who is also part of the Center for Smart Infrastructure and Construction at Cambridge. For academics at the center, a smart bridge—or another piece of smart infrastructure—is simply one that has evolved from traditional design and likely has an informatics element, he says.

And this history is driving efficiencies in design. An example of this is the emergence of "flexible design," which involves cost-effective modular units capable of serving immediate traffic needs, Brilakis says. With flexible design, a bridge's capacity can be relatively inexpensively expanded as a region grows. For example, every lane of a standard bridge can be a prefabricated element. "I could add more lanes just by prefabricating more of those same components," he explains. "It's the kind of design [by which] you can add lanes left and right, if necessary, without much hassle to the existing traffic." Entire decks could also be replaced using this concept, he says.

By enabling quicker expansions, bridge capacity can be increased only if and when it is actually needed. "Very often we create huge monstrosities that are definitely not necessary today but sometimes definitely not necessary [even] thirty years from now," Brilakis says. "So instead we can save money today. It's a smart asset in the sense that it is a flexible asset."

ILLUSTRATION COURTESY KHALID M. MOSALAM AND DAVID MCCALLEN



The double-deck west span of the San Francisco–Oakland Bay Bridge, which opened in 1936, is part of an ongoing smart bridge project that will help inform the seismic design of future bridges.

PHOTOGRAPH BY PETER BEELER/COURTESY OF METROPOLITAN TRANSPORTATION COMMISSION

"The vast majority of bridges are not unique," Brilakis explains. "They are not big cable-stayed bridges [but] run-of-the-mill overpasses over multiple highways and roads." What the vast majority of these have in common is that they need to be built on time, on budget, and with minimal disruption to the public. "You want to build standardized components in the factory, bring them onto the site, make the overpass quickly, and move on to the next overpass," he says. "The problem … has always been that we design bridges traditionally, in a bespoke way."

Brilakis and his team examined the entire design process of these types of simple-span crossings and mapped out which data are needed to automate their design. For a standard highway in the United Kingdom with two lanes in each direction, the team was able to isolate the independent variables to just more than a dozen. All other variables in a bridge's design were dependent ones that could be derived or specified by guidance documents or codes, he explains. "The system we created allows you to sit together with the owner and ask them sixteen questions, one for each one of these variables," he explains. "'How high do you want the clearance to be?' And so on. Once we get those answers, we press a button, [and] we get the final design. That's it."

A seven-week design process for such a crossing was thus reduced to just a few minutes, meaning that more time could be spent on the pros and cons of other options. "Now they can sit with the client and actually go through multiple design decisions. 'What if the clearance was that much? How much would that change my bridge?'" Brilakis says.

While universal adoption of smart bridges is challenging because of the complexity of the infrastructure and the cost to develop and install such technology, Mosalam believes the biggest hurdle facing the industry is standardization. "There are no standards on how, what, [and] why we should deploy networks of sensors and what we should do with the acquired data," he says. Finding answers to these questions will have a major impact on the future adoption of sensing and data analysis technologies and their scalability. "Without standards, it is not possible to deploy such monitoring systems on different scales from small to large bridge systems," he notes.

Enzer points out that "the whole point of creating smart infrastructure is to provide a better experience and better outcomes for people." Whether those improved outcomes are environmental, economic, or social, the benefit needs to be the starting point for all decisions, he says. "Sometimes we come at it the other way, and we think that the important thing is the bridge itself, when actually the important thing is the people who are using the bridge. … People should be our starting point and our end point, and that way we get driven toward making better decisions." **CE**

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