The National Academies of Sciences, Engineering, and Medicine
The Role of Advanced Technologies in Structural Engineering for More Resilient Communities
September 26, 2017 | Irvine, California

City as Terrestrial Crustacean: Structural Engineering and Resilient Cities

Paul R. Brown, AICP, M.ASCE
President, Paul Redvers Brown Inc.
Carlsbad, California

I'm honored and slightly intimidated by both this audience and the importance of the topic you are addressing today. I am not an engineer, much less a structural engineer. Nevertheless, I have worked in the engineering and construction industry of since 1975, for literally dozens of municipalities and utilities. So, I am pleased that the question you asked me is not about technology and structural engineering specifically, but rather what cities might be thinking regarding those topics.

Observations on Hurricane Season

Since being asked here, the City of Houston and other communities in Florida, the Gulf of Mexico, and the Caribbean have been assaulted by the impacts of four major hurricanes (Category 3 and above) Harvey, Irma, Jose, and Maria. Before Harvey struck, your question seemed more academic than it does today. And so, I have incorporated thoughts on these on-going disasters into this presentation. They begin with a few initial observations.

First, Hurricane Harvey demonstrates the reality of what steadily rising temperatures and resulting climatic non-stationarity hold in store for us (that is more extreme and unprecedented weather events).

When we talk about the resilience of cities, rebounding from these extraordinary and more frequent disruptions is one of our biggest challenges. Today, it takes years to recover from these events, and we appear to be in a time when the frequency of return events may be shorter than the time needed to recover. That cycle of "return event before complete recovery" is the slow death of a city.

Second, Hurricane Harvey served as reminder of just how enormous natural disasters can be. In that context, I am convinced that none of our current best practices could have fully protected Harris County and the City of Houston from the deluge of Hurricane Harvey.

There have been many critical reports on why Harvey knocked down Houston (and Houston was knocked down, not knocked out). And those reports tend to focus on perceived shortcomings. For example, here's a quote taken from a 2016 article by *ProPublica* and *The Texas Tribune*, entitled "Boomtown, Flood Town" published before Harvey: (1)

> "Scientists, other experts and federal officials say Houston's explosive growth is largely to blame. As millions have flocked to the metropolitan area in recent decades, local officials have largely snubbed stricter building regulations, allowing developers to pave over crucial acres of prairie land that once absorbed huge amounts of rainwater. That has led to an excess of floodwater during storms that chokes the city's vast bayou network, drainage systems and two huge federally owned reservoirs, endangering many nearby homes . . ."

From the tone of this reporting, you might infer that some different version of Houston, governed by more progressive policies, could have been able to deal with Hurricane Harvey. No doubt a different version of Houston might be better at dealing with the typical stormwater events that cause frequent localized flooding. But is there any metropolitan area in the United States that could have dealt with 8 trillion gallons[1] or 24 million acre feet of water (the total amount of water used in Southern California over nearly 6 years) falling on them during a 6-day period?

Our urban systems were designed and developed during a different epoch than the one we appear to be entering. The Holocene period, with its post-Ice Age warmth and wetter conditions made life easier for humans (including engineers), especially given the now disappearing benefits of climate stationarity.

Before going further, let me define "stationarity." I will use the definition offered in a 2008 article that appeared in *Science*, authored by a panel of academics and practitioners. It is ominously titled, "Stationarity is Dead: Wither Water Management?" and starts with the following definition: (2)

> ". . . stationarity — [is] the idea that natural systems fluctuate within an unchanging envelope of [statistical] variability — [stationarity] is a foundational concept that permeates training and practice in water-resource engineering."

As statistician Guy Nason describes it, "Loosely speaking, a stationary process is one whose statistical properties do not change over time." (3)

Stationarity has allowed for rational investments in large-scale infrastructure, designed to function safely within known and predictable average and extreme conditions. We made decisions based on our tolerance for quantifiable risk. In water supply planning, we quantified (and subsequently ratified with through a public process) the acceptable frequency and severity of water shortages and rationing, using deterministic forecasts based on past hydrology.

[1] Based on 9,444 square mile (6,004,160 acres) Houston MSA and 48 inches of rainfall over 6 days.

As we enter what is being called the Anthropocene period (where stationarity is reportedly dead), I'm not sure we will ever be fully prepared for events that fall outside of our experience, or our current tolerance for risk.

Further, let's confront the difference between quantifiable risk and genuine uncertainty – especially as it relates to the frequency of events. The concept of a 1,000-year storm event (as Harvey has been described) is not very useful – except to suggest that it's extremely rare in our experience to date. We would need thousands of years of data (that we don't have) to establish that estimate as accurate. Further, it may create the false belief that, in the future, there is only a one-in-one-thousand chance of the event occurring again in any given year. Because climate is changing, there is no way of telling how rare, an event like Hurricane Harvey will be in the future. That's the essence of uncertainty resulting from non-stationarity.

It constitutes a level of ignorance regarding future events – and that is a real challenge to planners, engineers, insurance providers, and policy makers whose recommendations and decisions are based on confident predictions of future risk.

The implications of this ignorance require that we avoid overstating our confidence in the risk associated with any design standard that is based on assumptions regarding the frequency and severity of weather-related events like wind speeds, storm surge, temperature, rainfall, snow pack, and associated flood elevations. And combined with that, we should be able to explain what happens during and after design criteria are exceeded. Decision-makers need to know and offering false confidence will leave many cities unprepared.

Changing the DNA of Cities

So, in response to your question, my short answer is: Cities need your help reinventing urban policies, decision-making, and governance for this new epoch we are entering — while you continue making the component parts of cities more durable, less energy-intensive, and smarter. Thinking at the highest level about how to drive rapid adaptation and agility into the ancient DNA of cities?

Today, cities are experiencing multi-pronged infrastructure threats driven by: not only increasingly frequent and extreme events, but rapid population growth, economic inequalities, neglected and deteriorating facilities, and the extreme complexity of the system-of-systems that governs urban process.

In addition to these threats, cities have chosen to function within a rigid institutional framework of building codes and design standards that potentially inhibit innovations and adaptation.

Eran Ben-Joseph describes the situation cities face in his book *The Code of the City: Standards and the Hidden Language of Place Making:* (4)

> "The past two centuries have been marked by a sustained effort to bring order and safety to the city building process. But what began in the early nineteenth century as a few local and

> national regulations throughout the United States and Europe is now a worldwide effort toward standardization.
>
> ". . . Methodical administration of public works, the centralized supervision of land development, and the rise of the engineering and urban planning professions have established design standards as absolutes."

The establishment of "absolute standards" on a worldwide basis offers enormous public health and safety benefits during "normal" conditions, but it comes at the price of inhibiting the adoption of innovations on a wide scale. Proposals to transition these prescriptive codes to performance based alternatives offers one clear path to addressing this issue.

But the 2017 Hurricane Season should remind us that the faster we reinvent our current design standards and codes — the greater the chances we not only survive changing times but learn from the events that threaten us.

So, What Is a Resilient City?

The Rockefeller Foundation, in its 100 Resilient Cities program, defines urban resilience as "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience." (5)

I like that definition because it highlights the distinction between the "chronic" and the "acute." The seismic hazards of earthquakes fall under acute shocks, together with floods, terrorist attacks, and disease outbreaks.

Chronic water shortages are clustered with other chronic stressors like high unemployment, overtaxed or inefficient public transportation systems, endemic violence, and food shortages. These chronic stresses are described as "slow moving disasters that weaken the fabric of a city."

In the water sector, cities have been responding to a slow-moving disaster for decades — periodically punctuated by acute shocks like the public health crisis in Flint, Michigan; the California drought; the Oroville Dam failure in Central California; the storm surges that destroyed coastal cities during Katrina, Sandy, Irma, and Maria; and severe flooding from Katrina, Sandy, and Harvey.

My colleague and friend Howard Neukrug, the former Commissioner of the City of Philadelphia Water Department, currently at the University of Pennsylvania, describes the situation this way: (6)

> ". . . Rising tides, water scarcity, floods, legacy and emerging contaminants, extreme storms, the threat of terrorism, non-stationarity and piping systems built in the 19th century combined with 20th century technologies have left us with little choice but to actively renew our thinking about the relation of water to our cities, our budgets and our future."

Every city is a unique and complex combination of interests and forces with diverse expectations. Resilience will mean something unique in all of them — an emergent capacity to adapt not a static designed solution.

Urban Process Versus Urban Design

I have come to appreciate how right the late Spiro Kostof was in focusing on "urban process" rather than "urban design." In his book *The City Shaped: Urban Patterns and Meanings Through History*, he explains it in the following terms: (7)

> "The tendency all too often is to see urban form as a finite thing, a closed thing, a complicated object. I want to stress that what we know instead to be the case – that a city, however perfect its initial shape, is never complete, never at rest. Thousands of witting and unwitting acts every day alter its lines in ways that are perceptible only over a certain stretch of time."

As engineers, architects, and builders we may be so attached to the idea that resilience is a design problem, we forget that cities are people, places, and processes that depend on the built environment but are not defined by it.

Cities evolve because of the collaboration and conflicts that exist among citizens, elected officials, local authorities, regulators, developers, businesses, and many other institutions – the long list of interests and stakeholders active in every community.

In a 2013 paper published in *Science*, Luís Bettencourt reported on his research to model relationships that might apply across all urban systems. He acknowledges the difficulties associated with simulating the behavior of urban systems right up front: (8)

> "Despite the increasing importance of cities in human societies, our ability to understand them scientifically and manage them in practice has remained limited. The greatest difficulties to any scientific approach to cities have resulted from their interdependent facets, as social, economic, infrastructural, and spatial complex systems that exist in similar but changing forms over a huge range of scales."

Bettencourt concludes his paper with the following observation, "although the form of cities may resemble the vasculature of river systems or biological organisms, their primary function is as open-ended social reactors."

When asked in an interview what the heck that meant, Bettencourt replied (referring the city), "it's really its own new thing, for which we don't have a strict analogy anywhere else in nature." (9)

City as Terrestrial Crustacean

But despite Bettencourt's caution that there is no good analogy for a city found in nature, I'm going to fall back on one to make a simple point. Let's imagine the city as a land-based crustacean — like a crab or a terrestrial lobster.

As cities, we nest in locations accessible to water and occasionally subject ourselves to the threat of drowning. We grow a complicated exoskeleton that adheres itself to solid surfaces, extending rigid linear arteries in all directions that transport food, water, and goods into the guts of the city, and then carry waste products away.

As engineers, architects, and builders, we have an important role on this "land lobster." We oversee the exoskeleton, including pincer and crusher claw design, construction, operations, and maintenance. Of course, the living heart and body of the city is inside the exoskeleton. It has no observable shape other than its eyes, antennae, and shell. And the living city takes the exoskeleton entirely for granted — never really thinks about it.

Now what if our habitat changes radically, and we need to quickly become more flexible, agile, and shape-shifting like say an octopus? How can that possibly happen? Probably it needs to happen from the inside out, gradually over time. Progressive changes in the city's DNA, rather than cosmetic surgery on its shell.

But that doesn't mean that those of us assigned to the "shell engineering" have nothing to do but wait for evolution to takes its course. Assuming we know the new objectives of flexibility, agility, and rapid response to unexpected attacks, maybe we do research and development on adaptation itself, on how to re-engineer the periodic molting process to improve mobility for example.

We need to encourage the acceleration of our evolution as cities and embrace the challenge of needing systems that are multi-purpose, durable, flexible, regenerative, and possibly "anti-fragile" (to use a term coined by Nassim Taleb). (10)

We could work on system components that comply with the Department of Defense's elegant definition of system resilience: (11)

> "A resilient system is trusted and effective out of the box, can be used in a wide range of contexts, is easily adapted to many others through reconfiguration and/or replacement, and has a graceful and detectable degradation of function."

The good news is we are not locked in a shell, and the shape-shifting capacity of our cities is remarkable, when they show the political will to do so.

How do we promote and accelerate a community's will to change? What is the relationship we want people to have with our engineered structures and technology?

In urban water infrastructure, we want much higher levels of engagement, understanding, participation, and even love of precious water. In fact, The Metropolitan Water District sponsored a very successful public service campaign that you might have encountered during your stay here. Advertising that reads simply: "H - 2 - Heart emoji."

But other public policy questions go deeper:

- How do we balance the benefits of standardization in codes and practices with the benefits of innovation and locally-developed solutions? Can we develop performance-based codes to accomplish that?

- How much do we rely upon artificial intelligence for operational decisions? How do we protect against hacking and cyberattacks? How do we implement manual operations when digital communications are down?

- How much should we spend on isolating communities from unpredictable hazards (for example providing higher sea walls and levies) versus providing communities with tools and preparedness to successfully manage through hazardous events (for example elevated or floatable structures)?

These are all big questions. They loom over the already complicated problems that engineers must answer during the design of any specific structure.

Learning from Failure

Accepting the need for resilience at the city scale is a bitter-sweet acknowledgment. Because while resilience is a noble attribute in an individual or a community; in the material world of buildings and infrastructure the implied acceptance of inadequacy is hard to swallow.

If we need to be resilient, we have probably failed to adequately protect people and property. Barriers and redundancy designed in the hope of eliminating hazards have let us down, and we are left with the need to minimize the damage done and enable a swift recovery.

And yet, resilience may be the most important virtue embedded in our concept of sustainability. Because, it's based on the humility and wisdom to provide for survival and rapid recovery, instead of bold promises of protection that may be unattainable and are almost always unaffordable. It calls for a fundamental rethinking of design principles.

Maybe it is slightly reassuring that for centuries, the failure of engineered structures has been a primary basis for advancing knowledge in structural, mechanical, and civil engineering. As Henry Petroski argues in his book *To Engineer is Human: The Role of Failure in Successful Design*, "it is important that engineers study failures at least as much, if not more than successes, and it is important that the causes of structural failures be as openly discussed as can be." (12)

The recovery process itself can be a catalyst for adaptation (as we have seen in the wake of Superstorm Sandy). What has failed once should not be replaced by what failed. Resilience can result from the rapid adoption of adaptive innovations on a wide scale – if we focus on adaptive innovations during the recovery process.

The Netherlands is a showroom of engineering approaches for living through frequent inundation. Water-centric cities are a reality around the world, not a dream. And yet, how much of what is currently being done in Rotterdam will become part of Houston's future?

As structural engineers, help cities invent a future of constant adaptation and renewal. Design ways to repurpose and reconfigure our built environment for uses we never thought we would need, and provide for "a graceful and detectable degradation of function" as we transition to something new and different. Listen to the city's many voices and create safe places where people can live and shelter confidently during and after foreseeable (if not predictable) events.

And finally, recognize that the source of urban resilience is people and community, everything else is a just a shell of potentially hazardous artifacts that should be designed to be safe and reusable when damaged. Be the responsible enablers of sound decision-making under extreme uncertainty, as communities of people are forced to adapt to an increasingly hazardous and unpredictable world.

Thank you.

References

1. Satija, Neena; Kiah Collier, and Al Shaw. Boomtown, Flood Town. *The Texas Tribune* and *ProPublica*. 7 December 2016. [accessed 27 August 2017]. https://www.propublica.org/article/boomtown-flood-town-text.

2. Milly, P. C. D.; Julio Betancourt; Malin Falkenmark; Robert M. Hirsch; Zbigniew W. and Dennis P. Lettenmaier Kundzewicz, Ronald J. Stouffer. Stationarity is Dead: Whither Water Management? *Science.* 2008. 319:573-574.

3. Nason, G.P. Stationary and non-stationary time series. Chapter 11 of *Statistics in Volcanology*, (Mader, H. and Coles, S.C., eds), Geological Society of London. 2006.

4. Ben-Joseph, Eran. *The Code of the City: Standards and the Hidden Language of Place Making*. Cambridge, Massachusetts: MIT Press. 2005.

5. 100 Resilient Cities: What is Urban Resilience. The Rockefeller Foundation. c2017. [accessed on 15 August 2017]. http://www.100resilientcities.org/resources/#section-1.

6. Expert Voices 2017: America's Urban Infrastructure. Philadelphia: Penn Institute for Urban Research. c2013. [accessed on 24 August 2017]. http://penniur.upenn.edu/publications/expert-voices-2017-americas-urban-infrastructure#Neukrug.

7. Kostof, Spiro. *The City Shaped: Urban Patterns and Meanings Through History*. Boston: Bullfinch. 1991.

8. Bettencourt, Luís. The Origins of Scaling in Cities. *Science.* 2013. 340:1438-1441.

9. Badger, Emily. Scientific Proof That Cities Are Like Nothing Else in Nature. CityLab.com. Washington, DC: Atlantic Media. 20 June 2013. [accessed on 2 September 2017] https://www.citylab.com/environment/2013/06/scientific-proof-cities-are-nothing-else-nature/5977/.

10. Taleb, Nassim Nicholas. *Antifragile: Things that Gain from Disorder*. New York: Random House. 2012.

11. Goerger, Simon R.; Azad M. Madni, and Owen J. Eslinger. Engineered Resilient Systems: A DoD Perspective. *Procedia Computer Science*. Los Angeles: Elsevier B.V. 2014. 28:865-872.

12. Petroski, Henry. *To Engineer is Human: The Role of Failure in Successful Design*. New York: Vintage Books. 1992.