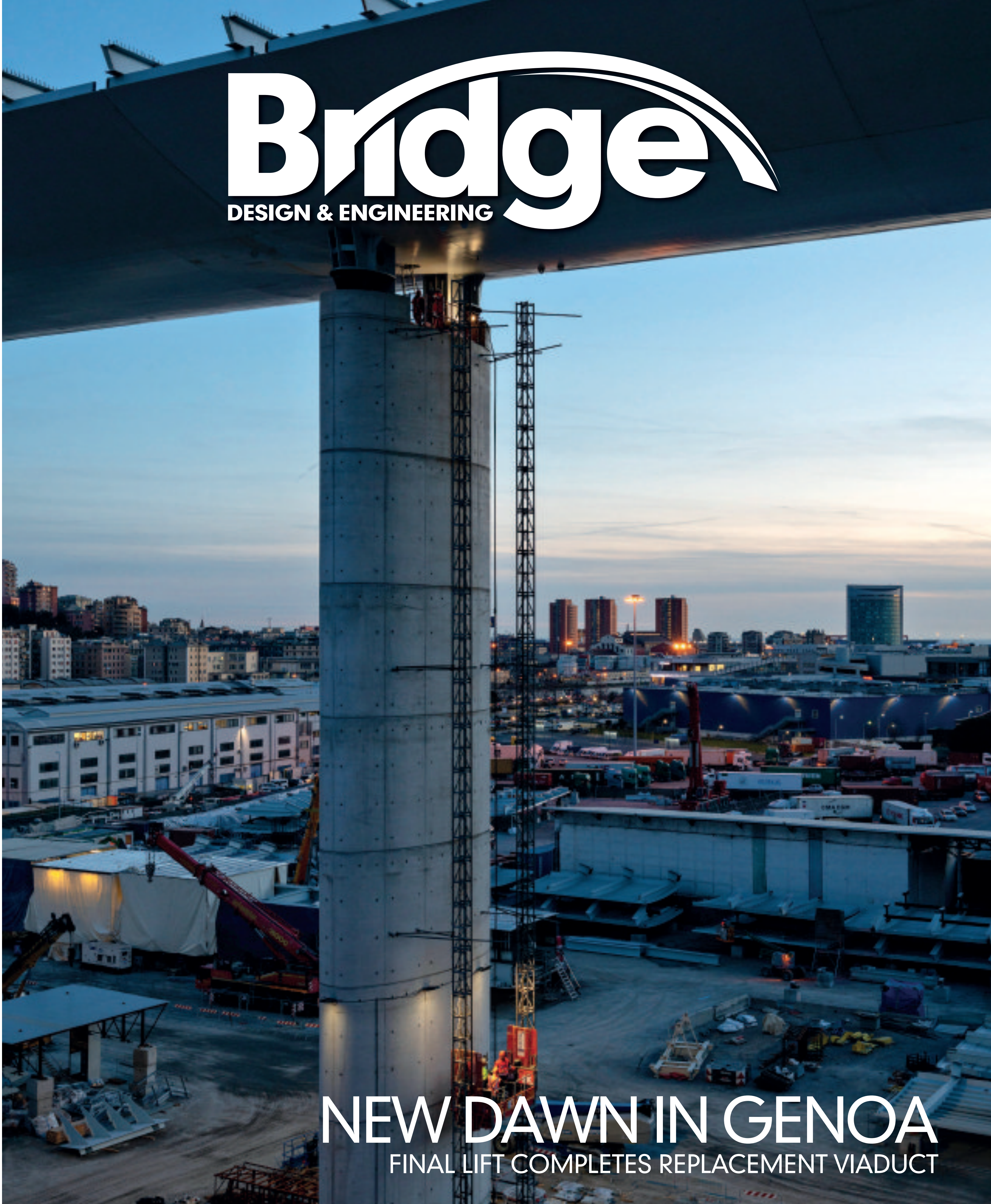
ISSUE NO. 99 SECOND QUARTER 2020

BRIDGE DESIGN & ENGINEERING

Bridge
DESIGN & ENGINEERING



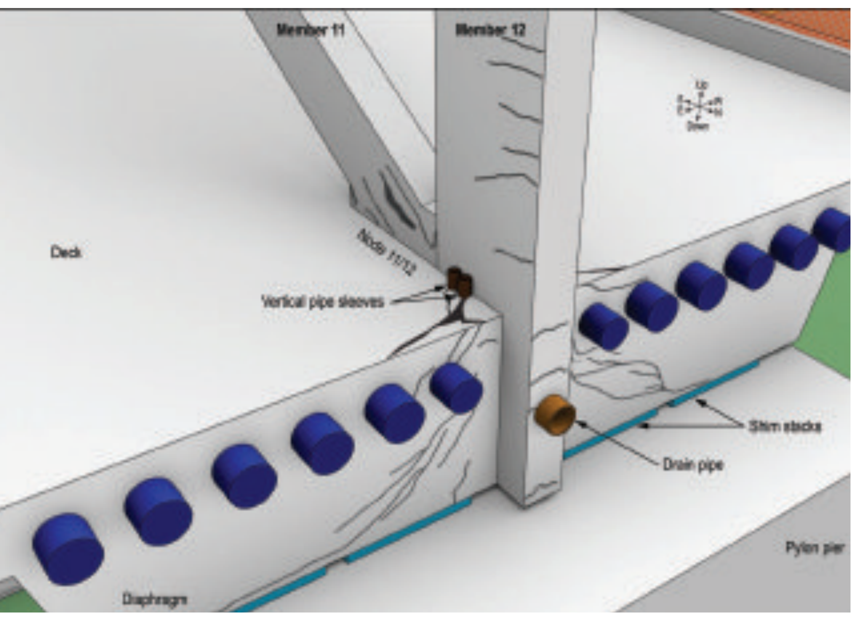
NEW DAWN IN GENOA
FINAL LIFT COMPLETES REPLACEMENT VIADUCT

THE DEFINITIVE PUBLICATION FOR BRIDGE PROFESSIONALS WORLDWIDE | ISSUE NO.99 | SECOND QUARTER 2020 | WWW.BRIDGEWEB.COM

BUT WHY?

Two years on from the collapse of a unique pedestrian bridge under construction at Florida International University, Scott Snelling seeks to identify the root causes in the hope such a tragedy does not occur again

The unique pedestrian bridge under construction at Florida International University (FIU) collapsed on 15 March 2018, in the city of Miami. Six people were killed and ten people were injured. The dead included one construction worker who had been working on top of the bridge, as part of a six-person crew at the time. Five of the dead were members of the public who were crushed in their vehicles when the bridge fell down upon Southwest 8th Street.



Rendering of cracking at node 11/12 immediately prior to failure, based upon field photo-documentation and measurements (*NTSB*). Top; the main span was erected overnight using self-propelled modular transporters (*FIU*)

The National Transportation Safety Board (NTSB) performed an exhaustive, authoritative investigation, culminating in the publication of *Highway accident report 19/02* which was published 22 October 2019. The NTSB report includes a precisely worded probable cause statement. The NTSB also published a docket of relevant reports, depositions, photos, emails, lab testing results, calculations, and contracts.

The first tenet of engineering ethics in the USA is to "hold paramount the safety, health, and welfare of the public". If we are to reduce the risk of future bridge collapse, the bridge industry must go beyond the proximate cause and grapple with the root causes.

The story of the FIU bridge collapse is a story of ambition, not incompetence. From the perspective of the bridge designer, the arc of the story has much in common with the main thrust of the story in Greek mythology of Icarus who, wearing wings invented by his father, soared skilfully into the sky. Overcome with confidence, he flew too close to the sun, which melted his wings; he then plummeted to his death in the sea.

The FIU pedestrian bridge superstructure is so unique that its type does not have a name. As the upper pylon tower and the steel pipes are not load bearing and are primarily aesthetic, it may be categorised as a faux cable-stayed bridge. It may be more accurately called a post-tensioned concrete truss bridge. Or it could alternatively be categorised as a post-tensioned concrete beam bridge with web cut-outs. Categories hardly apply to the FIU pedestrian bridge because no bridge like it has ever existed, nor is one likely to be attempted again in the future.

The main span of the bridge was 53m long spanning over the eight-lane-wide arterial highway of South-west 8th Street. The back span was 30m long over the Tamiami Canal. The bridge deck walking-surface was 5.6m above the roadway. The top of the pylon was 33.2m (109ft) tall, a height selected for symbolic reasons since the bridge was located adjacent to 109th Avenue.

The unique aspects of the bridge could be summarised as follows. It is a post-tensioned concrete truss superstructure and, given that concrete has negligible strength in tension, concrete trusses have rarely been attempted: The truss diagonals, with their non-uniform spacing and angles, are located to maintain visual alignment with the non-structural steel pipes above. The design concept enhances the faux-cable stay appearance of the bridge with a truss diagonal arrangement that is aesthetically logical, but not structurally logical; a single plane truss is used that renders the load carrying truss members non-redundant; a new 'self-cleaning' concrete mix containing titanium dioxide was used. While similar mixes have been used before, this is believed to be the first time that such a concrete mix was used for the structural members of a bridge. The concrete mix design did not contribute to the bridge collapse.

It is also worth noting that the bridge was built using accelerated bridge construction, a technique that has recently been gaining wider adoption whereby the superstructure is erected off-site and then quickly transported into place over one night in order to minimise roadway closures and traffic impacts.

The main span was cast in a yard adjacent to the bridge site. Three separate concrete pours were used: deck, truss diagonals, then canopy. Cold joints were at the interface between each pour. During construction the designer instructed the contractor to roughen to 6mm amplitude and to clean the cold joint surface before the subsequent pour, but this was not done. The later shear failure at node 11/12 occurred at the cold joint where member 11 was bearing upon the deck. The rebar, post-tensioning tendons, post-tensioning bars, and drain pipes embedded in the vicinity of node 11/12 can be seen on page 58.

Thin cracks were noted around node 11/12 after the concrete forms and falsework had been stripped from the main span while it was still in the casting yard. The falsework had been providing continuous support to the main span while the concrete cured and, upon removal, the main span was simply-supported, similar to how it would be supported upon the piers once erected.

The main span was erected overnight using self-propelled modular transporters on 10 March 2018, five days before its later collapse. During transport, the main span was supported under node 9/10 and node 3/4 while both ends of the span were cantilevered. This temporary support condition caused the end diagonal member 11 and member 2 to temporarily be in tension. As they were planned as compression members for the remainder of the bridge construction sequence and bridge life, the designer provided two post-tensioning bars within each member, while also specifying that the bars be tensioned before the span erection and de-tensioned after the span erection.

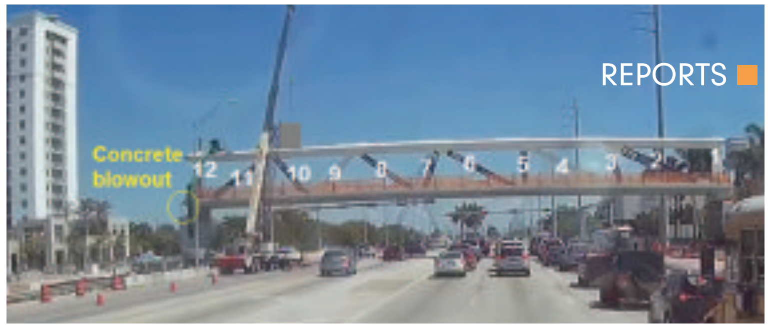
The cracks around node 11/12 (see opposite page) were monitored by the design engineers and the construction management firm during and after the span erection operation. The cracks did not significantly change from their condition in the casting yard, neither during the span movement operation nor once the span had been placed in its final location upon the piers. Upon de-tensioning the bars in member 11, the construction worker noted that the cracks around node 11/12 had greatly increased in size and severity. He texted photos of the cracks to his supervisor with the message: "It cracked to hell." This occurred on 10 March 2018, five days before the collapse.

The contractor emailed photos of the cracks at node 11/12 to the bridge design firm on 12 March 2015, three days before the collapse, with the message: "It is [the contractor's] opinion that some of these cracks are rather large and/or of concern; therefore, please review and comment as promptly as possible and advise if there is a required course of action to remedy or address these right away."

The photos show cracks encircling node 11 with crack widths up to 25mm wide and 178mm deep. For comparison, the American bridge inspection standard defines that cracks greater than 5mm wide in concrete structural members shall receive a rating of 'severe', the worst available rating. Cracks of the severity of those found around node 11/12, a non-redundant structural element, indicated that the concrete had exceeded its yield strength and had undergone significant plastic deformation.

The design firm reviewed the photos, reviewed their structural models, performed new hand calculations, but was unable to identify the cause of cracking around node 11/12. Two key engineers on the design team were on vacation at this time, adding difficulty to the response. The structural model that was used did not account for the drain pipes that penetrate three sides of the node. It was not updated to reflect the cracking in the field and, instead, modelled as a continuous material. The designer used multiple structural finite-element models and these provided different results with regards to loads and stresses at node 11/12.

The design engineer of record recommended re-tensioning member 11, reasoning that this would restore the main span to the previous condition, when the cracks were smaller. The independent review firm was not notified or involved in this decision. The design engineer of record advised the contractor and the department of transportation that the cracks were not a safety issue. The roadway remained open to traffic.



Collapse sequence from in-vehicle video feed – less than two seconds elapsed between the top and bottom images (*NTSB*)

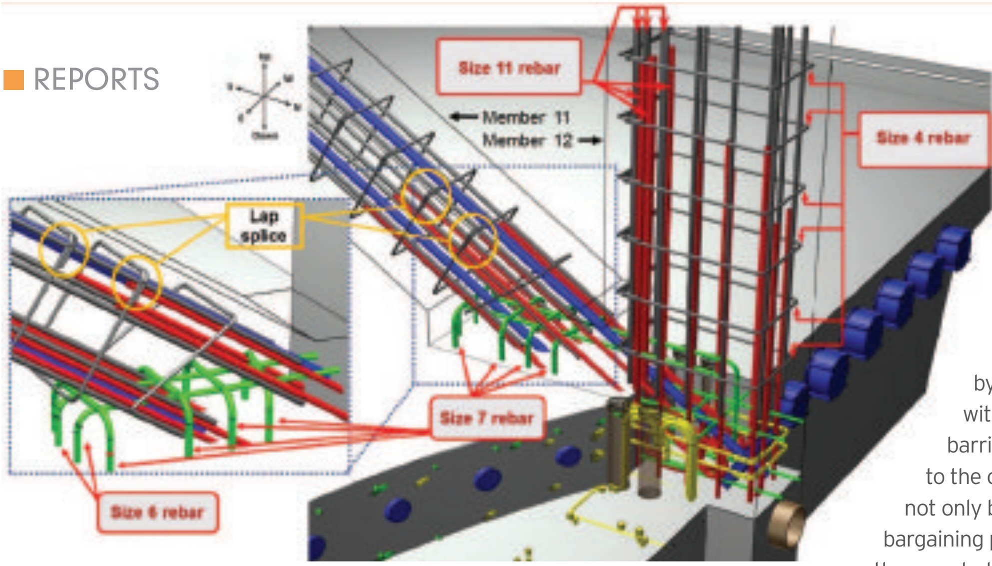
Moments after completing the re-tensioning of member 11, the main span collapsed on 15 March 2018. The design engineer of record was on an airplane flight home, having visited the site and presented his analysis and recommendations earlier the same morning.

After the collapse, the Federal Highway Administration calculated that 116cm^2 of shear steel was required at the interface of node 11/12 and the deck, compared with the 31cm^2 that was provided in the design.

The NTSB found, "the probable cause for the FIU pedestrian bridge collapse was the load and capacity calculation errors made by the [bridge design firm at the 11/12 node and connection to the deck]. Contributing to the collapse was inadequate peer review by [the independent review firm], which failed to detect the calculation errors in the bridge design. Further contributing to the collapse was the failure of the [...] engineer of record to identify the significance of structural cracking observed in this node before the collapse and [failure] to obtain independent review of the remedial plan to address the cracking. Contributing to the severity of the collapse outcome was the failure of [the contractor, designer, construction manager, owner, and the department of transportation to stop] work when the structure cracking reached unacceptable levels and to take appropriate action to close Southwest 8th Street as necessary to protect the public."

The key to mitigating the risk of future bridge collapses requires grappling with root causes. One must dig deeper to move from a proximate cause towards a root cause. One technique for identifying root cause is asking five 'whys'. First, why did the FIU Bridge collapse? Answer: Because truss node number 11-12 failed in shear at the cold-joint with the deck (this is the proximate cause).

Why? Because the capacity (strength) of the node was insufficient to support the demand (loads) imposed on the partially erected span ▶



Rendering of node 11/12 showing internal rebar, post-tensioning bars and tendons, and drain pipes (*NTSB*)

during construction.

Why? Because the bridge designer made design errors in calculating both the capacity and the demand of node number 11-12.

Why? Because the bridge designer was attempting to invent a unique new type of signature bridge superstructure. The bridge designer agreed to a superstructure design fee that was a fraction of what is typical. The superstructure design fee was US$135,000 and included the preparation of 51 final drawing sheets, calculations, structural models, and specifications. Assuming an average burdened rate of approximately US$150 per hour, the superstructure design fee works out to less than 18 hours per sheet. One common rule of thumb for typical bridge design is 70 hours per sheet. Considering the complexity and uniqueness of this bridge, the superstructure design fee was shockingly low. A second rule of thumb for typical bridge design fees is a maximum of 10% of the construction cost. This second rule of thumb appears to have set the maximum beyond which the designer was not able to negotiate.

Furthermore, the bridge designer's initial cost proposal had not budgeted for the required independent design review by an outside firm. Late in the design process, the owner required the designer to hire another firm to perform the independent design review. The bridge designer negotiated hard with the independent review firm and was able to reduce the agreed upon fee by almost half, to US$60,000. The parties dispute whether the scope of work for the independent review was reduced to include only the primary members in the final configuration. The independent reviewer did not check the design at nodes or construction stages.

The fifth 'why' is really two questions. Why was the designer developing a unique and complex bridge design on an inadequate budget? Because the owner's request for proposals (RFP) solicited an innovative, signature bridge while imposing a strict price cap of US$9.4 million. The design engineer and independent-checker engineer were too eager to please the owner and win the work. Commercial pressures prevailed over sound judgment.

And finally, why was an independent review performed with an inadequate budget and scope? Because there is an inherent conflict of interest in requiring a bridge design firm to hire and negotiate the fee and scope for the independent review. These final two questions reveal the root causes, which in turn lead to the lessons to be learned.

The bridge owner, in the project RFP document, incentivised an innovative, signature bridge within a strict price cap. This is not unethical. All consumers want the best possible product for the smallest possible amount of money. This is the essence of human nature and commerce. Competing design-build teams respond to the incentives established by RFPs. The winning bridge design proposed for the FIU project was more than innovative; it was truly unique and unprecedented. The winning bid necessarily complied with the owner's price cap.

Bridge design is a fragmented industry, as defined by Michael Porter in the book *Competitive strategy*, with low barriers-to-entry, diverse market needs, exit barriers, local regulation, and need for personal service to the customer. "Fragmented industries are characterised not only by many competitors but also by a generally weak bargaining position with suppliers and buyers," wrote Porter. In other words, the bridge design industry is highly competitive.

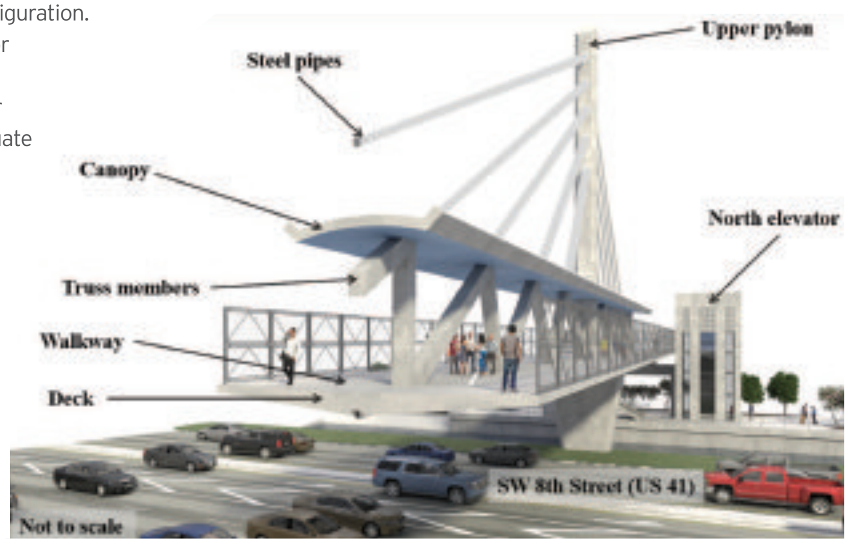
The bridge design firm did not have the market power to negotiate funds commensurate with their ambitious design, yet decided to proceed anyway. Perhaps the project was regarded as a loss-leader that could be used for marketing purposes to win future, more profitable bridge design projects.

The bridge superstructure design fee for a unique and complex new design was unreasonably low. Likewise, the independent design review fee was tight and was the result of negotiation. The engineer who performed the independent review was laid off shortly after completing the work (almost one year before the bridge later collapsed) and was likely under significant economic pressure when negotiating the fee for this project.

Ambitiously small engineering budgets increase the risk to the project and the public when compared to more typical budgets. As the American investor and businessman Charlie Munger once said, "Show me the incentives and I will show you the outcome."

Most of the firms involved in this failed project have not survived in their previous form. The bridge industry remains highly competitive. The FIU bridge collapse serves as a stark reminder to surviving bridge design firms to avoid the siren call of trying to do too much for too little when negotiating the scope, schedule, and budgets for their own projects ■

Scott Snelling is an engineer and project manager with 19 years of experience in the bridge and heavy civil industry gained with the US Army Corps of Engineers (current employer), Parsons Brinkerhoff, and Hardesty and Hanover



Cross-section rendering of the FIU pedestrian bridge (*FIU, annotated by NTSB*)