Infrastructure Resilience and Functional Recovery

by Scott Campbell and Brian Killingsworth, National Ready Mixed Concrete Association

Infrastructure investment is commonly discussed in the public forum, with some people decrying the current state of said infrastructure. The Infrastructure Investment and Jobs Act, which was passed by Congress and signed into law by President Biden in November 2021, has placed a renewed focus on the topic as $550 billion will be invested in hard infrastructure over the next decade. If this money is to be spent wisely, it is necessary to ensure that resilience is considered as part of the design and decision-making process for all projects.

To properly consider resilience, it is important to understand what is meant by the term. In a building industry statement,[1] based on work by the National Research Council and signed by more than 50 organizations, "resilience" is defined as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. Preparing for, planning for, and absorbing adverse events are typical parts of the design process, even if considering enhanced resilience requires some changes to how those steps are performed. However, the concept of recovering from an adverse event is seldom considered. That is, the time and funding required to bring infrastructure back into service are often overlooked in the decision process.

Identifying the need for recovery after earthquakes, the National Institute of Standards and Technology and the Federal Emergency Management Agency[2] created a definition for "functional recovery":

> *A post-earthquake performance state in which a building or lifeline infrastructure system is maintained, or restored, to safely and adequately support the basic intended functions associated with the pre-earthquake use or occupancy of a building, or the pre-earthquake service level of a lifeline infrastructure system.*

This concept can just as easily be applied to non-earthquake types of adverse events, and to types of structures other than buildings. To have true resilience, the structure must be able to return to functionality within a reasonable time frame, and the cost for doing so must be considered in the planning and design processes.

An example of the "cost" of not fully considering functional recovery is the aftermath of Hurricane Katrina in New Orleans, La. The city's population dropped by more than 50% after the hurricane struck in 2005 and has not fully recovered to date. Moreover, the most vulnerable members of the community have been the most affected. The fact that functional recovery of the infrastructure, including homes, offices, and industry, took so long was a major factor in peoples' decisions not to return—they had settled in other places.

Although the definition of functional recovery seems straightforward, the idea of what constitutes the "basic intended functions" of infrastructure can vary depending on the type of project and the goals of the owner and community. One possibility is that the basic intended functions are all the functions that were in place before the adverse event. This is the ultimate goal—but are all pre-event functions needed immediately after an adverse event? Is 50% capacity at a water treatment plant acceptable for a short period (days or weeks)? What about one open lane on a major bridge? These scenarios provide some functionality, and it is up to the community to decide if that is acceptable, and for how long.

The concept of resilience is often raised in terms of events that can cause physical damage to a system, but that is not the only time when resilience is relevant. For example, the shutdown of Interstate 95 in Virginia from January 3 to January 4, 2022, was not due to the roadway, bridges, or exits being physically damaged, but rather the state's winter storm response resources becoming overwhelmed. As a result, hundreds of travelers were left stranded in their vehicles, some for more than 24 hours, in freezing temperatures and often with no food or water. This was not a matter of design, but rather preparedness. Truck accidents that blocked traffic could not be cleared because allocated resources were simply overwhelmed by the severity of the storm. Note that this does not mean that the state should have had sufficient capacity to prevent any shutdown; however, there must be adequate resources or a plan to limit the downtime to a duration that is deemed acceptable.

It is possible to design, build, and operate infrastructure to achieve enhanced resilience. Along with concepts such as life-cycle analysis, functional recovery provides a way to quantify performance and therefore to measure whether the project goals are achieved. However, to implement these ideas, the levels of functionality required for various scenarios and different time frames must be developed. Once we have a firm scope of the desired performance, designs can be adjusted to provide the appropriate level of infrastructure resilience for each project.

References

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2. Federal Emergency Management Agency (FEMA) and National Institute of Standards and Technology (NIST). 2021. *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time.* FEMA P-2090/NIST SP-1254. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1254.pdf.

PROJECT

Selmon West Extension Improves Regional Connectivity

by Bob Anderson and Drew Miller, AECOM, and Russel Dingman, Kiewit

The recently completed $235 million Selmon West Extension in Tampa, Fla., is a 1.6-mile-long toll road consisting primarily of a viaduct above the median of Gandy Boulevard. The current configuration of the extension is generally one 15-ft-wide lane with two 6-ft-wide shoulders in each direction. This width is sufficient to allow for four lanes of traffic during an evacuation event or a future capacity increase with lane reconfiguration by restriping.

By separating commuter traffic from local trips, the Selmon West Extension provides safer and smarter regional connectivity while alleviating traffic congestion on Gandy Boulevard and creating greater capacity and access for neighborhood businesses and residents. The trip time through the corridor can now be cut from 20 minutes to 2 minutes.

The Selmon West Extension in Tampa, Fla., is a 1.6-mile-long toll road consisting primarily of a viaduct above the median of Gandy Boulevard. Travelers now have direct connections between the Lee Roy Selmon Expressway, Dale Mabry Highway, and the Gandy Bridge to St. Petersburg. Figure: Tampa Hillsborough Expressway Authority.

Integration of Design and Construction in an Urban Environment

The design-build team understood the importance of maintaining traffic on Gandy Boulevard and was tasked to provide a "best value" solution to the Tampa Hillsborough Expressway

profile

SELMON WEST EXTENSION / **TAMPA, FLORIDA**

BRIDGE DESIGN ENGINEER: AECOM, Tampa, Fla.

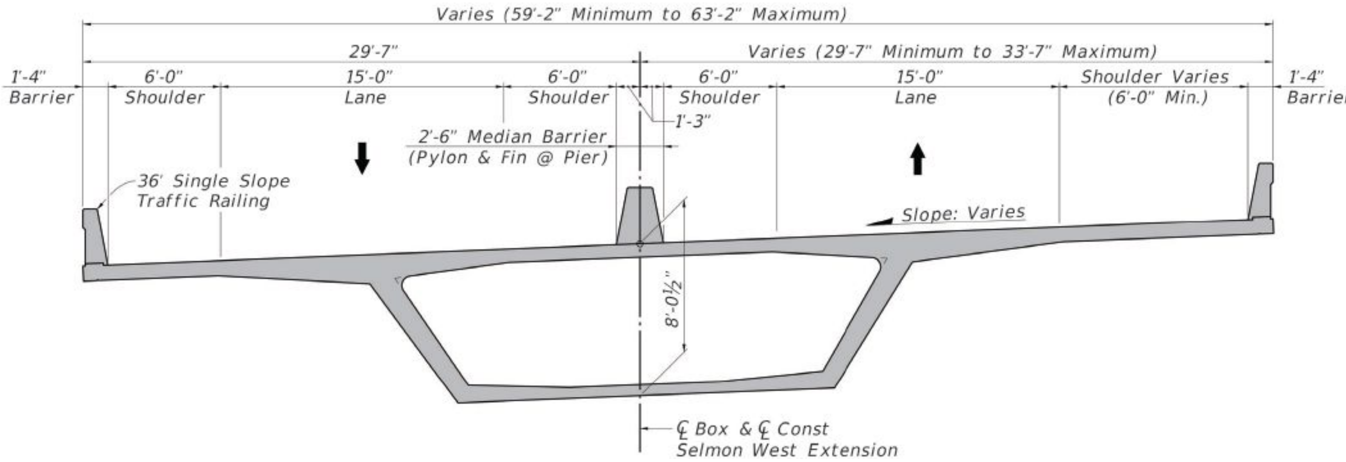
OTHER CONSULTANTS: Owner's engineer: HNTB, Tampa, Fla.; construction engineering services: McElhanney, Tampa, Fla.; Kiewit Infrastructure Engineers, Denver, Colo.; independent peer reviewer: SYSTRA–International Bridge Technologies, San Diego, Calif.; construction engineering inspection: Atkins, Tampa, Fla.

PRIME CONTRACTOR: Kiewit — Kiewit Infrastructure South Co., Tampa, Fla.

CONCRETE SUPPLIERS: Drilled shafts: Titan America, Tampa, Fla.; all other concrete: CEMEX USA, Tampa, Fla.

POST-TENSIONING CONTRACTOR: Schwager Davis Inc., San Jose, Calif.

OTHER MATERIAL SUPPLIERS: Formwork for precast concrete segments, erection girders, straddle carrier, and swivel crane: DEAL, Bay Harbor Islands, Fla.; form travelers for cast-in-place segments: Kiewit Engineering Group Inc., Tampa, Fla.; bearings: R. J. Watson Inc., Alden, N.Y.; expansion joints: D. S. Brown, North Baltimore, Ohio; epoxy and prepackaged grout supplier: Pilgrim Permocoat Inc., Tampa, Fla.; flexible filler for post-tensioning tendons: Fuchs Lubricant Company, West Palm Beach, Fla.



The typical section of the Selmon West Extension is generally configured with one 15-ft-wide lane and a 6-ft-wide shoulder in each direction. This width is sufficient to allow for four lanes of traffic during an evacuation event or a future capacity increase with lane reconfiguration by restriping. Figure: AECOM.

Completed elevated viaduct with street traffic below on the West Gandy corridor. Photo: AECOM.

Authority (THEA) with scoring criteria that included the total weighted sum of the letter of interest score (20%), design (15%), construction (15%), maintenance of traffic (10%), schedule (20%), and price (20%). The chosen design-build team fulfilled this challenge by submitting the most innovative, constructable, and cost-competitive design that met the goals established by THEA. (see the Authority article on THEA on page 58).

The highlight of the Selmon West Extension project is clearly the elevated concrete segmental viaduct structure. THEA required it to be supported entirely within the narrow (typically 10-ft-wide) median of the four-lane urban Gandy Boulevard, and prescribed an aesthetically pleasing, single box-girder superstructure with 30 ft of vertical clearance to allow open sightlines for businesses on opposite sides of the road and to minimize the tunnel effect below the elevated structure. Long span lengths and slender cantilever piers were also required to

TAMPA HILLSBOROUGH EXPRESSWAY AUTHORITY, OWNER

BRIDGE DESCRIPTION: The signature element is an eight-unit, 35-span, 7060-ft-long concrete segmental box-girder viaduct with spans up to 260 ft

STRUCTURAL COMPONENTS: 744 precast concrete box-girder segments, each weighing approximately 72 tons; cast-in-place finbacks that encase large post-tensioning tendons; cast-in-place cantilever piers with vertical and horizontal post-tensioning bars; and cast-in-place concrete footings and drilled shafts

PROJECT COST: $235 million

2021 AWARDS: *Roads & Bridges* Top 10 Bridges in America; International Bridge, Tunnel and Turnpike Association Toll Excellence Award; Florida Transportation Builders Association Best in Construction, Expressway Project of the Year; Construction Management Association of America Florida Project Achievement Award in Transportation; American Segmental Bridge Institute Bridge of Excellence Award; Hillsborough Planning Commission Planning & Design Award; American Council of Engineering Companies of Florida Grand Engineering Excellence Award; Greater Tampa Section Institute of Transportation Engineers Project of the Year

An innovative progressive span-by-span viaduct construction method was used to meet the project's constructability challenges. Using this method, the concrete segments were erected with self-launching underslung erection girders supported by temporary towers in the median. Photo: Kiewit.

provide for proper left-turn sight distance at all intersections and median openings. Spans over intersections are generally 230 ft, with the longest spanning 260 ft. Spans over left-turn movements into driveways are between 200 and 220 ft. The 59-ft 2-in.-wide viaduct overhangs most of the four lanes of Gandy Boulevard below. THEA required that the boulevard remain open during construction, with only single-lane overnight closures and rolling stops permitted.

Given the potential for restrictive impacts to the businesses, residents, and commuters during construction, the request for proposal stipulated the use of top-down construction techniques, an aggressive 1000-day design and construction schedule, and redundant support of the erection equipment and concrete segments during construction for the entire 7060-ft-long structure. There were also significant penalties written into the contract if all lanes along Gandy Boulevard were not open by 6:00 a.m. each day. THEA proactively managed constructability and redundancy concerns by requiring the submittal of an erection plan and protection plan for overhead construction detailing each design-builder's approach to construction before bid, which was included in the "best value" scoring.

Conventional Approaches Proved Inefficient

The conventional design for a viaduct with 230- to 260-ft spans requires a top-down construction method with a precast concrete segmental box girder built using the balanced-cantilever method with an overhead gantry. Using this method, one segment is set at a time on alternating ends of the cantilever, and the segment hangs from the gantry until post-tensioned to the cantilever. The gantry, in turn, is supported by the cantilever and temporary shoring may be required to stabilize the cantilever, especially for redundancy. The design-build team determined that this method of construction was not practical because it would require two headings, each having its own overhead gantry to complete erection within THEA's required time frame. In addition, for this project with this construction method, the overhead gantries would need to be supported on the final foundations, and that would often control the permanent substructure and foundation design. The resulting heavily loaded eccentric columns and foundations would not fit in the narrow median without long-term lane closures. Lastly, this gantry style does not afford a redundant means of supporting segments; thus, traffic would not be allowed to travel beneath construction the next morning if post-tensioning operations were not complete.

AESTHETICS **COMMENTARY**

by Frederick Gottemoeller

The design decisions that were most important in making this bridge beautiful were not made for aesthetic reasons—they were made for engineering or urban impact reasons. Many were made by the owner before design even started. Limiting the width of the substructure to the width of the median, requiring adequate left-turn sight distance at all intersections, and, related to both, requiring that the superstructure be a single box girder with wide overhangs, were all decisions made for the safety and convenience of the users of Gandy Boulevard. Setting the vertical clearance under the bridge at 30 ft, roughly twice the legal minimum, was done to maintain the viability of the Gandy Boulevard businesses. Taken together, these technical decisions produced the bright, open spaces under the bridge that make it so attractive.

The designers responded to the project's challenges with engineering decisions that both met the constructability requirements and improved the bridge's appearance. The finback design solved the constructability challenges and also lengthened the spans, reduced the depth of the girder, and gave travelers on the viaduct visual features to enjoy. Post-tensioning the piers improved the performance of the piers and reduced their thickness and visual mass.

Then there are the decisions that were made for solely aesthetic reasons. The vertical blue stripes on the columns and on the sides of the finback towers and the diagonal blue stripes on the fins themselves divide these massive forms longitudinally and make them appear thinner, as does the blue "racing stripe" on the face of the parapet. The "estuary" motif on the piers and towers works well in this landscaped commercial environment. Overall, these visual features perfectly complement the aesthetic qualities of the structural elements.

So, let's sum it up. Users of Gandy Boulevard can see along and through the structure from all angles. The signs and frontages of adjoining businesses are fully visible. Daylight penetrates across the whole width under the bridge, making the space bright and inviting. The aesthetic motifs complement the structural elements and the neighborhood. There is no dark forest of massive columns here, nor any pigeons lurking overhead in the shadowy spaces between I-girders. Compare the attractiveness and usability of the space under this viaduct to the spaces under any viaduct in your town. Where would you prefer to be?

New Construction Method and Structural System

Constructability was the primary focus of the innovative erection method that was developed for the Selmon West Extension project. Many segments would have to be erected at once, supported redundantly from below, and delivered to the heading from the completed bridge. The long-span structural system would need to be light and efficient while accommodating the new erection method. These challenging and unique requirements are what led the design-build team to create an innovative progressive span-by-span viaduct construction method and complementary extradosed post-tensioned finback structural system (see details of this system in the Concrete Bridge Technology article on page 44).

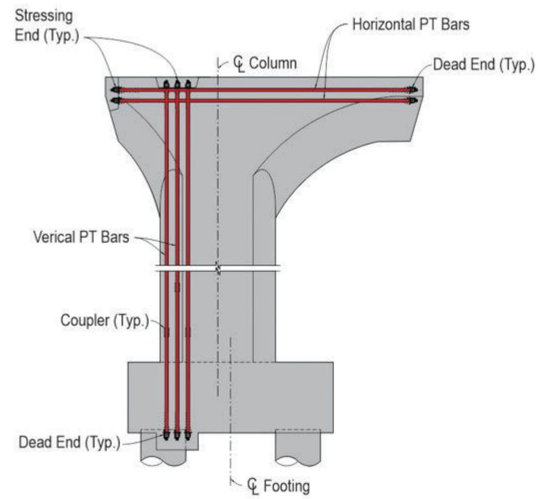
Using the progressive span-by-span scheme, the concrete segments were erected with self-launching underslung erection girders, which are not usually practical with spans longer than 180 ft. The erection girders were supported by three temporary towers in the median and did not load the permanent foundations. To accommodate the longer spans with reasonably sized erection girders, each span was erected in three sections: two 130-ft-long pier sections that were centered over adjacent interior piers, and a drop-in section that was placed to fill the gap between pier sections. For both types of sections, the segments, which were typically 10 ft long, were placed on the erection girders and moved into position. Then, joints were epoxied, temporary post-tensioning was applied, and the closure pours were placed. Finally, continuity post-tensioning tendons were installed, tensioned, and ducts were injected with flexible filler.

The progressive span-by-span erection method allowed segments to be delivered to the construction heading and staged along the recently completed spans without lane closures below. This method also eliminated lane reopening delays because the segments were always redundantly supported by the erection girders, allowing travel lanes below to be reopened before post-tensioning operations were completed. The only operations that could not be completed over traffic were erection girder launching and segment placement, which were completed at night. Erection using the progressive span-by-span method was 50% faster than the conventional balanced-cantilever method would have been for this project. Because the project needed only one construction heading and one set of erection equipment to meet the aggressive schedule, the cost of construction was significantly reduced.

Segment Fabrication and Materials

The property where the precast concrete segmental units were fabricated had been used for precasting operations on previous THEA projects and is located approximately 7 miles away from the jobsite. The fabrication site and the delivery route were selected to accommodate easy transportation to Gandy Boulevard.

Because the viaduct is located within 2500 ft of salt water, its environmental classification is "Extremely Aggressive" as defined by the Florida Department of Transportation's (FDOT's) *Structures Design Guidelines*.[1] This environmental classification dictates the concrete class for each bridge component, which then specifies the mixture proportions and cover requirements for the structure to ensure durability.



Post-tensioning bar layout in cantilever piers. Vertical and horizontal post-tensioned bars were used to avoid tensile stresses in the concrete under permanent loads by using post-tensioning forces to balance permanent loads. Controlled cracking was allowed under transient loading conditions. Figure: AECOM.

Table 1 summarizes the types of concrete used to construct components of the expressway, in accordance with Section 346 of the July 2017 edition of FDOT's *Florida Standard Specifications for Road and Bridge Construction*.[2]

Flexible wax fillers were used for all internal and external tendons per FDOT's *Structures Design Guidelines,* with the exception of the longitudinal cantilever tendons and the transverse tendons in the deck slab, for which cementitious grout was used.

Resiliency

The finback tendons are encased in post-tensioning ducts that deviate through the pier towers and are protected by

Table 1. Specified 28-day compressive strengths for concrete elements based on Section 346 of the Florida Department of Transportation (FDOT) *Standard Specifications for Road and Bridge Construction*[2]

FDOT class	Location in structure	Concrete strength, psi
V (mass)	Precast concrete superstructure, expansion joint segments	8500
V	Segmental box-girder superstructure (precast and cast-in-place concrete)	8500
V	Fin arms, finback tower, and median barrier at fin arms	6500
IV and IV (mass)	Cast-in-place substructure	5500
IV (drilled shafts)	Drilled shafts, ¾-in.-maximum aggregate size	4000
IV (drilled shafts, special)	Drilled shafts, ¾-in.-maximum aggregate size	5000

Tall cantilever piers with complementary aesthetics accommodated superstructure offsets at left-turn lanes and provided open sight lines beneath the structure between the two sides of Gandy Boulevard. Photo: AECOM.

a 30-in.-wide concrete fin encasement that fits within the viaduct median. The fin is integral with the median barrier at the pier and is designed to resist an equivalent static force of 600 kip, in accordance with Article 3.6.5.1, Vehicular Collision Force, in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[3]

Additional redundancy is provided by the finback structural system. Longitudinal load is carried by a combination of the girder and strut-and-tie system comprising the girder, finback arms, and tower, with the latter creating a direct load path up the finback arms and down to the foundation.

Based on its proximity to the Gulf Coast, the bridge was also designed to withstand 150 mph, hurricane-strength wind loads with appropriate gust factors and drag coefficients. To accurately account for the height and thickness of the finback, Figure 7.23 from Eurocode EN1991-1-4:2005[4] was used to determine its drag coefficient.

Use of Post-Tensioning in the Viaduct

Post-tensioning was used in four primary components on the concrete viaduct: cast-in-place cantilever piers (C-piers), precast concrete segmental box-girder longitudinal design, precast concrete box-girder deck transverse design, and cast-in-place concrete extradosed fins that extend above the deck level.

The multistrand longitudinal tendons in the box girder provide strength and a zero-tension design under service loads, as required by FDOT guidelines.[1] The longitudinal tendons used 0.6-in.-diameter strands with 12- to 19-strand internal tendons for the bottom and top slab cantilever tendons, and 23 to 31 strands for the finback and external continuity tendons.

The anchorages for all post-tensioning tendons, with the exception of the cantilever tendons, are located inside the enclosed box-girder section, which provides an additional layer of corrosion protection and makes the tendons easily accessible for tensioning, inspection, and retensioning (if necessary). The transverse post-tensioning allows for a shallow deck with 15-ft-long overhangs and provides strength to the delta frames that anchor the extradosed finback tendons. The extradosed post-tensioning fully prestresses the concrete fin arms and is designed to carry half of the span weight to the finback tower and pier. The post-tensioned finbacks make the progressive span-by-span erection method and the light and shallow superstructure possible. Longitudinal post-tensioning systems for the girder and finback are further described in the companion Concrete Bridge Technology article on page 44.

Partial Prestressed Design for C-Piers

As previously stated, most of the substructure elements located within the 10-ft-wide median of Gandy Boulevard were C-piers used to accommodate superstructure offsets at left-turn lanes. The eccentricity of the superstructure produces significant shear and overturning moment in the pier cantilever and the column, respectively. To avoid tensile stresses in the concrete under permanent loads, vertical and horizontal post-tensioned bars were used so that the post-tensioning forces can balance permanent loads. The prescribed post-tensioning allowed controlled cracking under transient loading conditions. The limiting crack widths required by THEA for the service limit state were more stringent than those specified in the AASHTO LRFD specifications.

Advantages of post-tensioning the C-piers included the following:

- More efficient use of reinforcing steel, less congestion, and improved constructability
- Superior geometry control because the use of post-tensioning limits the deflection and reduces long-term creep deformations and live-load deflections
- Mitigated cracking at service limit state for better corrosion protection of main reinforcing steel and enhanced durability
- Extended service life with less maintenance as a more sustainable solution

Conclusion

The innovative design and construction methods used for the Selmon West Extension enabled the design-build team to construct an elevated facility incorporating complementary aesthetics within a congested urban corridor while limiting the project's impact on the traveling public and local businesses. The completed project benefits both commuters and local residents by improving mobility within the region.

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