PAPER 5

Partial Reconstruction and Lengthening of a Continuous Post-tensioned Concrete Bridge Deck: Case Study of Emergency Rehabilitation of the Seaward Road Bridge

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ABSTRACT

Major modification or partial reconstruction of continuous post-tensioned concrete bridges is rarely undertaken. Instead, these structures are typically demolished and rebuilt in situations where a bridge is damaged or unable to meet new requirements. However, the option of re-using structural elements is much more environmentally sustainable and creates opportunities for large cost-savings and time-savings. This case study demonstrates how, in certain situations, it may be possible for a large, continuous, post-tensioned concrete bridge to be taken apart, modified from the original design and rebuilt.

The Seaward Road Bridge over the Umhlatuzana River underwent a partial collapse during flooding and municipal engineers successfully salvaged the three undamaged spans rather than demolish the entire structure. This required splitting the continuous prestress system at a construction joint between the damaged and undamaged portions of the bridge, then using the original prestress couplers to connect the new replacement spans to the salvaged existing spans. The length of the new portion of bridge was also increased.

This case study demonstrates how modification of existing structures is fraught with risks and technical challenges, some of which may be difficult to anticipate. Major challenges in this particular case included: (1) supporting a structure with an unusually high global instability through extreme and ongoing variations in loading and displacement, (2) demolishing deck spans of a concrete bridge suspended over a sensitive waterway through ongoing flood events, (3) meticulously quarrying out and exposing prestress couplers buried deep in existing reinforced concrete, so they could be safely reused, (4) modifying and testing bespoke prestress coupler components, (5) applying a precisely limited prestress force to the new deck spans, to account for the age-related differences in concrete behaviour, and increase in length, of the reconfigured bridge.

More broadly, the project emphasises how close coordination between the client, technical design team and contractor are critical to effectively managing the complex risks and challenges associated with modification of existing structures. The project provides a particular demonstration of how technical staff employed by the municipality may be best placed to achieve this technical cooperation if competent design, management, and construction supervision capacity is available in-house.

FIGURE 1: The collapsed eastern abutment and end span of the Seaward Road bridge over the Umhlatuzana River

INTRODUCTION

The rehabilitation and upgrading of ageing public infrastructure is an ever increasing part of the work of local authorities all over the world, including in South Africa.

Where structural elements have deteriorated beyond repair, or been damaged, they may need to be replaced. But ideally the replacement of one element in poor condition should not require the replacement of other elements that are still serviceable. Partial reconstruction of infrastructure may offer considerable benefits over full reconstruction. Similarly, where a piece of infrastructure no longer provides sufficient capacity for what is required, it may be possible to modify it to increase its capacity, rather than rebuilding it completely.

In practise, a partial compromise solution is often more technically advanced and complex to implement than wholesale replacement, because there are high levels of risk that must be managed, and unique problems to overcome. And so these projects require more technical and organisational competence to implement. But municipal officials and engineers cannot avoid the increasing prominence of these kinds of projects.

In many cases it may not be clear whether it is possible or practical to modify or repair existing infrastructure, rather than simply replacing it. This paper describes a case study of one such scenario involving a continuous, post-tensioned concrete bridge deck.

LITERATURE REVIEW

A careful review of the published literature makes it clear that both the lengthening and partial reconstruction of continuous bridge decks are distinctly unusual solutions.

Where significant modification of span configurations is undertaken, it invariably involves steel girder bridges (Warren et al. 2014), for which splicing beams together is relatively simple, as is balancing the load capacity of existing spans by attaching additional steel plates to girder flanges. There is also no need to deal with prestress cables in these structures.

When individual spans of a continuous bridge are damaged, the chosen solution is invariably to demolish the entire structure, or to go to whatever lengths may be necessary to repair the damaged members. The heroic rehabilitation of severely damaged bridge decks is a major field of ingenuity and ongoing innovation for suppliers, engineers and contractors, with published case studies showcasing numerous unique problems and

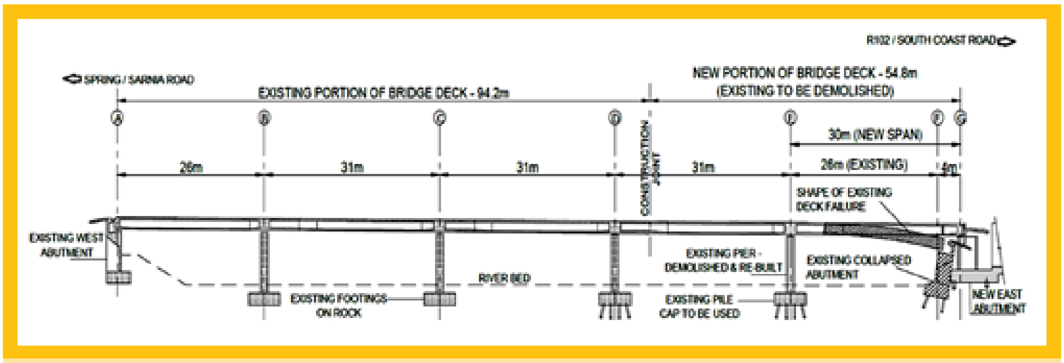

FIGURE 2: Long section through the entire 150m 5-span bridge

solutions. But if repair is not feasible or not possible, then the entire structure is usually demolished. A large research project into rapid bridge replacement techniques was initiated in the United States in response to the September 11 2001 terrorist attacks, and in the 26 case studies that were examined, the continuous decks were all repaired or replaced in their entirety (Bai et al. 2006).

The only other case study that this literature review found to compare with the case study under consideration was the reconstruction of a four-span continuous post-tensioned concrete bridge in Iraq that had two of its four spans damaged in a bomb blast. The demolished spans were replaced in a straightforward way with simply-supported steel plate-girders, but before these could be installed, a very complicated partial demolition had to be undertaken. The demolition was notable for the design and installation of special clamps for securing the prestress cables at an intermediate point between the anchors. These clamps then functioned as new prestress anchors at the location where the continuous prestress cables were cut (Oukaili 2019). It appears to have been a highly risky approach, with no obvious way to verify the clamp connections, and a reliance on a well-grouted cable duct to deal with any failure in the clamps. As such, it clearly demonstrates why significant tampering with continuous post-tensioned concrete bridges is unusual.

There thus appears to be a significant gap in the research regarding options for lengthening or partially reconstructing continuous post-tensioned concrete bridges, which this case study contributes to filling.

BACKGROUND: THE FLOOD AND THE FALL

The Seaward Road Bridge was constructed in 1979 as a five-span, prestressed, post-tensioned single-cell concrete box girder, continuous over a total length of 150m. It supports the only direct access between the Umhlatuzana Industrial Park and major road, rail and sea connections in the direction of the Port of Durban.

The April 2019 floods in the southern regions of Durban claimed at least 85 human lives and caused over R650 million in municipal infrastructure damage, including to the Seaward Road Bridge over the Umhlatuzana River.

The bridge crosses a complex curve in the river, which was originally intended to be canalised. The flooding first eroded the river's eastern embankment immediately upstream of the bridge, redirecting the flow directly at the face of the eastern abutment, where the piles were exposed, and the abutment wingwall dislodged. The saturated abutment fill pushed the precast piles out of position, then sheared them off. Without the piles, the abutment collapsed. The remainder of the deck was not strong enough to perform without the abutment's support, and the deck stresses were transmitted far beyond the end span, straining the prestress and reinforcing steel beyond serviceability and cracking the concrete. The deck was twisted over sideways on its bearings and the end span slumped down (Figure 1).

Fortunately, no persons were harmed in the vicinity during or after the collapse.

Access to the industrial park now required an additional 5km detour over a nearby hill along steep, narrow, winding suburban roads, where trucks had previously been completely forbidden. This was a hazard for both the large trucks carrying shipping containers and heavy machinery, and the local residents, including children walking to school. Congestion from trucks queuing to navigate difficult portions of road could introduce long delays in accessing the industrial park, holding up work and reducing productivity. Political pressure to replace the bridge as soon as possible came from both the residential and industrial areas.

THE PROBLEM: ENGINEERING FREEDOM

A rudimentary environmental impact assessment for the bridge reconstruction was quickly approved as part of a package of emergency flood repairs on the river, and funding was made available through a Municipal Finance Management Act Section 36(1)(a)(i) emergency procurement process with a shortened tender duration. But despite pressure to prioritise speed and reliability above cost-considerations, the project team still felt a responsibility to look at both the human and environmental impacts of their plans. Trying and failing to salvage the remaining deck might waste time. But success would instead save time, and also bring large benefits in terms of sustainability and cost-reduction.

A careful inspection was carried out to map the extent of the strain damage and the original as-built drawings were successfully tracked down. The conclusion was that the excessive strain stopped just short of a point where a cluster of prestressing couplers connected the prestress cables from intermediate construction stages together.

A key advantage was that the prestress cable layout in the bridge deck was extremely simple, with all of the prestress cables terminating in couplers between the construction stages. This is a typical arrangement in the 'span-by-span construction method', where "construction joints with couplers for the tendons are generally placed close to the theoretical point of inflection for dead load to minimize reinforcement requirements in the construction joint" (Seible 1985). Fortunately, the original designers ignored the recommendation that, "a balance between coupled and uncoupled tendons in each construction joint should be provided" (Seible 1985), since all of the prestress tendons were coupled at each construction joint.

In principle, a replacement deck was only needed in two of the bridge's original five spans (Figure 2). The original prestress couplers at the construction joint could be used to connect the new deck to the salvaged deck and share its loads. But first the team would need to dismantle a structure that was specifically designed to only be able to stay up as an integrated structural arrangement, and never supposed to be tampered with once complete.

THE SOLUTION: SEWING A PRE-STRESSED BRIDGE DECK BACK TOGETHER

The existing deck was first completely remodelled and analysed using modern design codes and software. The prestress analysis and design was made complicated by two factors. Firstly, because the original bridge is

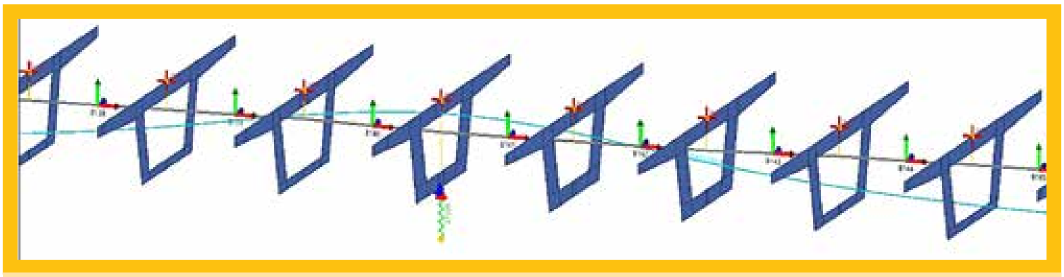

FIGURE 3: Typical extract from RM Bridge FEM Model – the entire bridge had to be modelled due to the increase in jack (end) span length and accurately account for time-related effects on the structure

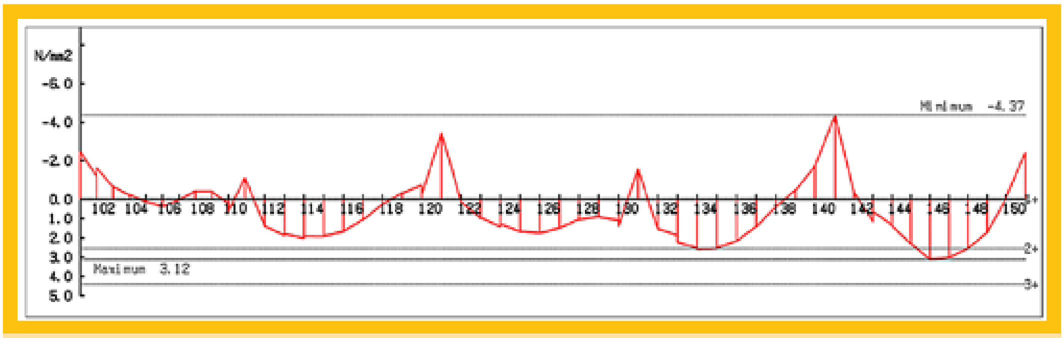

FIGURE 4: Maximum stresses at bottom fibre of structure for NA Loading – the end span showed, stresses slightly above the allowable limits for class 2 and as a result the modifications were designed as a class 3 structure (stresses shown are at full NA loading)

40 years old, its concrete behaves very differently to new concrete when tensioned. Secondly, the bridge had to be lengthened by 4m so the piles for the new abutment would not clash with the original driven piles, which remained in the ground. The increased length changed the loading and stiffness of the end span.

Careful modelling of the various stages of the bridge's construction, lifespan, demolition, reconstruction and future lifespan was done using advanced Bentley RM-Bridge software (Figure 3). The long-term prestress losses in the 40 year old portion of the deck are substantially complete, while the losses would only just be starting for the new portion. The designers needed to be confident that despite the future variability in prestress losses over time, the residual force at the prestress coupler would remain balanced and the connection would not be overstressed, which could have extremely serious consequences. The prestress in the new portion of the bridge is thus 64% of ultimate tensile strength, not 70% as per the as-built design.

It was reassuring that when modern NA and NB36 loadings were applied, it was close to a perfect fit, almost on the limit of the confines of a class 2 prestress structure (Figure 4). The effect of lengthening the bridge was for the end span to move from a class 2 prestress condition to a class 3 partially prestressed condition under full traffic loading, and it was designed with this in mind. The end span is thus still very capable of carrying NA and NB loads as per design codes

CHALLENGES

An unusually unstable old bridge

However, a number of complications were also confirmed, particularly relating to torsional stiffness and global stability. The bridge is completely straight in its horizontal alignment so has no intrinsic stability. The piers cannot help as each has just one bearing, so cannot provide any torsional restraint. The exclusive use of single-column piers gives a pleasingly sleek, minimalistic visual impression. But this means stability is only introduced at the abutments, which each have a pair of bearings. With the east abutment gone, the stability of the entire deck depended on that single additional bearing at the west abutment, 150m away.

Delicate demolition

The collapsed portion of bridge deck needed to be removed without causing the remaining portion to collapse and become unsalvageable or pose a safety risk for workers. Temporary stability was achieved with the urgent installation of ultra-heavy-duty 1 000kN props (Figure 5) on either side of each pier. The props had to be monitored and adjusted throughout the demolition and reconstruction phases, to balance the torsional forces

FIGURE 5: The remainder of the existing structure had negligible stability and needed to be carefully propped until construction was complete

FIGURE 6: Buried coupler being carefully exposed with sharpened chisels and no power tools

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FIGURE 7: Sacrificial props maintained stability until demolition

FIGURE 8: The demolition process was designed to minimise environmental effects

released as the collapsed spans were removed and then replaced. They also had to be able to handle ongoing flooding that occurred during the course of the project.

Once a reliable stabilising system was in place, the deck was cut all the way through with a wire saw at a position 2m away from the ten critical prestress couplers.

The latest South African specifications state that "Water jet removal of concrete is preferred wherever possible" (Committee of Transport Officials 2020). However, on making enquiries it was found that it is still true that "techniques for cutting the concrete and exposing tendons are highly specialised and expensive. Water jetting with a grit additive will cut the prestressing tendons. To avoid damage to the steel, water jetting without an abrasive additive must be specified." (Telford, 1995). Due to high cost and lack of suitable options, couplers were instead carefully exposed by hand, with sharpened chisels to minimise any microcracking (Figure 6). The existing steel reinforcement was also treated with care, so new rebar could be spliced onto it.

Demolition of prestressed, post-tensioned concrete structures carries high risks in all situations, as high stresses are suddenly released or transferred by the severing of cables. Grouted cables may present less risk than unbonded cables, because the stress is distributed through the grout into the surrounding concrete along the length of the deck. However even so, it is still recommended to undertake "debonding trials", since even when bonded, "a tendon is likely to slip on each side of a cut position, causing longitudinal cracks along the line of the ducts until it re-anchors by bond action" (Pritchard, 1995). More critically, the International Federation for Structural Concrete (FIB) emphatically warns in extra-bold text that "During the initial stages of any demolition it must be ascertained that the grouting is effective." (Fédération Internationale Du Béton, 1982)

The FIB guidance was relevant, since when prestress ducts and cables were examined, none had been successfully grouted during the original construction, and the cables could not be treated as homogenous with the surrounding material. Grout had been introduced into the prestress anchors and couplers but had not travelled into the ducts. Fortunately, there was no indication of corrosion in the unbonded strands, and no violent effects were noted when the cables were cut, presumably due to constrictions and contortions of the ducts during the original collapse, which prevented the prestress energy being released.

Rather than push the damaged deck off its support and demolish it on the ground, it was decided to break it up in situ using chemical explosives, simultaneously with its original supports. Despite the latest South African guidelines being that "Demolition by explosive means shall generally not be permitted," (Committee of Transport Officials, 2020), it is still generally accepted that "all structures and heavy bridge decks can be most effectively brought to the ground with explosives" (Pritchard, 1995). Using explosives to demolish the bridge directly over its supports also reduced the environmental impact of having a much larger platform in the river alongside the existing footprint, and reduced the time spent breaking up the material for recycling.

The portion to be demolished was stabilised with lightweight, sacrificial falsework props (Figure 7), which needed to be accurately designed. If the props were too strong, they would be a large, unnecessarily wasteful expense, and might delay the collapse and cause it to happen in an unpredictable, dangerous way. If the props were too weak, the deck could collapse prematurely, in a similarly dangerous, unpredictable way.

With the deck wrapped in geofabric to prevent flying debris, a carefully designed sequence of closely timed blasts created a safe, predictable collapse (Figure 8). The blasts were also designed to ensure that their vibrations would not destabilise the remaining portion of the deck, or affect nearby railway lines.

Customised coupler components

A major setback was discovered when the prestress couplers were exposed: the VSL fittings from 1979 are not compatible with the prestress systems available today. Extensive enquiries were made among South African prestress suppliers, but only one of them, OVM, could supply coupling components for 12.9mm strand. Unfortunately, the swage thickenings supplied by OVM would still not fit into the grooves of the old couplers (Figure 9). The only option was to modify the modern swages to fit and test the results in a laboratory empirically.

Five 500mm long sample strands were tested. A 70mm long swage was crimped onto the end of

FIGURE 9: Comparing the existing couplers with the closest available match on the contemporary market

FIGURE 10: Temporary supports had to withstand repeated flooding

FIGURE 11: The new abutment is unusually heavy and sits behind extensive protection works

each, and then either 10mm or 15mm of the crimped swage was ground off. Loading was applied using a single strand, twin ram stressing jack.

The first tests aimed to apply 85% of the ultimate load capacity of the strand, for a period of several hours. However, because of difficulties with maintaining the tension in the samples, the samples were then also tested to failure. In all cases the swages were unaffected, and the strands snapped at a load of around 195kN. This was about 5% more than their theoretical load capacity of 186kN.

Since the modified swages showed no sign of failure or distress at 195kN, it was concluded that they could safely carry the tendon design force of 119kN/strand.

Furthermore, as has been described, the prestress force was reduced in the new portion of the bridge to balance time-related effects across the new and the old portions. This also reduced the likelihood of the custom-trimmed swages failing. There were nevertheless still risks, because stress flow in concrete around prestress couplers is very complex, and this would be accentuated by the difference in material behaviour between the new and old concrete. In 1980, a comprehensive study of 2431 German bridges found that 66% of German bridges with coupling joints had visible cracks in the region of the coupler (Seible, 1985). But careful monitoring under loading indicates that in this case the connection performs adequately, with none of the visible cracks that Sieble warns against.

Future-proofing

During construction the site suffered significant additional flooding (Figure 10). The irregular bend and susceptibility to flooding of the Umhlatuzana river make it hard to predict its behaviour, and ongoing development upstream will produce stronger flows in the future. To safeguard the City's asset and public safety, an exceptionally robust new abutment and wingwall were designed. A mass abutment with encapsulated fill material provides the stability to withstand high loads and is protected by very long wingwalls. It sits atop a large, monolithic, three-tier pile cap, which required careful design, detailing and construction monitoring to ensure no thermal or shrinkage cracks occurred in the complex arrangement. The 39 piles of 500mm diameter were installed with a specialised 'overburden drilling eccentric' method, otherwise known as an 'Odex pile' or 'Rota-pile'. This uses 'down the hole' percussion impacting to penetrate boulders, and pull down permanent casings, which prevent river scour effects. Extensive gabion protection works were added upstream on the east bank to prevent a reoccurrence of the flood-related erosion of the riverbank that had initiated the collapse of the original abutment.

RESULTS

Environmental Excellence

As discussed, the chosen solution was complex, but left the existing footprint of the bridge in the watercourse unchanged, saved 850m^3 of concrete in the existing bridge, and avoided a larger demolition that would have destroyed nearby trees with nesting birds.

All 620m^3 of demolished reinforced concrete was recycled. The concrete recycling was done on site – it was crushed to a maximum particle size of 75mm and mixed in a 50/50 ratio with excavated material to create G7 material for use in layerworks and abutment fill. Additional environmental measures included adding debris filters to nearby stormwater outlets and clearing all alien vegetation in the site vicinity. A specialist aviologist was appointed to reposition birds' nests adjacent to the collapsed deck, prior to the nesting season.

Close coordination

The unusual nature of the project and its many unknowns required extremely close coordination between all construction stakeholders. The design, project management and contract administration were all done by municipality-employed engineers, who could also take major decisions as representatives of the client and engage with risk management in a knowledgeable way with the experienced contractor, Icon Construction. Despite the emergency conditions, 30% of the contract needed to be given to an emerging community subcontractor, and the absence of typical work stoppages from strikes or business forums demonstrates this arrangement's success. Despite more flooding, and Covid-related delays, the entire project, including design, procurement, and construction, was completed in eighteen months, from May 2019 to September 2020, and within its budget of R36 848 530,00.

CONCLUSION

This case study establishes that partial reconstruction and lengthening of continuous post-tensioned concrete bridges is possible, most particularly in the case where prestress couplers are all clustered together at construction joints. However, it also highlights many of the risks involved in modifying existing structures. In addition to an experienced contractor and skilled design team, this project relied on a lot of good luck – particularly the availability of as-built drawings, the particular arrangement of the original prestress couplers, and the precise limit of the strains in the bridge deck during its collapse. If any of these things had not been in place, the bridge could not have been salvaged so effectively.

Modifying bridges with more complex prestress cable arrangements may be possible but would require additional research into retrofit mechanisms for anchoring prestress cables, such as the clamps described by Oukaili 2019.

RECOMMENDATIONS

The success of the project should inspire structural engineers to attempt similarly substantial restoration or modification of large concrete structures, even when elements are connected together in a unified structural system with prestressing tendons. In particular it establishes that decision-makers should consider modifying the length of continuous multi-span bridges rather than rebuilding them. This may provide opportunities to expand jack spans on other bridges to enable more lanes below or allow ramps for a loop interchange under the jack span. Reconfiguring the spans may be a more sustainable alternative to demolishing and rebuilding bridges where capacity is constrained.

Most importantly, the project demonstrates the value of in-house technical capacity for municipalities in the undertaking of complex projects where time, cost and safety risks need to be dealt with on an ongoing basis through the course of the project. An in-house project team can be particularly agile in dealing with these unpredictable scenarios and taking advantage of fortunate coincidences that may appear. Choosing to manage risk rather than avoid it has the potential to unlock significant benefits in terms of sustainability, and time and cost efficiency, which can have direct benefits for affected communities.

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