IABSE Bulletins

Case Studies

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The Story of the Koror Bridge

International Association for Bridge and Structural Engineering (IABSE)

ISBN 978-3-85748-136-9
DOI: https://doi.org/10.2749/cs001

Publisher:
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Preface

Koror Babeldaob Bridge, also called Koror Babelthuap Bridge or simply Koror Bridge, connects the islands of Koror and Babeldaob in the Republic of Palau. The design of the bridge began in 1974 and was based on the prevailing AASHO Standard Specifications at that time and was supplemented by ACI and CEB-FIP design recommendations on an as-needed basis.

When the Koror Bridge was opened to traffic in April 1977, it was the world's longest concrete girder span. A few years later, the bridge began to deflect more than had been anticipated. The owner commissioned a Japanese engineering firm in 1985 and then a US engineering firm in 1993 to conduct in-depth investigations of the structure. Both firms came to the same conclusion that the bridge was structurally safe and that the excessive deflection was an unexplainable phenomenon. Nevertheless, in order to improve the driving quality of the bridge deck, the owner decided to repair the bridge. The repair scheme made changes to the structural system and added a large amount of post-tensioning force to the bridge. Unfortunately, less than three months after the repair, late in the afternoon on 26 September, 1996, the bridge collapsed. Thereafter, most of the documents were sealed as a result of litigation between the various parties and the debris was cleared. For a long time, it was impossible to study the facts surrounding the bridge's collapse. Only recently, through continuous probing by a group of engineers, were these documents made accessible to researchers.

Engineering is not science. The aim of science is to search for truth. The aim of engineering is to serve human society's needs. Based on what they already know, scientists make discoveries about nature that are pre-existing. Based on an accumulation of experience, engineers improve the built environment of human beings. Experience is never complete, but engineers obviously cannot wait for scientific discoveries of all the necessary truths they need to design and build. At the time of the construction of the Great Wall of China, the Pyramids of ancient Egypt and many other great structures, the laws of gravity had not yet been discovered and an understanding of the physical properties of building materials did not yet exist. Engineers must design and build based on their present-day experience. This was the case 2000 years ago. And so this is the case today!

The foundation of engineering is what we learn from past experience; this includes both successful and unsuccessful experiences. Learning from our mistakes is especially useful, as it can teach us what can be done and what cannot be done. But, for the past to be useful, we must present the facts carefully and honestly. This is the reason why I have written this book.

Man-Chung Tang

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A Brief History

Republic of Palau

The Koror Bridge, also called Koror Babelthuap Bridge, or Koror Babeldaob Bridge, or Palau Bridge (see *Fig. 1*), is located in the Republic of Palau, a country that consists of about 300 islands in the South Pacific Ocean, and is a part of the Caroline Island group. In 1899, Spain sold these islands to Germany. In 1914, the Germans ceded them to Japan. During the Second World War, there were several severe battles between the US and the Japanese armies on these islands that led to the death of over 12,000 soldiers. After the war, the United Nations trusted these islands to the US in 1947 as the US Trust Territory of Pacific Islands. In 1979, the entire Caroline Island group declared independence from the US. Palau did not join them and established the Republic of Palau in 1981.

When the islands were under US trusteeship, the US navy had a military base there. The construction of the Koror Bridge was, in part, financed by the US government.

Fig. 1: Koror Babeldaob Bridge

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The Original Design

Design Concept

Selection of the type of structural system for the Koror Bridge was based on local conditions. Palau is a remote island whose closest neighbour is the Philippines—at least 800 km away. Both communication and transportation were difficult at that time. Most construction materials had to be imported. The population was small, and there was not much infrastructure in the area. Under such conditions, it would have been difficult to expect the owner to implement a high-quality maintenance program for the bridge. In addition, the area is very humid and the air is salty. Therefore, the selection of a prestressed concrete bridge for the original design was a reasonable and logical choice. These conditions were considered and subsequently applied to the redesign as well.

Several alternative structural systems were studied during the preliminary design stage. The three final options were:

1. A continuous girder on four piers with sliding bearings at all of the piers, except at one of the main piers, where the girder was restrained in the longitudinal direction;
2. A bridge girder monolithically fixed with the main piers and sliding bearings at the side piers, plus a sliding hinge at mid-span to allow relative longitudinal movements;
3. Same as Option 2 except that the concrete hinge was used at the main piers to reduce possible bending of the foundation.

Owing to the bridge location any metal component such as bearings could be subject to severe corrosion. And, even with a 790 ft (240.79 m) span, the two main piers were still very close in proximity to the salt water which would have regularly splashed the bridge and its main piers. Therefore, any moveable bearing at these locations was not an appropriate solution. Besides, these bearings would have been very large and difficult to fabricate in the 1970s. Consequently, among the three options described above, Option 1 was deemed not acceptable.

Option 3 was not selected for two reasons. First, for such a long span, the concrete hinges would have been exceptionally large and difficult to build and, secondly, a concrete hinge would only work after the covering concrete had cracked, which would also be unacceptable due to possible corrosion, given the environment. Thus, Option 2 was selected. The bridge girder was

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Construction

The bridge was supported by 16 inch × 16 inch (410 mm × 410 mm) precast concrete piles about 100 ft (33 m) long each; there were 104 piles under each main pier and 21 piles under each end pier, totaling 250 piles. The piles under the main piers were all battered at a 1:8 angle—with half toward the water and the other half toward the shore. The design capacity (service condition) of each pile was 400 kips (1.82 MN). There were 40 rejected piles which were left in place and the replacement piles were driven next to them. Due to time constraints, 15 of the replacement piles were steel H piles, H350 × 350 × 19 × 19, which has about the same design capacity as the original precast piles. The total capacity of the pile group was not affected.

Two test piles were loaded to about 800 kips (3.6 MN) and, each had performed well up to that load.

Except for stones and sand, all other construction materials and equipment had to be imported because the bridge is located in a remote area. Therefore, saving construction materials and avoiding the use of heavy equipment was important. The most expensive construction equipment for the bridge was the form travelers. There was no steel fabricator in Palau so the form travelers had to be imported, making them even more expensive (see *Fig. 11*).

The construction of the superstructure began in May 1976 at the Koror side. The pier-table, which was the first segment on top of the main pier, was 37 ft (11.28 m) long, 19 ft (5.79 m) towards the water and 18 ft (5.49 m) towards the land. The subsequent cantilever segments were all 15 ft (4.57 m) long except the first was 14 ft (4.27 m) long and, the second last segment was 13 ft (3.96 m) long plus a 4 ft (1.22 m) long segment with a hinge and diaphragm.

In segmental cantilever construction, it is customary to build the two cantilevers, one on each side of a pier, simultaneously in an approximately balanced manner; so two form travelers were required for this pair of cantilevers. To save on the number of form travelers, the original design was based on using two form travelers. Thus, one half of the bridge was designed to be built first and then the same form travelers were to be used to build the other half of the bridge, as shown in *Fig. 12*. However, after inspecting the site conditions, the construction sequence was modified to build both sides simultaneously to shorten the construction schedule. In the side span area, the bridge girder was very close to the ground. The contractor first filled the area with dead corals dredged from the ocean and used relatively simple falsework on top of the fill to build the side

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Bridge Performance

The Koror Bridge was a long-span concrete bridge; the design live load was relatively minor compared to its dead load. Once the bridge was completed, bending moment due to live load was only about 8% of the bending moment due to total load (*Fig. 18*). It did not cause much of a stress variation in the bridge.

The elastic deflection at the span centre under total permanent load after 10% prestress loss was 370 mm. When this is multiplied by the creep coefficient of 1.30, this resulted in a creep deflection of 481 mm after completion of the bridge. *Figure 19* shows the time function of creep progress according to CEB-FIP 1970. It demonstrated that most creep deformation should have been completed around 1000 days after load application, and the progression of creep should be as shown in *Fig. 10*. However the reality is quite different from the calculation.

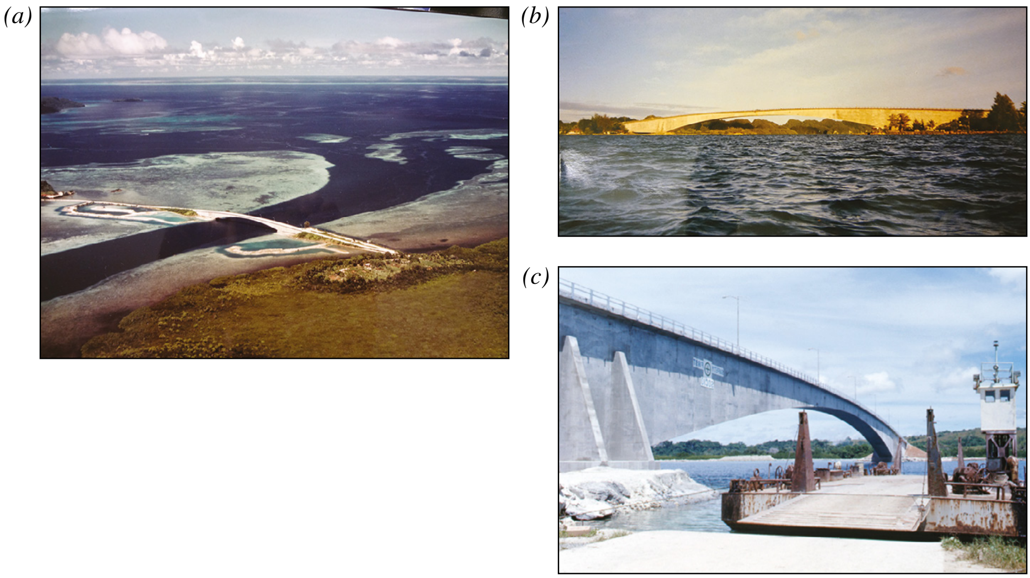

Fig. 18: Koror Bridge and its surrounding landscape: (a) The completed Bridge; (b) Bridge May 1986; (c) Bridge and the Ferry it replaced

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The Repair

Repair Scheme

VSL, a prestressing material supplier, through a general contractor, Black Micro Construction Co., proposed an alternative repair scheme [18], for a lower price and was accepted by the owner. *Figure 24* shows the shape of the bridge before the repair. This scheme significantly changed the bridge structure in three ways:

1. At the centre hinge, jacks were used to push the two cantilevers against each other at the top slab level in several steps. Four 1000 t jacks introduced a large longitudinal force into the structure (*Fig. 25a*). The repair design plans specified the force to be 4400 kips (18 MN) if the foundation was stiff and 6000 kips (27 MN) if the foundation was soft. Site records are presently not available, but the soil was quite soft, and it appears most likely that a 6000

Fig. 24: Condition of bridge before repair (1996)

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The Collapse

The actual repair work began in April 1996 and was completed in July 1996. Less than three months after the repair, on 26 September 1996 around 5:35pm, on a relatively calm afternoon, the bridge collapsed, and a portion of the bridge fell into the water.

Witnesses described that before the collapse, there were sounds of concrete cracking and steel rubbing against each other for about 30 minutes, then the top deck of the girder near the Babeldaob main pier suddenly crumbled and separated from the webs while the end spans on the Koror side rose and fell back down, and finally, the bridge span fell into the water.

The Koror Bridge was the world's longest span at the time, so many engineers were interested in the cause of its collapse. Several hypotheses were presented in various articles [19–23], but none of them could satisfactorily pinpoint the reason for the failure. The task of understanding what went wrong was further hindered by the sealing of almost all documents due to settlements from various litigations. It was not until 2009, through the effort of a group of engineers, that the documents were unsealed and made accessible to researchers. Unfortunately, too much time had passed and specific evidence from the site had been removed. So, further testing was no longer possible.

Forensic Observations

Figures 26 to *33* show the condition of the bridge after the collapse. Several clues tell the story of the bridge's failure [19]:

1. The deck of the Babeldaob cantilever showed signs of crushing, due to either buckling or crushing of the concrete deck. The triangular cracking pattern in the deck is typical of concrete plate failure under high compression. The deck was also separated from the webs at several locations.
2. The bottom slab of the Babeldaob cantilever near the main pier had become crushed and dislocated downward—a sign of failure due to shear and compression. The webs between segment 0 and segment 1 were partially dislocated and the two sides pushed past each other (i.e., overlapping).

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Why Was The Deflection of The Bridge So Much Larger Than Anticipated?

Calculation of Creep and Shrinkage

To date, several hundred long-span prestressed concrete bridges have been built worldwide. While there has been extensive research conducted on creep and shrinkage of concrete bridges, it is still difficult to correctly predict their plastic deformation. The problem is that we have various calculation models from different specifications and codes that do not match each other, as indicated by Robertson [24] and others. Even the more popular CEB-FIP Model Code has been revised several times, and each time the revision results in different numerical values in creep and shrinkage predictions. This poses an on-going dilemma for practicing engineers.

Fortunately, inaccuracies in estimating creep and shrinkage deformation do not affect the safety of structures. It is basically a geometry problem, but the unpredictable deformation does create psychological and traffic disturbances. It is also not easy to fix!

The design of the Koror Bridge began in 1974, or about 40 years ago. Since then, the industry has extensively researched creep and shrinkage of concrete bridges. If we had designed the Koror Bridge according to the current specifications, what would we have been done differently?

Current AASHTO/LRFD Model

The creep coefficient according to the current AASHTO/LRFD model is

$\phi = 3.5\, k_f\, k_{hc}\, k_{ld}\, k_c\, k_{td}$

where

k_f considers the concrete strength,

$k_f = 1/(0.67 + fc'/9) = 0.816$ for $f'c = 5.0$ ksi

k_{hc} considers the relative humidity,

$k_{hc} = 1.58 - RH/120 = 0.90$ for RH = 82%

k_c considers the thickness of the concrete member,

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Other Failure Hypotheses

Many people shared their opinion on why and how they believed the Koror Bridge collapsed, other than what we described in this book. We have investigated most of these theories and found them to be incomplete. Following are several of them:

1. *Shear failure of the webs*: Because the webs of the box-girder at the Babeldaob side crashed, some engineers believed that the failure was instigated by shear failure of the webs. If the bridge was designed based on today's British Code, Chinese Code or German Code, the webs would likely have been thicker. However, pictures of the bridge after the failure showed that the webs on the two sides of the failure plane had actually crushed against each other, which indicated that the webs had failed under compression, not shear. Shear failure would have shown a completely different picture (see *Fig. 29*).

   Even though the centre span of the Koror Bridge was large, overall the bridge was very narrow. It was designed to carry only two traffic lanes and one pedestrian path. The actual shear force and shear stress in the webs of the Koror Bridge were relatively low. The possibility of a shear failure was rather remote.
2. *Preparation of construction joints:* There were no shear keys at the vertical interface of the construction joint of the Koror Bridge. The bulkhead surface at the joint was cleaned before casting of the subsequent segment took place. The necessity of shear keys at the construction joints of a cast-in-place, prestressed concrete segmental bridge is still debatable. However, if a failure did occur due to the lack of shear capacity of the webs at the construction joint, the failure surface should have shown a vertical slippage at the joint. We have not observed any joint slippage in the Koror Bridge before or after the collapse. Thus we can conclude that the preparation of the construction joint could not have contributed to the failure of the bridge.
3. *Damage of the deck plate during repair of the pavement*: There was a suggestion that the failure was instigated due to damage of the deck plate during repair and resurfacing of the deck. Originally, the bridge had a concrete overlay which cracked extensively after 18 years of service. It was replaced by an asphalt blacktop as part of the repair. During the removal of the original overlay the deck concrete might have been damaged. We have no record of those possible damages. However, if these damages were the *main* cause of failure, the bridge should have collapsed right at the time the damages took place, not two months later.

11 Discussions

Purpose of This Book

The purpose of this book is to present the facts about the Koror Bridge from a practicing engineer's point of view. That is, to explain how the bridge was designed, how it was built and what happened after it collapsed. It also tries to theorize any differences in outcome were we to design this same bridge today according to the current codes and specifications.

This book is not meant to be a forensic research report, but rather, a way to help future researchers in understanding the possible causes of the collapse of the Koror Bridge. It may be long before we can fully comprehend what happened. Presenting what we know now may encourage researchers to take steps to finally solve this intriguing riddle.

The Koror Bridge Was Structurally Safe

For 19 years, from its completion in 1977 to its collapse in 1996, and before the repair, there were no safety issues on the Koror Bridge. The structural safety of the bridge had never been called into question. The two consulting firms, JICA and ABAM, commissioned by the owner to investigate the bridge had both come to the conclusion that the bridge was structurally safe. Our calculations in previous chapters also indicated the safety factor of the bridge under ultimate capacity was higher than required.

Therefore, we can conclude that the bridge would have had no problem if the long-term deflection had not been excessive. There would have been no need for any repair and consequently no reason for the bridge to collapse. Therefore, making sure that future bridges do not have unacceptable excessive deflection is of utmost importance. Unfortunately, it appears that none of the current relevant codes and specifications, ACI, AASHTO and CEB-FIP (now *fib)*, could have predicted the large deflection of the Koror Bridge, even if we were to design the bridge again today.

Long-Term Deflection

The main issue therefore is certainly the long-term deflection. There are various hypotheses of relaxation, shrinkage and creep besides those that the codes would indicate. Unfortunately, each

Summary

It appears that the only conclusion we can make based on the analysis we have done up to now is that, none of the codes and specifications, ACI, AASHTO or CEB-FIP, can predict the large long-term deflection of the Koror Bridge. The problem is the same today as it was in 1974, when the Koror Bridge was designed.

The main culprit seems to be the prestress loss, which was much higher than these specifications had predicted. On the other hand, no engineer, even today, would accept a prestress loss of 50% as rational. But this was the result of actual tests. The prestress loss is affected mainly by the long-term creep and shrinkage of the surrounding concrete, so we will have to be able to estimate the creep and shrinkage of concrete more accurately before we can better estimate the prestress loss. Further research into this problem is recommended.

Based on what happened in the Koror Bridge, we may offer a few suggestions for engineers to consider in the design or repair of long-span prestressed concrete bridges:

1. *Increase the amount of prestress:* Increasing prestressing can have two beneficial effects: firstly, it will reduce the elastic deflection, and consequently, the long-term creep deflection no matter what the creep coefficient may be; and secondly, it reduces the possibility of high-tensile stress caused by uncertainty in the estimation of prestress loss. In most cases, the cost of additional prestressing is not significant when compared to the overall cost of the bridge. However, note that excessive prestressing is also not advisable because this may cause congestion and a higher compressive stress and thus higher creep deformation, which, in turn, also increases prestress loss.
2. *Use higher-strength steel for the tendons:* Because almost all new bridges are using seven wire strands for post-tensioning nowadays, this suggestion may not be relevant. Still, it may be useful to keep in mind as an option. As indicated in the last chapter, the percentage of prestress loss for a higher-strength tendon is lower.
3. *Provide an additional camber to the bridge:* In addition to the theoretically calculated value, providing an additional upward camber is more visually appealing. A bridge that bends upward looks better than a bridge that droops downwards.
4. *Consider the use of a 3D model:* If the geometry of the girder is more extraordinary, for example, for exceptionally deep or wide box-cross sections, supplement the 2D analysis with a 3D analysis may offer a clearer picture of the actual stress distribution in the structure.

5. *Assure the applicability of the existing structural details:* When we perform a repair of an existing bridge, we are usually changing the stress in the structure. Therefore, we must carefully review the original details to understand whether they are suitable for the modified stress conditions. It would be most ideal to redesign the bridge and compare the new design to the old design to identify discrepancies or issues.
6. *Consider the history of the original bridge:* A repair design must carefully consider the history of the existing structure. Obviously, any bridge would only require repair if it has been distressed in some way. It is highly likely that part or all of the bridge was weakened before the repair.

Acknowledgement

The writer would like to thank Alfred Yee, Khaled Shawwaf, Ray Zelinski, Zdenek Bazant, Qiang Yu, John Lee, and Chuck Seim for their valuable discussions. Thanks to Delan Yin, Lionel Bellevue, Yu Deng and Yue Li for their help in the numerical analysis and preparation of the sketches, and thanks to Pam Ching for her effort in reading and editing the manuscript.

Following are the participants in the design and construction of the original bridge:

Owner
Trust Territory of the Pacific Islands, Saipan, Mariana Islands, Micronesia
Koichi Wong, Director of Public Works and Contracting Officer
Bill Burmeister, Chief Inspector

Engineer of Record
Alfred A. Yee & Associates, Honolulu, HI, USA
Alfred A. Yee, President
Fred Masuda, Chief Design Engineer
Ray Zelinski, Project Resident Engineer

Contractor
Socio Construction Company, Seoul, South Korea
B. W. Chung, President
J. D. Lee, Project Manager
B. Y. Chung, Site Engineer

Designer and Field Engineers
Dyckerhoff&Widmann, New York, NY, USA
Man-Chung Tang, Vice President & Chief Engineer
Khaled Shawwaf, Project Manager, Design
Don Ward, Western Region Chief Construction Manager
Simeon Crosier, Construction Project Engineer

The above list of individuals does not include those involved with condition surveys, inspection, repair design and repair execution.

Units

The bridge was designed using the US system of measurements.

Readers who are not familiar with these units can use the conversion table below:

1 ft = 1 ft = 0.3048 m

1 ft = 12” = 12 inches

Example: 5 ft 6” = 5 feet 6 inches

1 kip = 1000 US pounds = 4.4482 kN

1 US ton = 2 kips = 2000 US pounds

1 ksi = 1 kip per square inch = 144 ksf = 6.897 MPa

1 ksf = 1 kip per square foot = 0.0479 MPa

1 MPa = 0.145 ksi = 20.88 ksf

1 MN= 1000 kN = 224.809 kips

1 m = 3.2808 ft

1 MNm = 737.55 kip-ft

1 cubic meter = 35.315 cubic feet

1 kip per cubic foot = 157.09 kN per cubic meter

References

[1] Yee, A.A. Record span box girder bridge connects Pacific Islands. *Concrete International* 1979; **1**(6): 22–25.
[2] Private correspondence with Alfred Yee, 2011, 2012.
[3] Private correspondence with Ray Zelinski, 2011, 2012.
[4] Private correspondence with John Li, 2012.
[5] Engineering News Records. *Deep, fast water spawns record span*, New York, July 14 1977.
[6] American Association of State and Transportation Engineers. *LRFD Bridge Design Specifications*, Washington, D.C., 1998.
[7] American Concrete Institute Committee 209. *Prediction of creep, shrinkage and temperature effects in concrete structures*. reported by Subcommittee II, Report No. ACI209R-82, ACI Publication SP-76, 1982 and subsequent revisions.
[8] CEB-FIP. *International Recommendations for the design and construction of concrete structures*, Paris/London, 1970, 1978 and 1990.
[9] Tang, M.C. Koror-Babelthuap Bridge – a world record span. *International Conference of Large Structures, Proceedings, ASCE Annual Convention and Exposition*, Chicago, IL, October 1978.
[10] Tang, M.C. Shear design of large box girders. *ACI Symposium*, SP 42–14, 1973.
[11] *Design drawings by Dyckerhoff and Widmann, Inc. for construction of the Koror Babelthuap Bridge*, July 1975.
[12] Leonhardt, F. Spannbetonfuer die Praxis, 3rd edn. Wilhelm Ernst & Sohn: Berlin, Germany; 1973.
[13] *Koror Bridge Project Diary by Ray Zelinski*.
[14] Japanese International Cooperation Agency. *Present Condition Assessment of the Koror-Babelthuap Bridge*, February 1990.
[15] ABAM Engineers Inc. *Basis for Design, Koror-Babeldaob Bridge Repairs, Bridge Condition and Survey Report*, 1993.
[16] Berger/ABAM Engineers, Inc. *Koror-Babeldaob Bridge Modifications and Repairs, 100% Submittal Design Drawings*, October 1995.
[17] Louis Berger International Inc. *Evaluating Quality Defects of Specific Projects, Report to the Department of Interior,* 1988.
[18] Pacific Sunday News. *Palau Bridge Story*, Guam, October 1996.

[19] SSFM Engineers, Inc. *Preliminary assessment of Koror Babelthuap Bridge Failure for the United States Army Corps of Engineers*, Honolulu, HI, 21 October 1996.

[20] Pilz, M. The Koror-Babeldaob Bridge in the Republic of Palau, History and Time Dependent Stress and Deflection Analysis. Dissertation, Imperial College, Department of Civil Engineering: London, June 1997.

[21] Tang, M.C. The collapse of the koror Bridge. *Proceedings, FIB Congress, Osaka, Japan*, October 2002.

[22] McDonald, B., Saraf, V., Ross, B. A spectacular collapse: the Koror Babeldaob (Palau) balanced cantilever prestressed post-tensioned bridge. *Proceedings of the 27th Conference on Our World in Concrete & Structures, Singapore*, August, 2002.

[23] Burgoyne, C., Scantlebury, R. Why did Palau bridge collapse? *The Structural Engineer* 2006; **6**: 30–36.

[24] Robertson, I.N. Correlation of creep and shrinkage models with field observations. *The Adam Neville Symposium, American Concrete Institute Special Publication SP-194*, 2000.

[25] Bazant, Z.P., Hubler, M.H., Yu, Q. Excessive creep deflection – an awakening. *Concrete International* 2011; **33**(8): 44.

[26] Bazant, Z.P., Huber, M.J., Yu, Q. Pervasiveness of excessive segmental bridge deflections: wake-up call for creep. *ACI Structural Journal* 2011; **108**(6): 766–774.

[27] Bazant, Z.P., Yu, Q., Li, G.H. Excessive long-time deflection of prestressed box girder. I: Record-span bridge in Palau and other paradigms. *ASCE Journal of Structural Engineering* 2012; **138**(6): 676–686.

[28] Private correspondence with Qiang Yu, 2012.

[29] Private correspondence with Khaled Shawwaf, 2011, 2012.

[30] PCI. Prestressed Concrete Bridge Design Handbook. Prestressed / Precast Concrete Institute: Chicago; 1998.

[31] fib, *Model Code 2010, Final draft, fib Bulletin 65*, The International Federation for Structural Concrete, Paris/London, 2014.

[32] Bazant, Z.P., Yu, Q., Li, G.H., Klein, G.J., Kristek, V. Excessive deflections of record–span prestressed box girdeer. *Concrete International* 2010; **32**(6): 44–52.

[33] Bazant, Z.P., Yu, Q., Li, G.H. Excessive long-time deflection of prestressed box girder. II: Numerical analysis and lessons learned. *ASCE Journal of Structural Engineering* 2012; **138**(6): 687–696.

[34] Yu, Q., Bazant, Z.P., Wendner, R. Improved algorithm for efficient and realistic creep analysis of large creep-sensitivie concrete structures. *ACI Structural Journal* 2012; **109**(5): 665–675.

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The Story of the Koror Bridge

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