PROJECT HIGHLIGHTS

Objectives

Why did an International Contractor building the 840m signature Sheikh Zayed Bridge in the Middle East go to the opposite side of the world to have its construction engineering performed by a Canadian engineering firm?

Answer: the Contractor's Objective was to ensure the highest quality of construction engineering available because the bridge was so complex.

Specifically, the detailed objectives of the Contractor, Archirodon, were to obtain a step by step analysis of every stage of construction as the bridge was built, including the placement of steel or concrete, prestressing sequences, and the effects of creep and shrinkage. Recommended sequencing of pouring concrete, stressing tendons and releasing formwork so that nothing would be overstressed at any time was also requested.

Buckland & Taylor Ltd. also was to perform a full check of the design of 12,000 tonnes of structural steel temporary works designed by the Contractor, as well as complete the calculation of formwork geometry, allowing for the sequence of construction, elastic shortening, creep, shrinkage and temporary works flexibility, so that when the bridge was completed it would have exactly the right geometry and right stress condition.

Buckland & Taylor Ltd. was also required to provide recommendations for heat control measures for mass concrete poured in temperatures up to 50^{o}C as well as perform an unofficial check of the design of the completed bridge.

Technical Excellence & Innovation

The advanced engineering approach comprised a huge computer model, rapid exchange of information (usually overnight), and treating human relationships as a priority.

The extensive falsework, including the 60 m high towers that were used to position the 600 t arch segments, the welding of 90 mm thick plate in 30 to 50^{o}C temperatures, the use of thermocouples and insulation for the mass concrete pours were all innovative.

Challenges and Solutions

Complexity of Project

The most striking features of the bridge are its arch-like structures that rise above the roadway decks in the centre of the bridge for two spans, and dive under the bridge and come up on the outsides for a third span. These “arches” are really bent box girders in a non-vertical plane, fixed at their ends with little or no allowance for adjustment during erection. Consequently any applied load causes bending in all directions and torsion and compression or tension. Above deck they are steel boxes about 4m wide and 5m deep (the height of a two-storey building) with plate thicknesses up to 90mm, and below deck they are of prestressed concrete.

When wet concrete is poured, it is supported partly by temporary structures which are flexible, and partly by concrete that has already hardened. This results in differential deflections that require compensation during construction.

Problems and Difficulties to be Overcome

In addition to the complexities of the structure and its changes of shape as it is constructed, there was the issue of the massive concrete pours in the foundations of up to 3,000 m^3 at a time. As concrete cures, it generates heat, which will cause cracking of the concrete if it gets too hot, or if it does not all cool at the same rate.

A very real problem was the possibility that because the unusual bridge shape was so difficult to analyze, Buckland & Taylor's calculations might not agree with those of the Owner's Engineer (High-Point Rendel of the UK) resulting in the Contractor's methods not being approved.

Finally, Abu Dhabi is 12 hours ahead of Vancouver, and their "weekend" is Friday, so there was no overlap of working hours and only four common working days.

Solutions to Meet Objectives

Once Buckland & Taylor Ltd.'s ADINA computer model was built, checked and de-bugged, approximately 300 steps of construction were modeled to simulate construction of the bridge. Typically it took about ten iterations before the Contractor's erection scheme was balanced for all 300 steps. For various reasons, the proposed erection scheme was changed and the model and the step-by-step analysis would start all over again. This happened five times!

Buckland & Taylor Ltd. was responsible for revising rebar details and post-tensioning profiles from those in the design drawings, to keep stresses within limits at all times.

Instead of using conventional cooling methods for the temperature control for the concrete pouring, specialist sub-consultant Levelton recommended thermocouples in the fresh concrete, and insulation. By reading the thermocouples, stresses induced by differential temperatures can be calculated, and compared with the concrete strength at the same moment, which indicates when it is safe to remove the insulation.

Achievements

Outstanding Engineering Achievements

The bridge was built to a high standard, with the correct geometry and the correct loads in the cable hangers. The mass concrete pours were completed with no detrimental cracking.

Approximately 400 changes were made to the permanent design to suit the erection and when complete, the bridge flawlessly passed a load test of double normal design loads.

Not only was a bridge built, but professional and cordial relations between all parties concerned were maintained.

Buckland & Taylor Ltd. was able to provide a rapid turn around of all services required by having a dedicated team who treated this job as its instant priority, typically providing overnight responses to queries, so the Contractor would receive his answers in the morning.

Role of Project Management

Project Management was key in regards to relationships between parties; keeping track of all correspondence; ensuring that all the technical work was performed on time, independently checked, and accurately communicated; and keeping up morale for a team that embarked on a 7 month task, that became one of 7 years.

FULL PROJECT DESCRIPTION

Project Description

The Sheikh Zayed Bridge, located in Abu Dhabi, UAE is a twin deck bridge comprising prestressed concrete box girders supported by bearings on concrete piers and by hangers on a pair of 3D steel "arches". The total length of the bridge is 842 m (2762 ft.) and the main span is approximately 140 m (459 ft.). The steel arches are connected to the concrete piers to transfer their loads to the foundation.

The bridge arches were designed to resemble sand dunes to fit with the surroundings. This resulted in unusually shaped piers and arches. The deck consists of a multi-cell post-tensioned concrete box girder, which has a constant depth for the entire length of the bridge. Two of the three arches support the deck with hangers while the deck is supported by corbels on the third arch. The bearing and hanger locations are different from span to span and they affect the behaviour of the bridge significantly.

New Application of Existing Techniques/Originality/Innovation

Breakthrough in Technology or Science

The Sheikh Zayed Bridge represents an advanced engineering approach comprising a huge computer model, extreme care in its use, rapid exchange of information (usually overnight), and treating human relationships as a priority.

Unique Mix of Different Techniques, Materials or Equipment

The extensive falsework, including the 60 m high towers that were used to position the 600 t arch segments, the welding of 90 mm thick plate in 30 to 50°C temperatures, the use of thermocouples and insulation for the mass concrete pours were all innovative.

Advanced the State of the Engineer’s Art and Skills

The project advanced the state of the engineer’s art and skills with the following outstanding engineering achievements:

- Despite having been labeled as the "almost unbuildable" bridge, it was in fact completed to a high standard, with the correct geometry and the correct distribution of stresses.
- The computer program accurately predicted the step-by-step and long term geometry changes.
- The mass concrete pours were completed with no detrimental cracking.
- Professional and cordial relations between the parties concerned were maintained through all the inevitable frustrations.
- The complex falsework safely supported the 11,000 tonnes of structural steel, 4,500 t of prestressing steel, 36,000 t of reinforcing steel and 250,000 m3 of concrete.
- Approximately 400 changes were made to the permanent design to suit the erection.

When complete, the bridge flawlessly passed a load test of double normal design loads.

Project Management skill was key, in terms of (a) relationships between parties, (b) keeping track of all correspondence, some 2,000 emails each way, and the status of follow-up, (c) ensuring that all the technical work was performed on time, independently checked, and accurately communicated, and (d) keeping up morale for a team that embarked on a 7 month task, and was still revising it at the Contractor's request 7 years later.

The project could not have been completed without making use of Buckland & Taylor's in-house team of 60 specialized bridge engineers, who between them have a massive accumulation of expertise and experience.

Complexity

Complex Criteria and Types of Problems

The most striking features of the bridge are its arch-like structures that rise above the roadway decks in the centre of the bridge for two spans, and dive under the bridge and come up on the outsides for a third span. These “arches” do not behave like arches: they are bent box girders in a non-vertical plane, fixed at their ends with little or no allowance for adjustment during erection. Consequently any applied load causes bending in all directions and torsion and compression or tension. Above deck they are steel boxes about 4m wide and 5m deep (the height of a two-storey building) with plate thicknesses up to 90mm, and below deck they are of prestressed concrete.

When wet concrete is poured, it is supported partly by temporary structures which are flexible, and partly by concrete that has already hardened. This results in differential deflections that require compensation during construction.

Extraordinary Problems of Site, Location, Hazardous Conditions

In addition to the complexities of the structure and its changes of shape as it is constructed, there was the issue of the massive concrete pours in the foundations of up to 3,000 m3 at a time. As concrete cures, it generates heat, which will cause cracking of the concrete if it gets too hot, or if it does not all cool at the same rate.

A very real problem was the possibility that because it was so difficult to analyze, Buckland & Taylor's calculations might not agree with those of the Owner's Engineer (High-Point Rendel of the UK) resulting in the Contractor's methods not being approved.

Finally, Abu Dhabi is 12 hours ahead of Vancouver, and their "weekend" is Friday, so there was no overlap of working hours and only four common working days.

Environmental Impact

Environmental Benefits

The bridge is intended to be a signature structure, and to last for many years. To this end, great care was taken to provide the maximum durability, such as providing high quality concrete, providing good cover to the reinforcing steel, and even by painting the concrete.

The task of Buckland & Taylor and sub-consultant Levelton was to provide to the contractor Archirodon a system of erection that minimized the use of consumables and the impact on the surrounding environment.

Archirodon spent much time on finding the most efficient methods of constructing the bridge. The temporary works (falsework) were designed to be re-used at as many locations as possible. The tower structures were designed to be relocated from one span to another with minimal modification. The giant steel boxes were entirely welded from the outside to avoid creating noxious fumes in the closed interiors.

Promotion of Sustainability

Longevity was produced by the use of stainless reinforcing steel, high performance concrete, and particular care in ensuring that the bridge was built so that there would be no weakness in the concrete, caused by either deflections or long term effects, that would allow water to ingress and corrosion to attack the deeper non-stainless reinforcement and prestressing.

Social and Economic Benefits

Social and Economic Benefits

The project demonstrated the benefits of obtaining consulting engineering from the most qualified firm, rather than the most local or least expensive. This raises the reputation of all engineers, and the Client was well satisfied.

Additional Benefits Realized as a Spin-Off

This is such an unusual bridge that it has received considerable coverage in the technical press, and the difficulty of constructing it has been emphasized. This publicity has shown that Canadian bridge engineering is among the best in the world.

Meeting and Exceeding Owner's/Client's Needs

Economical and Cost-Effective Solution

The road to solving these problems was a four-pronged policy:

1. Good and friendly relations between the Contractor, the Contractors' Engineer, the Owner's Engineer and the Owner were a high priority.
2. Buckland & Taylor's computer model of the bridge would be so detailed and sophisticated that it would be more credible than anyone else's model.
3. British Columbia-based sub-consultant Levelton was retained to advise on the control of heat during the massive concrete pours.
4. An effective rhythm in which we worked while they slept, and communication by email overnight enhanced the efficiency of the project - and the relationships.

Buckland & Taylor Ltd.'s computer model using the commercial program ADINA was the largest in the company's history. It had 162,728 nodes and 49,701 elements for the bridge alone, and many more for the temporary falsework.

Once the computer model was built, checked and de-bugged, approximately 300 steps of construction were modeled to simulate construction of the bridge. Always the first attempt would be found to overstress one or more components, and a second iteration would relieve these overstresses but usually create others. Typically it took about ten iterations before the Contractor's erection scheme was made to work. Then, for various reasons, the proposed erection scheme would change and the model and the step-by-step analysis would start all over again. This happened five times!

A large part of Buckland & Taylor's work was revising rebar details and post-tensioning profiles from those in the design drawings, to keep stresses within limits at all times.

Conventional ways of controlling the temperature of massive concrete pours include adding ice to the mix or installing cooling tubes in the concrete. However, instead of using these methods, specialist sub-consultant Levelton recommended thermocouples in the fresh concrete, and insulation. Initially the concrete heats and then it cools, while at the same time its strength gradually increases. The cooling is uneven because it cools faster at the outside faces, and this induces internal stresses in the concrete. By reading the thermocouples, stresses induced by differential temperatures can be calculated, and compared with the concrete strength at the same moment. This indicates when it is safe to remove the insulation.

<u>Final Cost Relating to Original Budget Estimate</u>

The contract for erection engineering was on a lump sum basis, but due to so many changes and revisions, the contract was converted to hourly rates for most of the work. The erection engineering was completed on the revised budget.

<u>Solution to Meeting the Overall Goals of the Owner/Client</u>

An International Contractor building the 840m signature Sheikh Zayed Bridge in the Middle East turned to the opposite side of the world to have its construction engineering performed by a British Columbia engineering firm because the Contractor's Objective was to ensure the highest quality of construction engineering available because the bridge was so complex.

To commemorate his highness the first president of the United Arab Emirates, it was required that the bridge, a new gateway to the island of Abu Dhabi, should be a visually striking "signature structure". The vision of UK-based Iraqi-born architect Zaha Hadid was that the arches of the bridge should resemble sand dunes. The result is a ten lane wide sculpture. It does not look like a conventional bridge – deliberately – and it does not behave like one structurally, and that is where the complexity begins.

Specifically, the detailed objectives, which B&T achieved, of the Contractor, Archirodon, were to obtain:

1. Step by step analysis of every stage of construction as the bridge was built, including the placement of steel or concrete, prestressing sequences, and the effects of creep and shrinkage.
2. Recommended sequencing of pouring concrete, stressing tendons and releasing formwork so that nothing would be overstressed at any time.

3. A full check of the design of 12,000 tonnes of structural steel temporary works designed by the Contractor.
4. Calculation of formwork geometry, allowing for the sequence of construction, elastic shortening, creep, shrinkage and temporary works flexibility, so that when the bridge was completed it would have exactly the right geometry and stresses.
5. Recommendations for heat control measures for mass concrete poured in temperatures up to 50°C.
6. An unofficial check of the design of the completed bridge.

Meeting the Client's Schedule

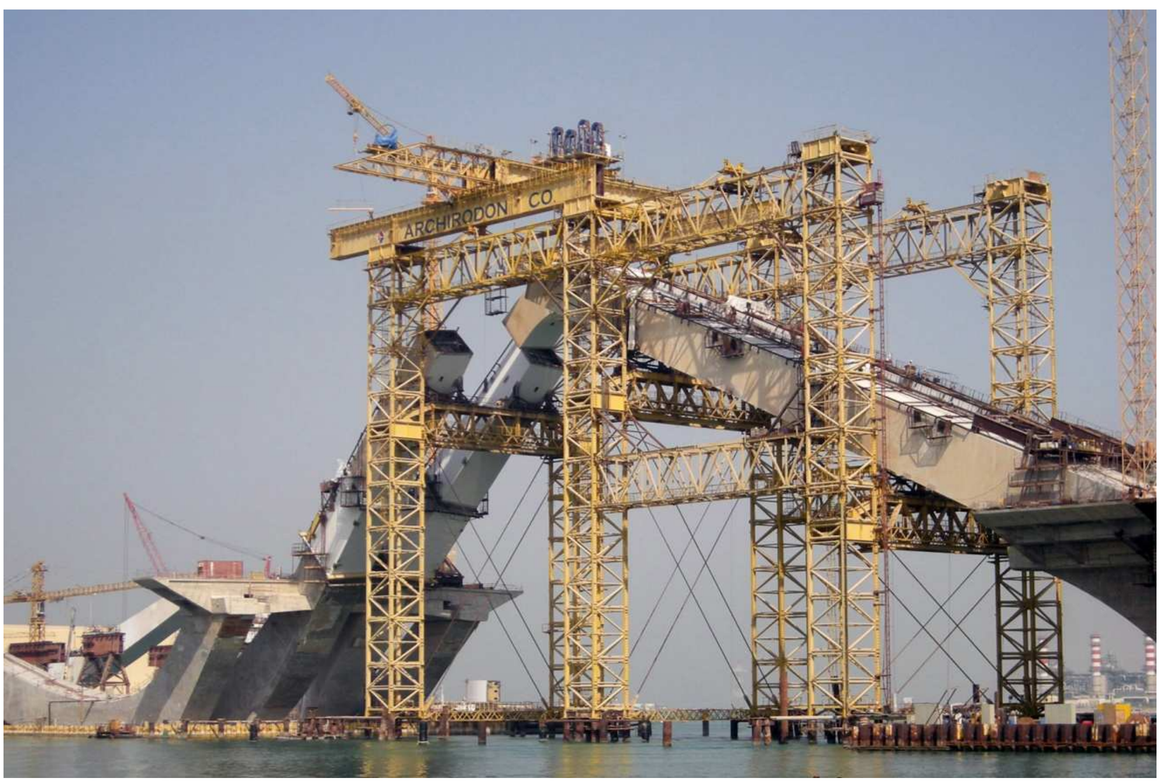
It seems that everyone initially underestimated the complexity of the project. So while the Contractor was struggling to find the best way of building the bridge, it was imperative that Buckland & Taylor give rapid turnaround of any analysis, design or checking that was required. This was achieved by having a dedicated team for the full seven years of the project that treated this job as its instant priority when needed, and typically gave overnight responses to queries, so that when the Contractor sent an email in his evening, the response was waiting for him in the morning. This rapid response commitment went a long way to maintaining good relationships.

Bridge Photos

Rendering of the Sheikh Zayed Bridge

Insulation to keep the mass concrete warm in temperatures up to 50℃

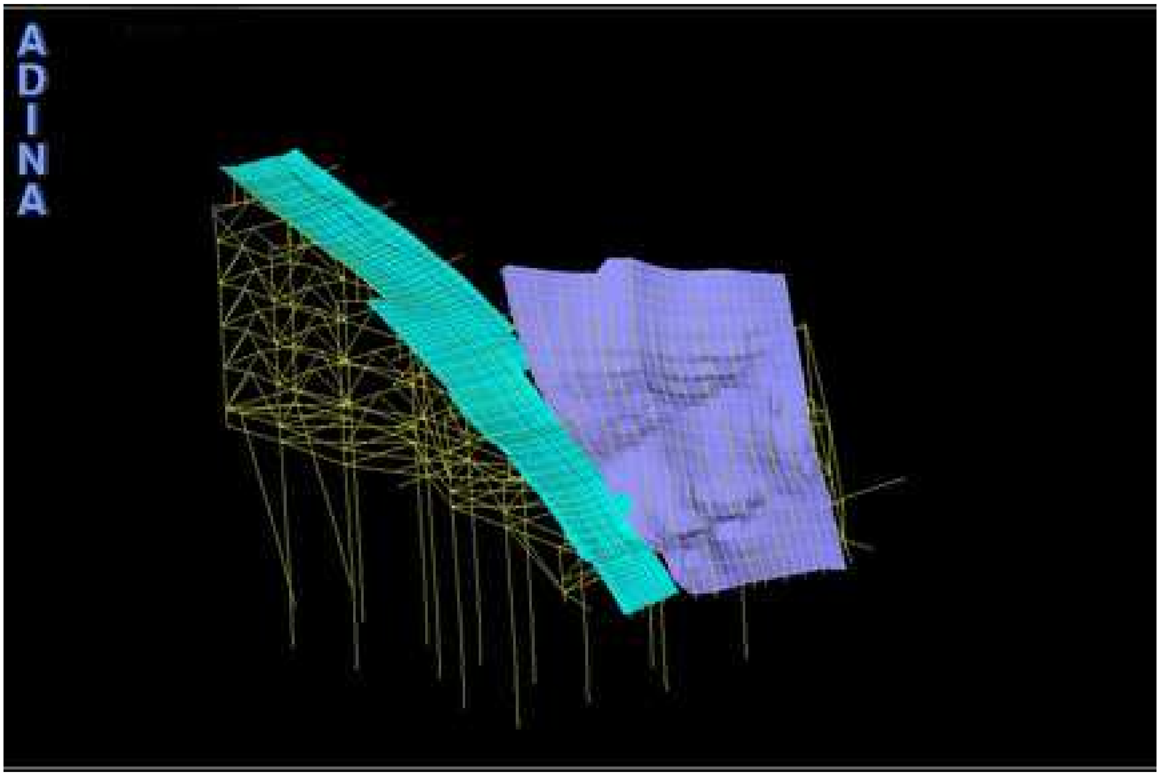
The arches under construction at the Marina Piers



60 m high towers for lifting, turning and rotating arch segments up to 600 t

A typical detail of temporary formwork supports

Aerial View of the Bridge during load testing



A detail of the computer model showing deflections at a particular stage (to an exaggerated scale)

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