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Innovative Design Concepts for Boston's New Chelsea Street Bridge

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INTRODUCTION

The City of Boston, owner and operator of the Chelsea Street Bridge, had been issued an "Order To Alter" by the United States Coast Guard for the replacement of the Chelsea Street Bridge over the Chelsea River. This order was issued under the provisions of the Truman-Hobbs Act to eliminate structures that impose a severe maritime navigational restriction. The existing channel clearance at the bridge was determined to be inadequate to provide safe passage for commercial navigation. Between the years of 1975 and 1994 the bridge and fender system had been hit numerous times by vessels. In three of these incidents the collisions were so great as to take the bridge out of service for a total of four years. Vessels are currently restricted to a beam of 90.5 feet due to the narrow channel. (Fig. 1) This restriction limits the size of the vessels to approximately 30,000 DWT.

The Chelsea River is a vital waterway for the storage and distribution of fuels of various types. Approximately 70% of all jet fuel and 55% of all the gasoline and home heating oil supplies received in the Port of Boston are stored on the Chelsea River. These oil farms serve as a major unloading and storage area prior to distribution to customers throughout the New England region.

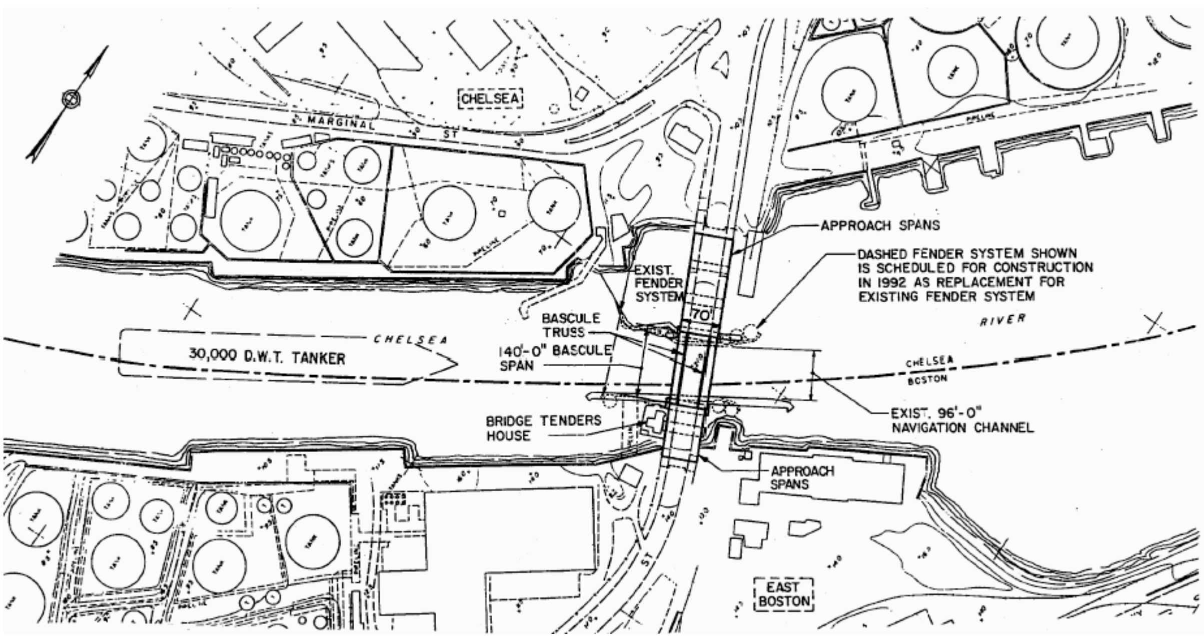

Fig. 1 Existing Restrictive Bridge

Existing Structure

The existing bridge has an overall length of 446.5 feet and is a six span structure with a main span consisting of a 140 ft heel trunnion Strauss bascule with 66 ft and 42.5 ft spans on the east side and three - 66 ft spans on the west side. The bascule span provides a 96 ft wide channel. The roadway is 50 ft wide and has one 10 ft sidewalk on either side of the roadway. The original structure was built in 1936.

New Structure

It was determined that the bridge and channel needed to accommodate a size vessel increase from 30,000 DWT to 100,000 DWT as shown in Fig. 2. This would significantly increase the delivery capacity of the tankers and reduce the frequency of vessels.

A study by another consultant was performed to develop a concept for the minimum requirements of a new structure that would serve the demands of the waterway and the City of Boston.

Minimum requirements for the new channel were the following:

- Clear channel width of 220 feet
- Provide 175 feet of vertical clearance.
- Provide 40 feet of channel depth.

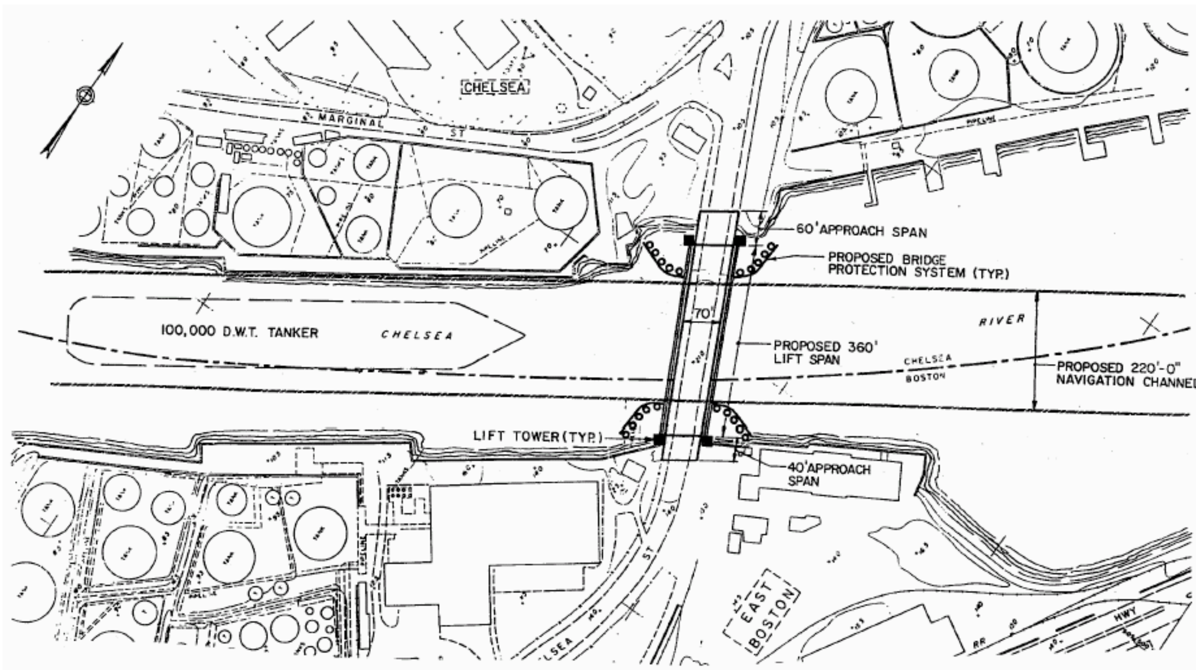

Fig. 2: Proposed New Bridge and Channel

The consultant determined a new vertical lift would be used to replace the existing structure. Conceptual design of the new structure by the consultant determined it would consist of a 360 foot vertical lift span with a 40 and 60 foot approach span on either side. The towers were estimated to be 250 feet tall to provide the 166 foot lift for the 175 foot vertical clearance. The existing 20 feet deep channel would be dredged to provide a 220 foot channel that would be 40 feet deep. (Fig. 3).

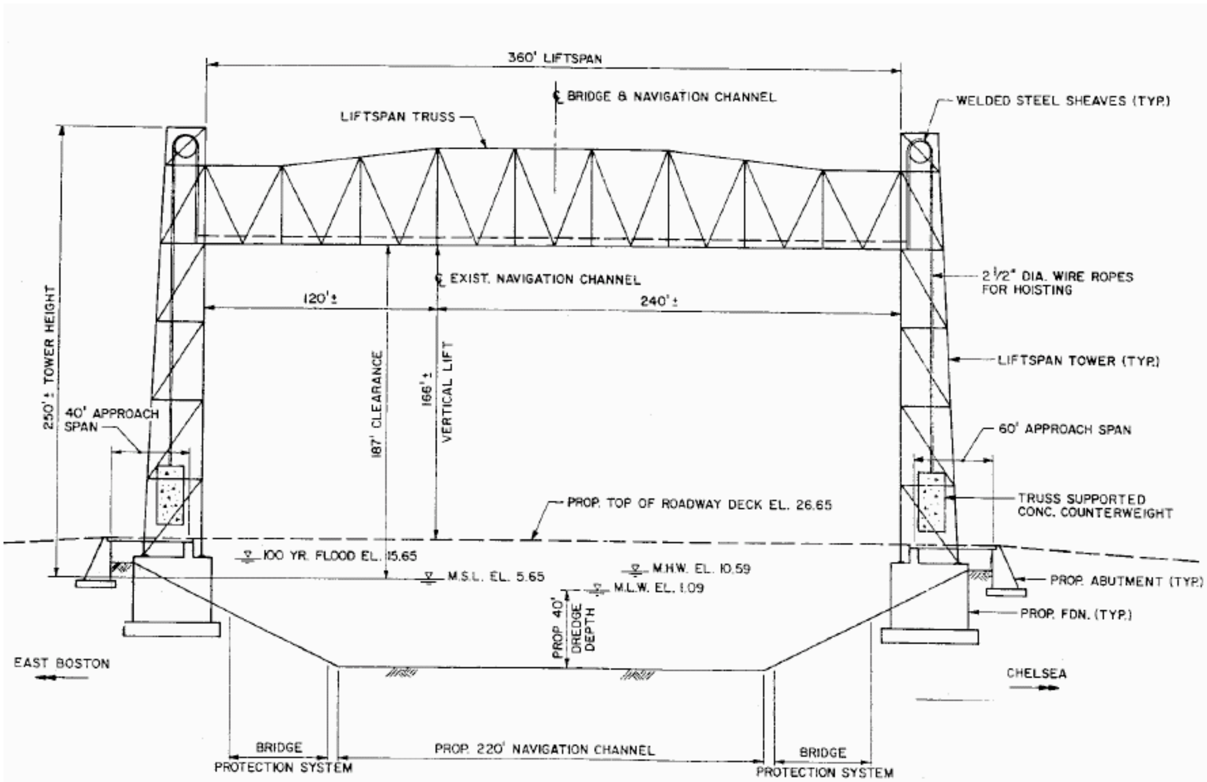

Fig. 3: Proposed New Structure

Estimated cost for the proposed structure in 1991 dollars was the following:

Bridge Related Costs	
Demolition	$9,000,000
Substructure	$9,000,000
Superstructure	$14,000,000
Roadway	$1,000,000
Mechanical & Electrical	$2,000,000
Bridge Protection	$6,000,000
Total	$41,000,000

Other Costs	
Utilities Relocation	$4,000,000
Dredging	$2,000,000
Total	$6,000,000

Project Total = $47,000,000

HTNB reviewed the requirements and preliminary scheme of the proposed structure and started to devise ways to improve the overall bridge while being able to reduce the costs for construction. The structure connects East Boston to Boston proper and is considered an urban minor arterial roadway. With the significant structures being built for the Central Artery project elsewhere in Boston, HNTB believed a cost effective signature bridge could be placed at this location.

DESIGN INNOVATIONS

Our philosophy criteria for design involved several complex considerations which were desirable for bridge improvements and providing a safe and reliable movable bridge system:

1. **Integrity and Safety** – The integrity of the new design had to be such that existing and future larger tankers would not impose damage to the new bridge piers or worse, cause an environmental disaster from a major spill.
2. **Reliability -** Because of the size and critical function of marine vessels that would demand bridge openings, redundancies needed to be incorporated for power, bridge control system, motor drive control and cross-channel data communications.
3. **Bridge Control** - Bridge operation needed to be reliable, safe, automatic and consistent, regardless of the operator on duty. Doing so will ensure longevity of the structure and systems.
4. **Aesthetics -** Aesthetic appearance of the structure was to be preserved. The structure was to have a clean uncluttered appearance, consequently, no equipment or conduits were to be seen anywhere on the exterior of the bridge.
5. **Space –** In order to keep the structure cost effective, the features of the bridge were streamlined creating optimum use of concrete and steel. As a result, available space throughout the structure as well as within the tower legs was very limited for electrical equipment and conduits.
6. **Startup -** To ensure a smooth startup, the design layout would be modular, with minimal field wiring, reducing problems during installation. The design would be such that troubleshooting would be simplified for maintenance.
7. **Cross-Channel Communications -** Dredging 40 ft. of the channel after construction of the new structure would preclude a typical submarine cable installation. A reliable alternative would need to be developed.

These design parameters led to the following final design innovations:

- Lengthening of the lift span
- Reduction in structural steel
- Improvements to towers
- Elimination of auxiliary counterweights
- Reduced concern of skew control through modified guides
- Elimination of submarine cables
- Dual sources of power
- Remote MCC operation
- Distributed PLC control system
- Fiber optics in droop cable for PLC/Data communication
- Reduction in conduit

LENGTHENING OF THE SPAN

The first step was to develop improvements to the lift span. HNTB first examined the possibility of increasing the span length from 360 to 450 feet. This added span length moves the piers out of the water and does two critical things. First, it eliminates the costly pier protection since the new piers would now be on land and away from the potential of ship collision. Second, by increasing the lift span length, it eliminates the two small approach spans and makes the lift span tower piers the abutments also.

REDUCTION IN STRUCTURAL STEEL

To make the structure aesthetically pleasing, HNTB decided to utilize a very economical structure type. It is a modified Warren Through Truss that utilizes parallel chords. This keeps the truss at a constant depth for the full length of the span. This is possible by varying the grades of steel used in the truss. Grade 70 is used at mid-span, then grade 50 and finally grade 36 at the ends. In turn, this makes the geometry of the structure simpler and the fabrication details easier due to not having to detail the geometry for a varying depth truss. The modified Warren Truss also has the vertical members and sway bracing eliminated. This makes for a much cleaner, open and pleasing structure.

The final step was to relocate the lifting girder at each end of the span. On conventional truss lift bridges, the lifting girder consists of a vertical and horizontal member which ties a transverse beam to the upper truss chord. This girder is not used for carrying vehicular live load. They are to secure the wire rope connections at the top of the truss. By relocating the lifting girder to the lower chord there is a reduction in steel, but also, the tower height can be reduced since the sheaves can be closer to the ground for the same amount of required lift. This became an important issue since the structure is 4,000 feet away from the end of runway 15L-33R at Logan International Airport. FAA requirements stipulate prior application, permitting and approval of any structure that is more that 150 feet tall within 13,000 feet of the airport. Any reduction in height is critical since any construction above the stipulated limits would require a variance.

ELIMINATION OF AUXILIARY COUNTERWEIGHTS

To enhance the appearance, it was decided to eliminate the auxiliary counterweights. These auxiliary counterweights are used to counteract the weight of the wire ropes. In the down position, the majority of the rope weight is on the span side, but in the raised position, this weight goes to the counterweight side. This is an unbalance that has to be accounted for. The most efficient type of auxiliary counterweight has the weights hanging at approximately mid lift point on the tower. The weights pass over sheave and are connected to the lift span. The weights assist in pulling the span up until the midpoint of the lift. At that point they then are used as an added weight to the span. This counterbalances for the rope weight. The connection is generally at the centerline of roadway on the lifting girder. Since the lifting girder was relocated to below the roadway, this could not be ideally achieved.

HNTB realized these ropes can be a long term maintenance issue since they require access for lubrication. This would have been costly since it would have required a platform on all four tower legs as well as ladders to gain access to the platforms. Rather HNTB performed a life cycle analysis to determine that the initial cost to increase the machinery size was a more cost effective approach than to add the auxiliary counterweights. The added size of the motors (from dual 75 HP to dual 125 HP per tower) proved to be less expensive than to add the weights, ropes, access for lubrication as well as the person to perform the maintenance. By doing this, it also kept the face of the towers uncluttered with the platforms and sheaves, ropes and weights.

IMPROVEMENTS TO TOWERS

With the refinement of the bridge superstructure came other methods of making a more pleasing, cost effective structure. The next most prominent portion of the bridge is the towers. For this structure, concrete was proposed to be utilized. Concrete had many distinct advantages over steel. Over the long term, maintenance of concrete towers is significantly less that steel. This is primarily due to not having to paint the towers. These towers will rise close to 250 feet above the roadway and containment would be extensive and cost prohibitive. Second, is the fact that concrete is readily available in the Boston area while steel of this large quantity would have to be shipped from out-of-state. These factors played an important decision on the utilization of concrete. The treatment to the façade of the concrete towers can also be easily performed to create many eye pleasing patterns or shapes without adding cost.

It was estimated that with these refinements and improvements that a savings of at least $6,000,000 could be obtained with the possibilities of even more. With these innovations in place, HNTB presented to the City of Boston a clean, aesthetically pleasing cost effective structure (Fig. 4) to replace the existing Chelsea Street Bridge.

Fig. 4 Designed Structure

REDUCED CONCERN OF SKEW CONTROL THROUGH MODIFIED GUIDES

During the development of the final design certain specific issues came up that further refined the structure. With the relocation of the lifting girder, the need for upper and lower span guides was no longer necessary. Span guides were only placed at the lower chord of the truss. This makes for one significant improvement. That is that the requirement for close monitoring to prevent longitudinal bridge skew is no longer required. With the use of one set of guides, there's no possibility for the structure to become jammed if it goes into skew. Although the electronic controls are in place for the prevention of excessive skew, if for some reason the structure does go too much out of skew, there will not be the damage and or disruption that a conventional truss vertical lift bridge would create.

ELIMINATION OF SUBMARINE CABLES

Due to the lengthening of the span to 450 feet and the tower heights being 250 feet, there were significant concerns regarding voltage drop and signal loss between machinery rooms on opposite sides of the channel. Initial calculations for some portions of the system would require #8 AWG copper control conductors or larger in order to overcome the voltage loss. The cables for power and control distribution would have been too large and numerous to be practical. Most importantly, dredging of the channel by 10 to 15 feet below the existing depth was to occur after the construction of the bridge. Certainly, the cables could not be jetted or installed in a traditional manner. Directional drilling was analyzed as an option for installation, but would have required lowering the large drilling equipment down into the pier excavation pits because drilling before and after the piers would have meant longer cable lengths. The process proved to be costly at estimate of more than $2M and would require more complex coordination with the pouring of the piers.

It was finally determined that the best option would be to festoon the cables from the tower rooms and route them across the movable span to the tower room on the opposite side. However, doing so would not have eliminated the problem of extended cables and signal loss and the quantity of required power and control conductors would be large, detracting from the appearance of the structure. Feeding independent power service to each tower respectively was feasible based on coordination with the utility company. The problem of numerous control conductor quantities was reduced by the implementation of fiber optic cable. By utilizing only a few strands of fiber, the entire bridge control and voice/data communications can be achieved. Only a small quantity of copper conductors were kept for auxiliary motor and brake operation if there were loss of fiber communications. Thus, the aesthetic appearance of the bridge was preserved with no costly installation of submarine cables. In fact, the cost was reduced by more than 60% because of the reduction in materials and labor required.

DUAL SOURCES OF POWER

Distributing separate utility service to each tower was essential in eliminating larger power conductors from having to cross the channel or movable span. Each individual service consisted of 480/277V, 3-Phase power at 1200Amps. With virtually no space for equipment at the base of the towers, the Motor Control Centers (MCCs) were designed to be placed in the tower machinery rooms. Likewise a 350kW emergency generator was placed in the machinery rooms. This served several key advantages:

1. All distribution equipment was placed in the same room as the operating machinery, thus making maintenance and troubleshooting more convenient.
2. Separate equipment in-site disconnect switches were no longer required since all machinery was in-site of the MCC switches and less than 50 feet away (OSHA requirement)
3. Only one set of power feeders needed to be routed up each tower from the roadway level, since all distributing feeders from the MCC to the operating machinery was now accomplished locally in the machinery rooms.
4. Conductor sizes from the MCC to the operating machinery were kept small, since voltage drop from long runs was no longer an issue. The cost of wiring and conduit was significantly reduced.
5. No power equipment or large generator houses were necessary at the roadway level, thus preserving the aesthetic appeal of the structure.

Only the MCC sections for the gates were located within the tower legs to serve gate power and operation. Again, this provided a power distributed and control distributed approach to the overall system, reducing bridge system wiring and conduit and simplifying future troubleshooting for maintenance. In summary, there were four (4) key MCC locations throughout the bridge; each machinery room (operating machinery) and in one tower leg of each tower (gates and signals).

A small 70kW, 480/277V, 3-Phase generator was located in the bridge control house to maintain power during typical outages. The larger machinery room generators would only be started when necessary for a bridge opening. This was to optimize fuel consumption and necessary wear on the large generators. Online uninterruptible power supplies (UPS) are placed throughout the bridge to maintain critical PLC and fiber-optic communications during typical outages.

REMOTE MCC OPERATION

Emergency Monitoring and Control Software (EMCS) was utilized for remote operation and monitoring of the MCC units. This software provides the owner with real time device metering information, event information, waveforms, and historical profile data. Remote operation of the MCC circuit breakers and overloads is also achieved through the use of the EMCS. This was all accomplished using TCP/IP Ethernet protocol.

DISTRIBUTED PLC CONTROL SYSTEM

Dual processors and PLC hardware was located in each tower adjacent to the MCCs. Distributed PLC units were located down at the tower leg MCCs. Again, this was employed to help reduce the quantity of field wiring and simplify maintenance troubleshooting. The redundant PLC processors in the towers were labeled A and B. Switching between them would be automatic in the event of failure of any processor. PLC memory would be non-volatile so as not to rely on battery backup for memory retention. The PLC would support the following basic functions:

1. Bridge Control
2. Data Logging signals via RS-232 or RS-485 out to a locally installed laptop PC
3. Alarm Evaluation And Annunciation

Fiber optic I/O cards for the PLC were employed for communications over the fiber network to distributed points throughout the bridge.

FIBER OPTICS IN DROOP CABLE FOR PLC/DATA COMMUNICATION

With the combined implementation of dual power services, and distributed PLC for bridge control, communications between these key bridge components could be simply achieved using fiber-optic cable. Essentially, for cross channel communications only an 18-fiber cable and two (2) RG-6U coaxial cables were used.

The local device network communication signal was designed using a Frequency Shift Keyed (FSK), carrier-based, 115 kHz nominal frequency to ensure no interference from 60-cycle power system. The configuration utilized two (2) 62.5-micron multi-mode fibers in a ring configuration using a wavelength of 850 nm to transmit control and feedback information. The linkage across the span utilized redundant pathways in a ring configuration that are separated on different sides of the span. This separation was to provide diversity in path should there be an inadvertent loss of communication on either one of the pathways, the available functioning alternate pathway would be immediately switched into service. Reports would be generated should there be any degrading of capability on either fiber pathway for PLC communication.

However, it was necessary to have a failsafe backup plan should the fiber communications equipment fail. With this a small quantity of copper control wiring was routed with the fiber droop cables to directly and manually control the auxiliary motors and brakes.

REDUCTION IN CONDUIT

Other than egress lighting within the tower legs and aviation beacon lighting, there was no need to run more than one set of power feeders in the tower legs. In fact, only four (4) 3" conduits were required between the roadway level and tower machinery rooms. All necessary conduit quantities were from the MCCs to equipment they operate. And since the generators were in the machinery rooms as well, the automatic transfer switch (ATS) and normal/emergency feeder distribution was all local in the machinery rooms. A raised floor raceway was employed in the machinery rooms directly in front of the MCCs. This simplified wiring and conduit routing between devices and provided a clean appearance.

In the end, the amount a typical field wiring errors is significantly reduced because of the almost complete elimination of copper wiring terminations. Installation was simplified and the reduction in conduit helps expedite the construction schedule. The majority of work is being accomplished by the fiber and shop-built bridge control components. Therefore, what is tested in the shop can be translated to the field with reduced field wiring errors resulting in less dependence on the electrical contractor. Fig. 5 shows the complete bridge power & control system layout, which reveals the reduction in conduits and wiring between the extreme points of the bridge. The majority of conduit was kept localized.

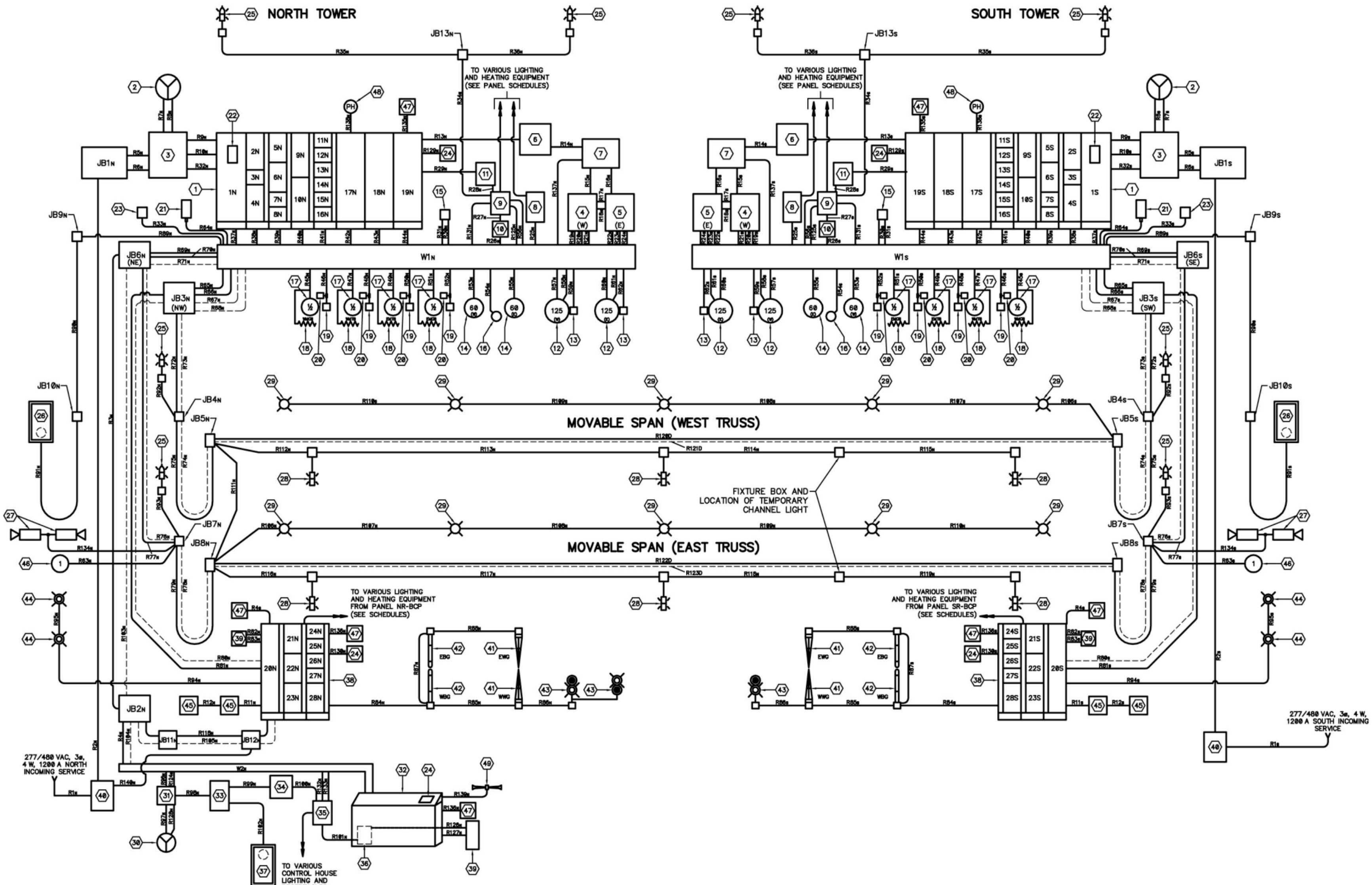

Fig. 5 Bridge Power & Control System Block Diagram

FINAL OUTCOME

The lack of data on the performance of concrete towers for vertical lift bridges was a concern by the client with the use of concrete towers. These had not been utilized on a movable bridge in the United States before. For this reason, during final design the towers were changed to steel. This was performed and the Fig. 6 shows the final design of the bridge. It should be noted that the front and rear legs are not symmetrical. Rather they are sized based upon the loading they are subject to. Since the rear legs only receive 30% of the load, they are significantly smaller in section. This gives the towers a trapezoidal shape in plan.

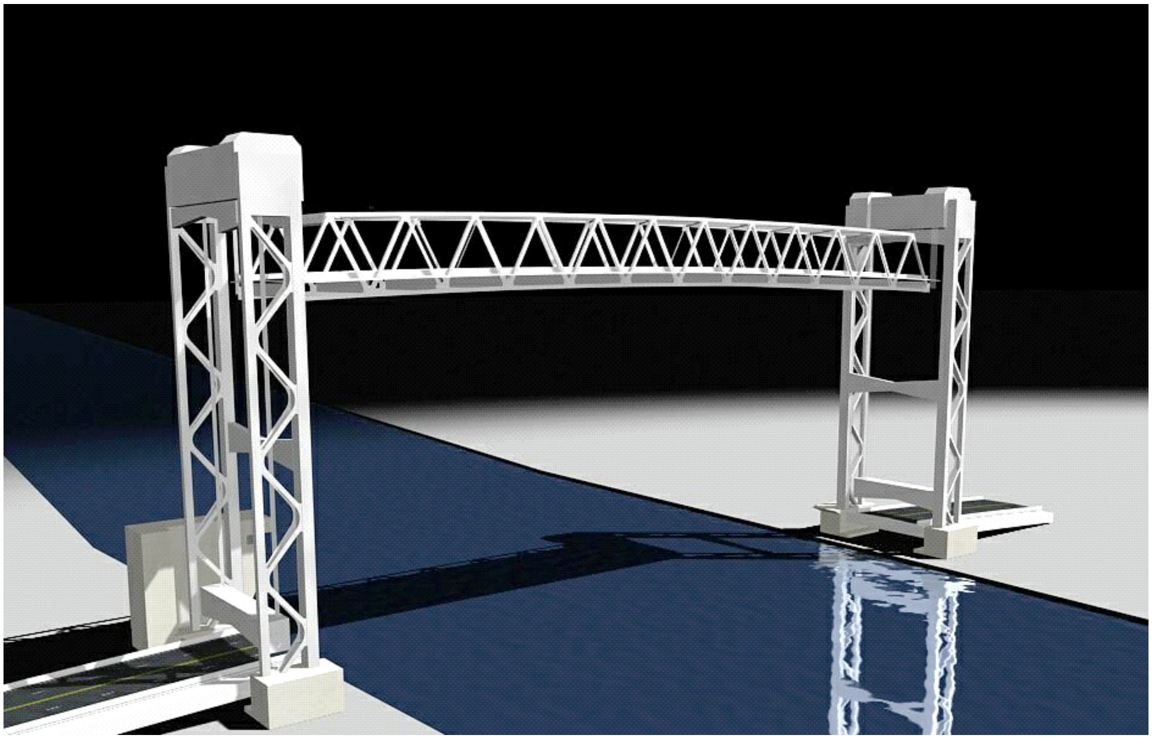

Fig. 6 Final Designed Structure

CONCLUSIONS

The seven (7) key design criteria and considerations were achieved as follows:

Integrity

- Towers placed outside of the channel using a longer 450 foot span, eliminating the potential of damage to the structure from large tankers.
- The concern over skew control operation was eliminated through the design of modified guides; greatly reducing the potential of binding of the movable span should skew control monitoring fail.

Reliability

- Redundant power sources (normal and emergency)
- UPS powered bridge control system
- Redundant Motor operation
- Redundant DC Drive capability within each tower
- Redundant PLC processors

- Self-Healing fiber-optics communication ring topology
- Direct control backup should PLC and/or fiber fail.
- Implementation of fiber helps reduce lightning transients from damaging system components throughout the bridge.

Bridge Control

- Operation kept consistent due to fully automatic bridge operation under PLC control. Reduces the potential for operator error and provides consistency, resulting in machinery longevity.
- Automatic alarm, monitoring and logging system which helps maintenance troubleshoot and identify problems even before they would occur.

Aesthetics

- Structural steel reduced and through the innovative fabrication of the steel truss, the appearance of the movable span is kept uniform.
- No electrical equipment exterior either on or off the structure, with the exception of lighting, beacons and roadway traffic control devices.
- Elimination of auxiliary counterweights.
- Cables crossing the movable span will be hardly detected due to a tower chase developed to contain the droop cables and streamlined reduction in control wiring.

Space

- Optimized due to structural design innovation concepts.
- Reduction in electrical conduit throughout the structure due to innovative PLC and fiber communications design.

Startup

- Bridge system startup will simplified through the elimination of copper control conductors and complex field wiring by employing fiber-optic Ethernet communications between devices. Most problems, should they occur, will be identified as equipment related and not field wiring related.
- Construction duration reduced due to the reduction in conduit and wiring.

Cross-Channel Communications

- Elimination of costly submarine cable installation.
- Power distributed separately to each tower eliminating power distribution across the channel or span.
- All communications achieved over 18-fiber cable, coaxial cable and limited copper conductor quantities via the movable span.