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"The Evolution, Analysis, Design and Construction of the Bascule Pier for the 17th Street Causeway Bridge"

by

Richard J. Beaupre, EC Driver & Associates

THE EVOLUTION, ANALYSIS, DESIGN AND CONSTRUCTION OF THE BASCULE PIER FOR THE 17TH ST. CAUSEWAY BRIDGE

Richard J. Beaupre, P.E.
E.C. Driver & Associates, Inc.
Tampa, Florida

INTRODUCTION

The design team led by E.C. Driver & Associates have designed a one-of-a-kind double-leaf bascule bridge which will replace an existing drawbridge at the 17th Street Causeway over the Intracoastal Waterway (Stranahan River) at Fort Lauderdale, Florida. District Four of the Florida Department of Transportation had directed the design team to give special attention to aesthetic issues on the project. A unique V-Shaped bascule pier was developed for the 17th St. Causeway Bridge currently under construction. This pier shape has since been labeled the Carina Pier after the latin word "carina" for the delta shaped keel of a boat. This pier was the result of a significant design study performed for all elements of the bridge to develop a signature bascule bridge that would be more aesthetically pleasing than a typical bascule bridge. The shape evolved from a study of the wide and narrow pier alternatives, which produced a strong distinctive pier element worthy of a Signature Bascule Bridge. This paper presents the evolution, analysis, design, and construction of this post-tensioned concrete structure.

STANDARD WIDE BASCULE PIER

Typically, bascule piers are relatively wide elements in the longitudinal direction of the bridge in comparison to other types of bridge substructure elements (see Figure 1). As bridge designers are aware, standard bascule piers are wide because the counterweight of the bascule span is enclosed within the interior of the bascule pier along with the bascule span machinery and electrical equipment. As a result, the wide piers are blocky structures with poor aesthetic characteristics. The wide pier detracts from the proportions of the bridge and appears heavy leading to suggestions of structural imbalance. Additional factors that limit the aesthetic appeal of bascule bridges are the discontinuity of the bridge superstructure at the interface between the bascule piers and the approaches.

Figure 2 is showing a split front and rear elevation of a standard wide bascule pier. Due to the wide roadway, the transverse width of the pier was very large. This would be an extremely heavy blocky pier. Figure 3 is showing a split plan. The plan below deck showing the areas for machinery and electrical equipment is shown on the left and the plan above the foundation on the right shows the void where the counterweight swings down in the lower portion of the pier.

One way to lighten up the standard wide pier would have been to place openings in the lower portion of the pier. Figures 4 and 5 show elevations of the standard wide bascule pier with openings. This was a big improvement over the pier option without the openings. The pier has a much lighter impression. This pier will have the same machinery and electrical areas as the pier without the openings. However, discrete columns instead of continuous walls will support the upper pier.

NARROW BASCULE PIER

Initially, the approach to developing an aesthetically pleasing bascule bridge was to attempt to narrow the pier in the longitudinal direction so that the pier width to span ratio would be smaller (see Figure 6). In addition to narrowing the pier, placing transverse openings in the pier was attempted to make the pier seem lighter since such a large pier width was required to accommodate the wide roadway section. The narrow pier first proposed was a modified closed bascule pier. The counterweight extended beyond the pier requiring dual counterweights outboard of the approach span. The interior of the pier enclosed the machinery and electrical equipment as in a conventional closed type pier. By removing the counterweight from the interior of the pier, it was possible to reduce the pier width. The disadvantages of the narrow pier option were that the bearing support for the approach span was more complex, a more complicated dual counterweight was required, the machinery and electrical equipment areas were reduced, and the distance from the centerline of the trunnion to the live load shoe was minimized. Although this pier option would have been an improvement aesthetically over the typical wide pier, the design team was not satisfied that they had achieved a bridge design that would qualify as a signature bascule bridge.

There were several narrow pier alternatives. Figure 7 is showing the longitudinal elevation of the elliptical pier option. As shown in this figure, the openings are very small since it was necessary to have an additional support for the approach span box since the approach span side of the pier was intercepted by the bascule span counterweight. The additional support was not required for the wide pier option since the pier encircles the counterweight, which enables the approach superstructure to be supported on the back transverse member of the pier.

EVOLUTION OF THE CARINA PIER

The final solution for this bridge was developed based on further study of the wide and narrow pier options. This final pier configuration selected by the design team was the product of a search for an alternative design solution that would provide structural and visual continuity between the approach span and the bascule span structure. This pier element is V-shaped in the longitudinal direction. This pier has since been named the Carina pier after the Latin word "carina" for the delta-shaped keel of a boat. The pier innovation that was developed combines the structural and aesthetic advantages of both the wide and the narrow pier option. Structurally, this pier configuration incorporates an integral connection with the approach span concrete box superstructure to permit the base of the pier to be reduced to only 2.3 m which is approximately 1/3 the width of the narrow pier option. As previously stated, bascule piers are typically wide elements in comparison to other types of bridge substructure elements for the reasons explained. The major advantages of the wide pier are the simplified connection with the approach span and the increased area for machinery and electrical equipment. The major advantage for the narrow pier was the more desirable proportions of the pier width as compared to the bascule span length.

Figure 8 shows the original Carina pier shape that was developed. With the bascule span closed, there was more continuity in the bottom soffit line of the superstructure than in a typical bascule bridge. It was decided by members of the design team that this shape was too geometrical. An architect was brought on to the team after the basic Carina pier shape was developed and the shape of the pier was refined (see Figure 9). The front of the bascule pier curves down toward the channel making the pier appear less geometric. The machinery area was recess to lighten the appearance of the outer elevation. Figure 10 shows a front elevation of the Carina Pier. The outer plane of the pier was sloped out to accommodate the pedestrian overlooks. Figure 11 shows a computer generated rendering superimposed on a photo of the site.

For fixed bridges, the use of V-shaped piers is not a new concept. For bascule bridges; however, the designers are not aware any bridge in the world where the V-shaped pier has been used. The V-shaped pier shown in Figure 12 was utilized for a railway bridge in Germany where a concrete box girder superstructure was supported on integral V-shape piers. This frame bridge was chosen because it permitted the smallest beam depth in the center for the given site conditions. According to the designers, this structure was much lighter than all other options investigated. The chosen solution was the only option which was approved by the citizens living in the vicinity of the bridge. This bridge has received a prestigious German Structural Award in 1988. The awarding jury summarized their remarks as follows:

> "Taking into account the large loads from the high-speed railway trains, an unobtrusive but unique structure was created which fits the surrounding landscape harmonically."

FURTHER DISCUSSION OF THE CARINA PIER

An advantage of this pier structure was that it has a lighter impression of all pier types studied. Another major advantage of this option was the decreased bascule span superstructure length which was revised from 70 m based on a narrow pier configuration to 64 m. This resulted in savings for the machinery/electrical elements and a reduced counterweight. Also, the connection of the approach span at the Carina Pier no longer required a maintenance prone expansion joint. This pier type also accommodates large transverse openings in the pier. These openings are much larger than those for the narrow pier since an intermediate support was required for each approach span in that option. The openings in the Carina pier correspond to the width of the counterweight, which will be exposed when the bridge is opened. It was also possible to move the pier foundation centerline further from the center of the channel to improve the overall span proportions. Finally, the carina pier will provide a strong unique element worthy of a "signature bascule bridge". The disadvantage for this pier configuration was the more complex pier erection and the fact that the designers were in new territory with the design and construction since no V-shaped bascule piers are in existence.

Figure 13 shows the pier plan below deck level. This will most likely be the most spacious bascule pier with regard to machinery and electrical areas of any bascule bridge in the state of Florida. The center section is utilized for the electrical and emergency generator equipment. A portion of this space will be climate controlled. The machinery area is located below the bascule superstructure. A walkway to access the counterweight encircles the pier. A large area at the outside faces is provided for storage and access into the pier from deck level.

DESIGN

Lower Pier

The foundation for each bascule pier consists of 26-1.22 meter diameter (4 foot) drilled shafts with a mudline foundation cap. A 2.75 meter seal was utilized to build the foundation caps (see Figure 14). The controlling load case for the number of drilled shafts was the vertical dead and live loads. The barge impact force of 10676 kN (2400 kips) did not control the design. To accommodate the phase construction, three shafts are placed at the widened edge of the foundation near the bridge centerline since the dead load is eccentric to the foundation cap during the phase construction.

The plinth is the vertical portion of the pier supporting the V-shaped section of the bascule pier that distributes the loads to the foundation caps (see Figure 14). The plinth section was made solid for constructability. The lower pier was vertically post-tensioned with 4 loop tendons (12-15 mm diameter strands) up to an approximate elevation of +11.0 meters to reduce the concrete stresses to less $0.5*(f'c)^{1/2}$ at service level. The reason the stresses were kept to this level was to increase the long-term durability of the pier by reducing the possibility this section will crack in the splash zone since cracking would accelerate the chloride penetration. For the serviceability check, the friction of the approach span bearings was taken into account. The plinth section was also checked for the ultimate flexural strength where the friction in the approach span bearings was ignored. The shear strength of the plinth section was not critical. Group II loadings (dead plus wind) controlled the plinth design. For increased durability, microsilica concrete was specified for the lower portion of the pier. The percentage of mild reinforcement was slightly greater than 1%. Once all the dead loads were finalized, the base of the Carina pier was shifted (upper pier remained in same location) to minimize the dead load moments in the plinth.

As mentioned above, the lower portion of the columns was post-tensioned with the same loop tendons for the plinth. The same design criteria were utilized for the lower column legs as for the plinth. The upper column legs in the rear portion of the pier were not post-tensioned. This upper portion of the rear columns was designed for ultimate strength and serviceability criteria were checked. The shear strength of the column legs was not critical. As for the plinth, the column legs were made solid to ease construction. The percentage of mild reinforcement was slightly greater than 1%. Group II loadings (dead plus wind) controlled the column design.

Upper Pier

The upper pier is supported on the front and rear column legs. The upper portion of the pier consists of both transverse (rear and front diaphragm) and longitudinal (diaphragm A and B and the outer diaphragm) post-tensioned members which support the approach span superstructure, the bascule span superstructure, and the housing for the counterweight and the electrical/machinery equipment (see Figure 13).

The rear transverse post-tensioned diaphragm that supports the approach span superstructure is a large torsional member since the bascule pier column legs are placed outside the width of the superstructure to allow the counterweight to swing down between them. This element is approximately 3.0 by 3.0 meters. The service level stresses are kept below $0.25*(f'c)^{1/2}$. The controlling longitudinal tensile stress for the rear diaphragm is at the centerline of the rear diaphragm for Group I loadings (dead plus live). Relative to the section, very little post-tensioning was required since the section was controlled by the torsional loading (two 19-15mm diameter strands were provided). Group II loadings (dead plus wind) controlled the shear and torsion design. Closed stirrups were detailed in the sections with the highest torsional loading (between the superstructure web and the column leg).

The front diaphragm is also a large torsional member carrying the bascule span superstructure to the column legs. This element has large notch-outs to allow the bascule span superstructure to swing open. The area between the notch-outs supports a machinery area and the two interior trunnion pedestals. This cantilever portion between the notch-outs acts as a large corbel. This portion of the front diaphragm was analyzed with a strut-tie model. P-T bars were conservatively provided in this large corbel as a top tie. The overall controlling load case for the front diaphragm was Group II (dead plus full longitudinal wind) for shear and torsion design. The maximum torsion is located at the face of the notch-out. The critical horizontal wind load acting on the trunnions (which creates the torsion in the front diaphragm) is that wind which occurs when the bascule span is open and a longitudinal wind is directed away from the channel. This wind loading creates a torsional moment which is additive to the dead load torsional moment. For the design of the front diaphragm, in the event of a machinery breakdown it was assumed that the inside trunnions on the front diaphragm would never function as hopkins trunnions. If the outside bearing fails, the inside bearings will be moved to the outside position to function as a hopkin trunnion. The front diaphragm was designed for a 1.2 impact factor. This factor was applied to the entire dead load case, which was conservative. With respect to torsion, live load on the bascule span has an opposite effect to the dead load torsion on the front diaphragm. As expected, there is very little effect in the front diaphragm due to the approach span live load. Downward live load reaction on the trunnions (truck located near the trunnion supports) has a small torsional effect on the front diaphragm, which is smaller than the torsion from the wind loading. The same design criteria as for the rear diaphragm was used for the front diaphragm. The controlling load case for the post-tensioning design is Group I (dead plus live load) at the center and Group II (dead plus full transverse wind) at the column face (three 19 -15 mm diameter strands were provided).

The live load shoe supports for the bascule span is located on a wall that is supported on the front diaphragm. Due to the sloping front face of the bascule pier, a significant analysis effort was required for this front wall. A 3-D plate type element (6 DOF at each node) in GTSTRUDL was utilized to analyze this wall. This wall is fixed on three sides with the top edge free (where the live load shoe supports are located). At the side interface at the top of the wall on the machinery side, the channel side face at the live load shoe support, and at the base of the wall on the machinery side, high tensile stresses were apparent from the analysis. This wall was designed by the load factor design method and serviceability criteria were checked. An independent grid analysis was performed to verify the 3-D finite element model. The grid model results agreed well with the finite element model results.

The longitudinal diaphragms ("A", "B", and outer) (see Figure 13) of the pier were designed using service load method. These members are longitudinally post-tensioned. The design allowable stress for tension was assumed to be $0.25*(f'c)^{1/2}$ and for compression was $0.4*(f'c)$. The controlling load case for these members was Group II (dead plus wind). Three 19-15 mm diameter strands were provided in longitudinal diaphragms "A" and "B" and two 19-15 mm diameter strands were provided in the outer diaphragm. The frame action wind moments in these diaphragms was significantly higher than those due to live load (truck loading on the pier itself and lane loading on the approach spans and the bascule span). The forces and moments for the critical load conditions were obtained from the GTSTRUDL space frame beam models. Due to the complexity of the diaphragms, a plane stress finite element model was generated for diaphragm "B" to verify the results of the space frame model. The results of the space frame model were conservative with respect to the final erection moments (includes all erection stages including the post-tensioning). Therefore, the final stresses were determined from the space frame model results rather than the plane stress model results. There was good correlation between the models for the global structure behavior. Results for the wind forces and moments in the diaphragm also correlated well. The effective post-tensioning levels assumed for the model were $0.65*f's$ (assuming long-term losses) and $0.74*f's$ (assuming short-term losses only). The final tendon loss diagrams for each tendon configuration confirmed these values. The ultimate strength of the diaphragms was also checked. The diaphragm permanent load forces and moments do not change significantly for the assumption that the trunnion bearing on the outside (at the longitudinal diaphragm) acts as a hopkins trunnion.

The bascule pier deck slab was designed utilizing load factor design. A finite element model was used for the analysis. The pier slab is not post-tensioned which will facilitate future deck replacement if required. An independent analysis was performed utilizing Pucher charts to verify the finite element model.

CARINA PIER ERECTION AND PHASE CONSTRUCTION

The bridge will be constructed in phases to maintain traffic at the site and to allow the bridge to be built along the same bridge centerline as the existing bridge. First, the north half is constructed two meters off the existing bridge centerline. After the north half is complete, all the traffic is moved to the new north bridge half and then the south half is constructed. After completion of both halves, a closure pour will be made. A temporary control tower will be placed on the north side of the north half since the final control tower will be located in the center of the bridge above the closure pour.

Figures 15-22 show the assumed erection sequence for one phase of the Carina pier. In stage 1, the installation of the cofferdam and seal, the footing cap and plinth is shown. The pier legs are cast utilizing jump forms and the lower pier is post-tensioned in stage 2. In stage 3, a tie is placed between the pier legs and the remaining rear pier legs are cast utilizing jump forms. In stage 4, the tie between column legs is stressed to adjust the column leg moments and the front and rear diaphragms are cast on falsework. In stage 5, the upper pier is cast and post-tensioned and the tie between pier legs can be released after the upper pier is post-tensioned. In stage 6, the closure pour between the approach span superstructure and the pier is cast and the continuity tendons are stressed. Also, the approach span temporary support can be removed. Once the post-tensioned bars in the machinery platform are stressed, the trunnion pedestals and the walls adjacent to machinery areas are cast. In stage 7, the falsework is modified as required for the bascule leaf installation. The counterweight and the bascule span deck are cast. In stage 8, the pier deck and the upper front wall between the bascule leaf box girders are cast.

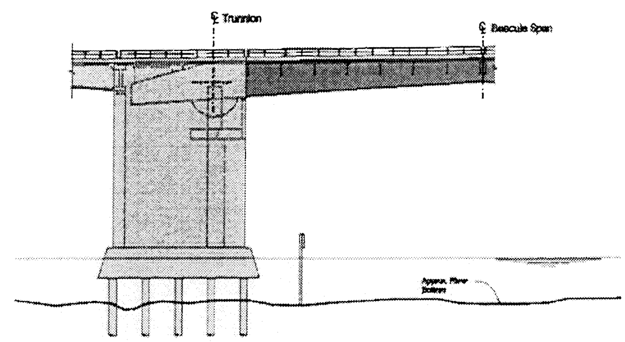
CONCLUSION

It is the opinion of the design team, that the 17th Street Causeway replacement bridge will be a "Signature Bascule Bridge" (see Figure 23). The proposed bridge is appropriate for the site and is structurally expressive. The Carina bascule pier was the product of a search for an alternative design solution that would provide structural and visual continuity between the approach span and the bascule span structure. The shape evolved from a study of the wide and narrow pier alternatives, which produced a strong distinctive pier element worthy of a signature bascule bridge. The shape of the Carina Pier allows the relocation of the trunnion point inward towards the channel centerline, shortening and lightening the bascule span in the process. Additionally, the Carina Pier will provide a strong unique element worthy of a "Signature Bascule Bridge".

REFERENCES

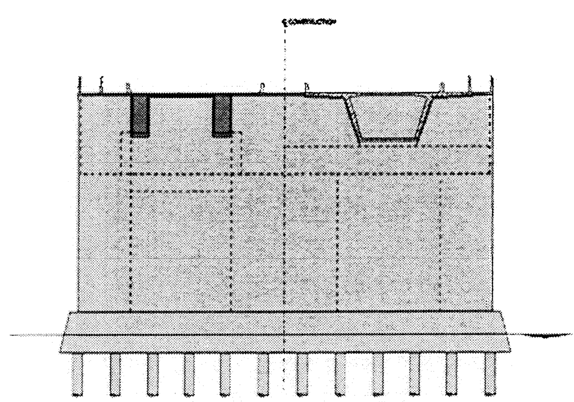
1. Leonhardt, Andra und Partner, Incrementally Launched Bridges, unpublished text, Stuttgart, Germany.

Fig. 1
Standard Wide Bascule Pier



BASCULE ELEVATION

Fig. 2
Standard Wide Bascule Pier



HALF FRONT ELEVATION HALF REAR ELEVATION

Fig. 3
Standard Wide Bascule Pier

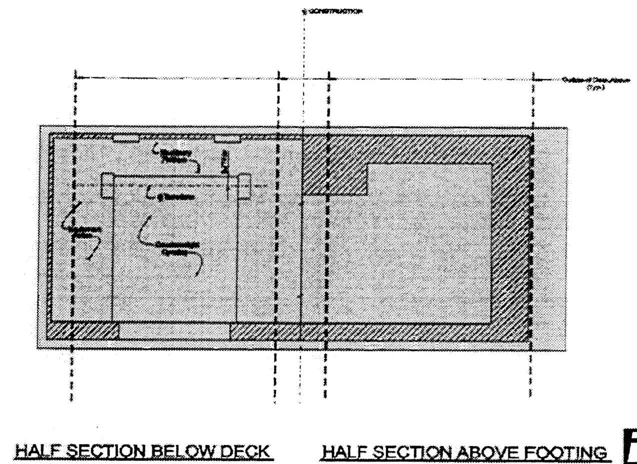


Fig. 4 Standard Wide Bascule Pier with Openings

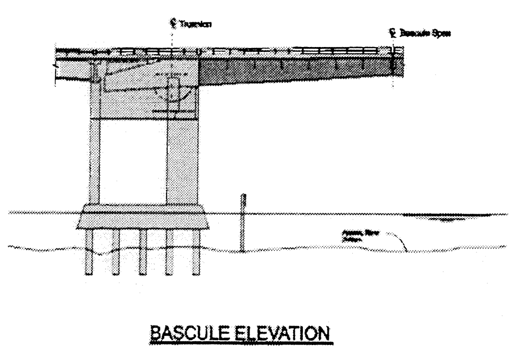
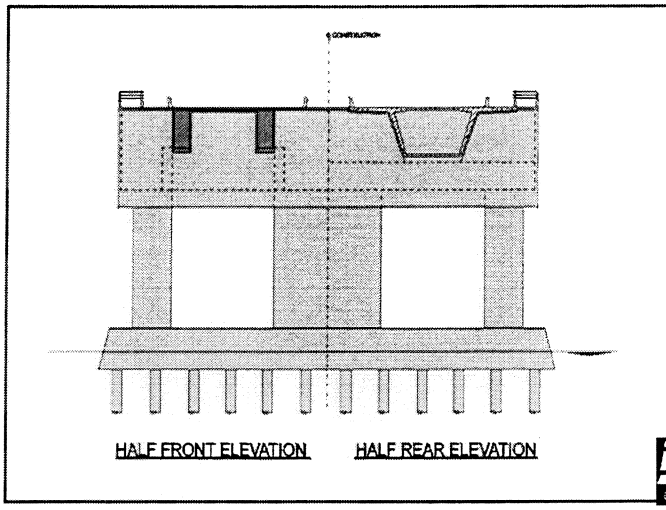
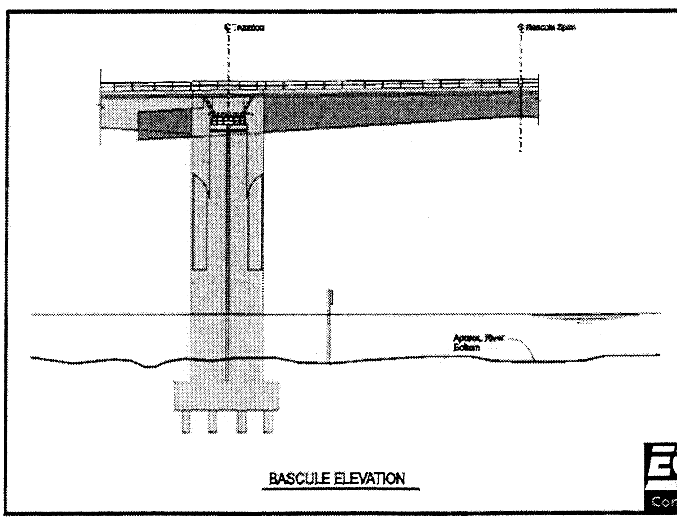


Fig. 5 Standard Wide Bascule Pier with Openings



EC Driver & Associates Consulting Engineers

Fig. 6 Narrow Bascule Pier with Openings



EC Driver & Associates Consulting Engineers

Fig. 7 Narrow Bascule Pier with Openings

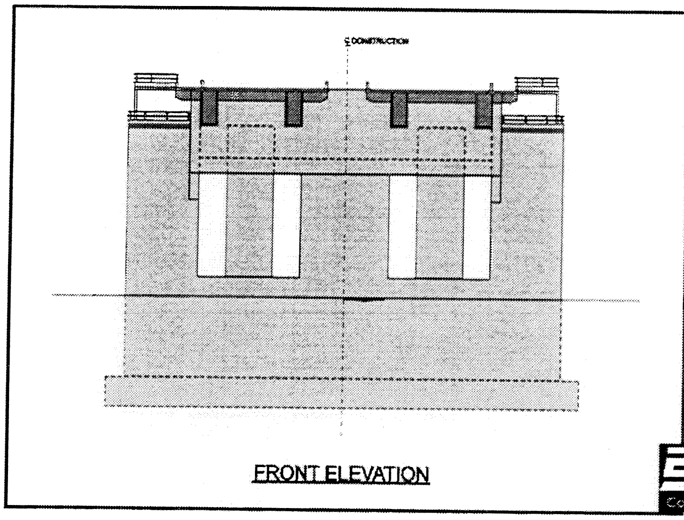


Fig. 8 Original Carina Pier

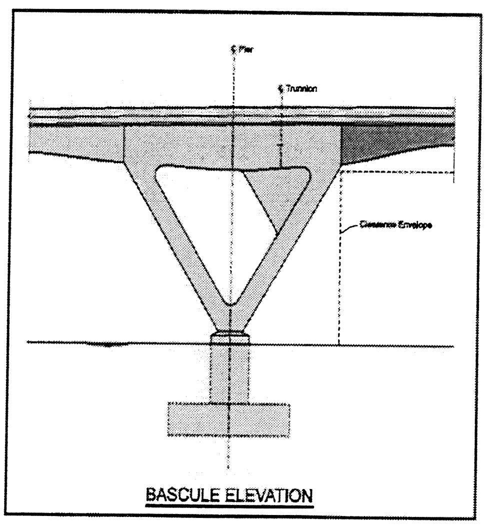
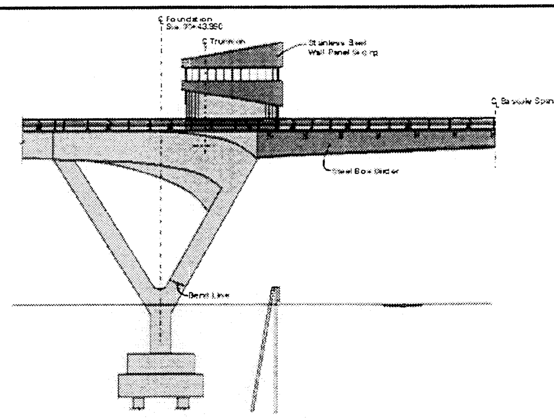
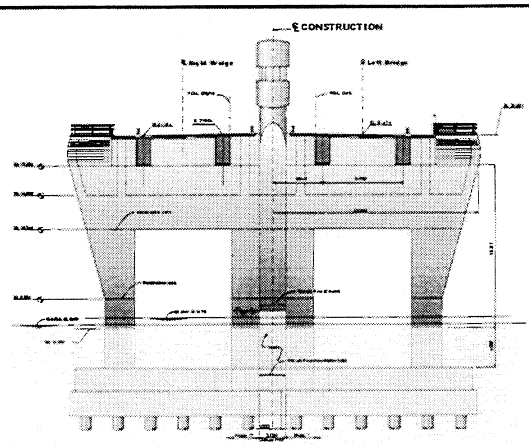


Fig. 9
Final Carina Pier Configuration



BASCULE ELEVATION

Fig. 10
Final Carina Pier Configuration



EAST ELEVATION

Fig. 11
Carina Pier

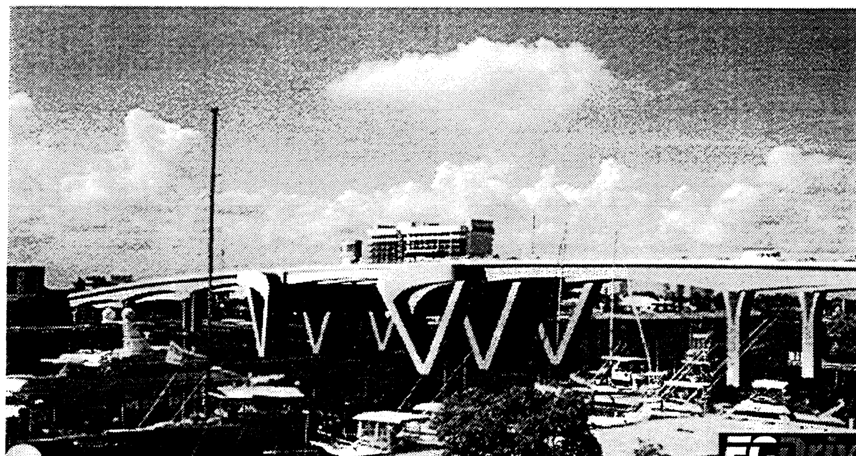
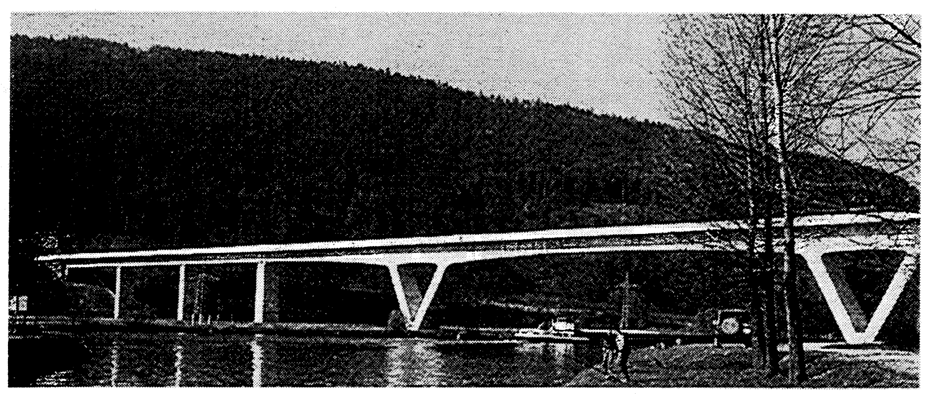


Fig. 12
European Railway Bridge



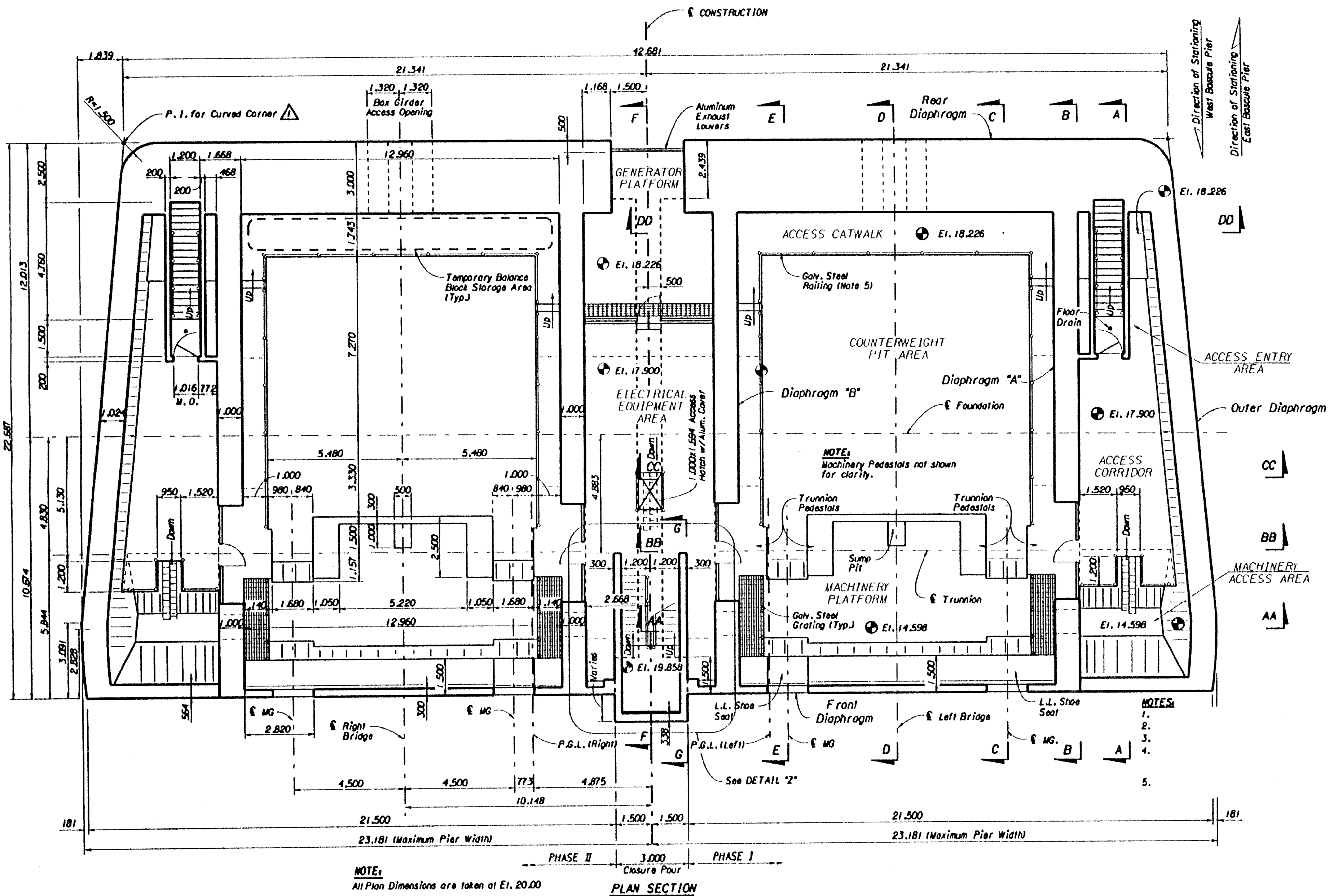
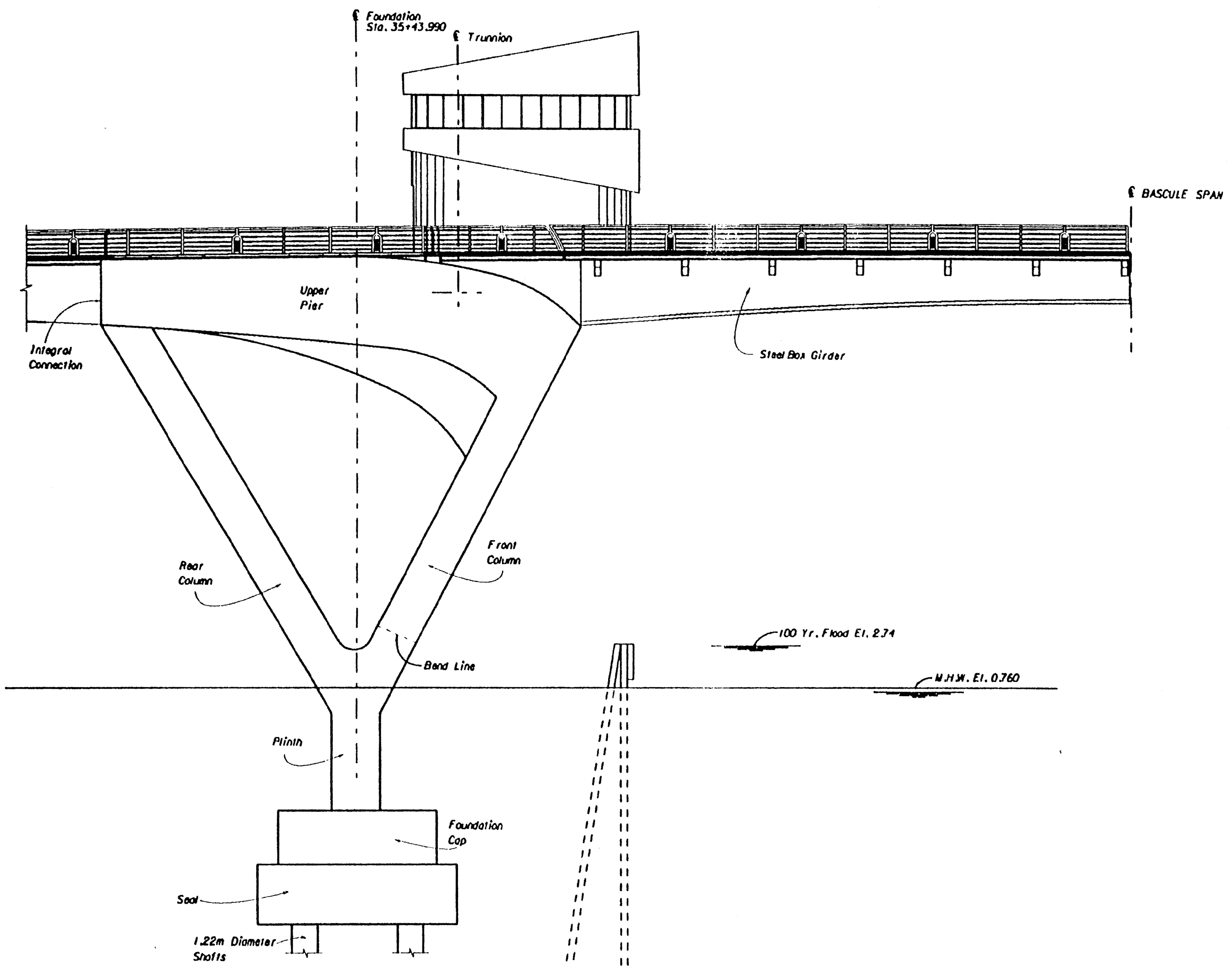


Figure 13 Upper Pier Layout



SOUTH ELEVATION

Fig. 15
Carina Pier Erection Stage 1

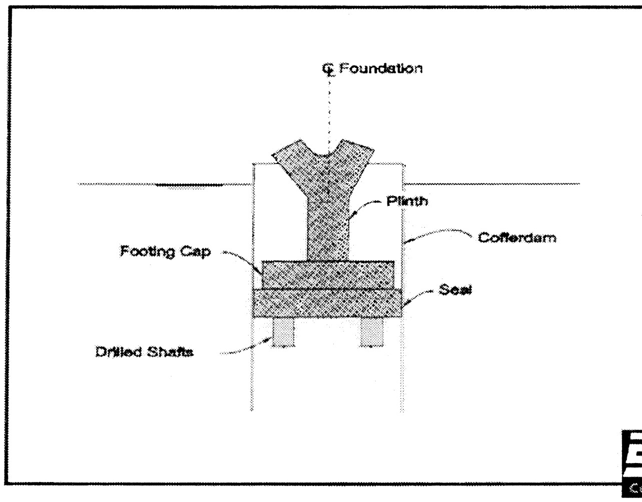


Fig. 16
Carina Pier Erection Stage 2

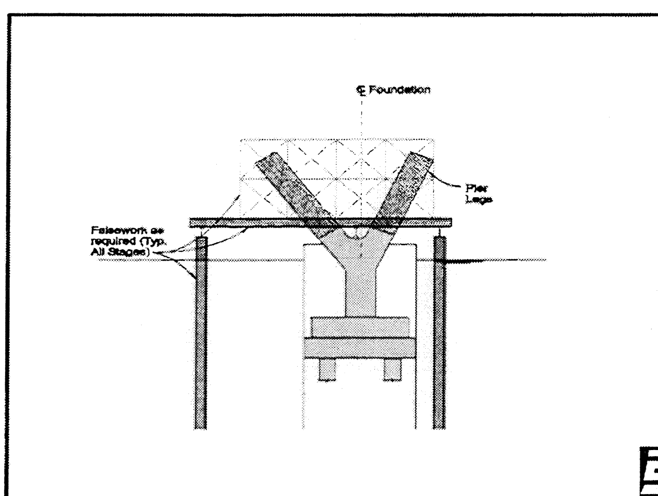


Fig. 17
Carina Pier Erection Stage 3

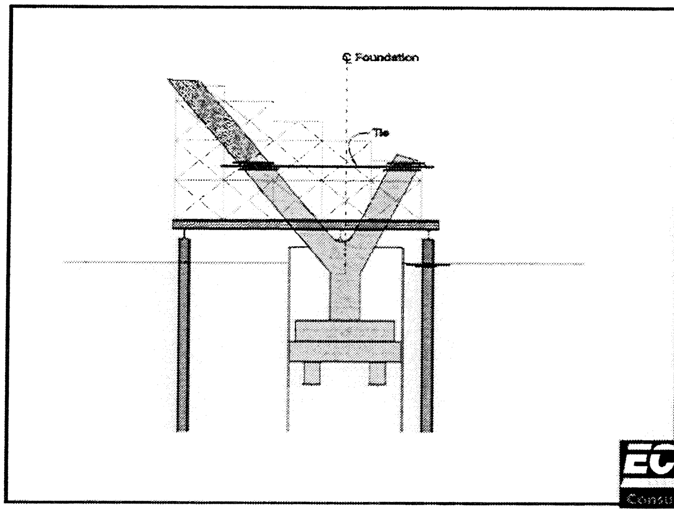


Fig. 18
Carina Pier Erection Stage 4

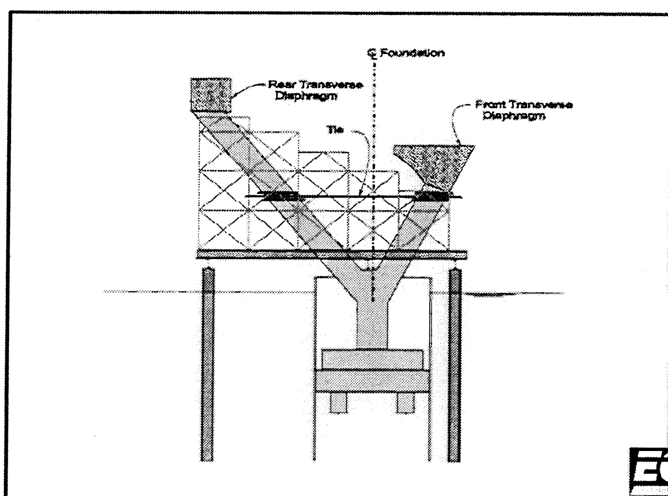


Fig. 19
Carina Pier Erection Stage 5

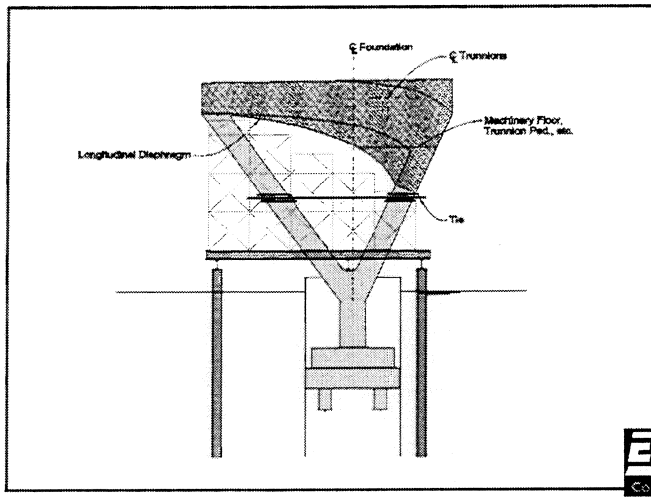


Fig. 20
Carina Pier Erection Stage 6

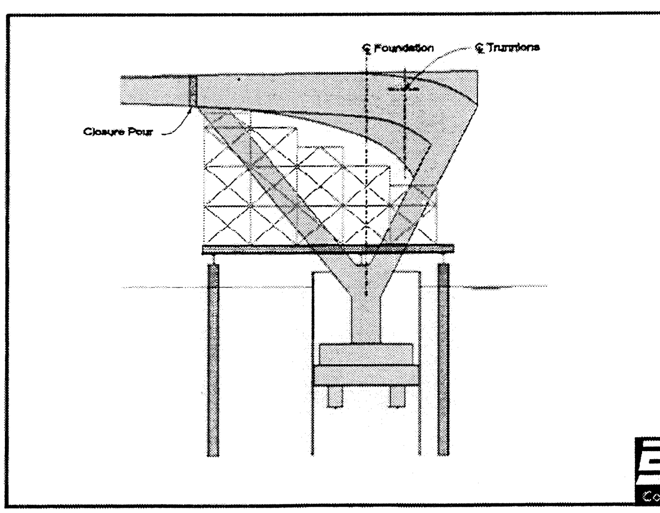


Fig. 21
Carina Pier Erection Stage 7

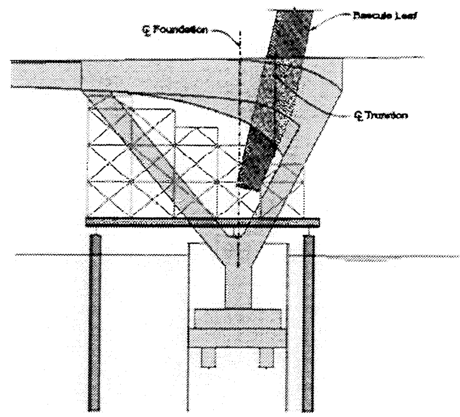


Fig. 22
Carina Pier Erection Stage 8

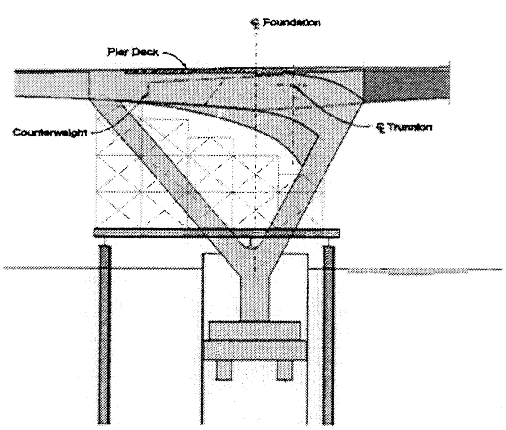


Fig. 23 Artist Rendering