**March 23, 2011**

Mr. Joseph Ettore, P.E.

County Engineer

Monmouth County Engineering Department

Hall of Records Annex

Freehold, NJ 07728

**RE: Oceanic Bridge S-31**

**Renewal, Retrofit and Preservation Analysis**

**Supplement Number 1, Task 1 and Task 2**

Dear Mr. Ettore:

Please find below a summary of the finite element (FE) modeling efforts and results obtained under Tasks 1 and 2 of the Supplement Number 1. This report presents the influence of the Hardesty & Hanover (H&H) retrofit plans on the stress distributions of the bascule girders and floor beams. In addition, the report presents the results of the modeling related to the retrofit concept proposed by Pennoni Associates (Pennoni). The report concludes with a summary of findings and recommendations.

**Overview of FE Model Construction**

The FE models developed under the original contract were modified to include the H&H retrofit plans and Pennoni’s retrofit concept design. This section provides a description of the initial FE model construction and relevant details.

In order to fully understand the geometry of the Oceanic Bridge, a three dimensional model was created based on the available construction drawings obtained from the County Engineering office. The 3D model was built in both AutoCAD and Google Sketchup® to allow for proper error screening. These models served as excellent tools to understand and conceptualize the interaction of the components and load paths of the structure. In addition, these models were employed to (1) visualize deterioration, (2) aid in instrumentation planning, and (3) establish the geometry of the preliminary and refined FE models. The 3D models are shown in   
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| oceanic_bridge_layered4-underside.png | oceanic_bridge_layered4-2.png |
| Figure 1. 3D Google Sketchup® Model for Oceanic Bridge | |

Using simple benchmark models together with closed-form solutions, the use of four node quadrilateral shell elements with six degrees of freedom per node (employed using SAP2000) was shown to sufficiently capture both the in-plane and out-of-plane response of the primary members of the Oceanic Bridge. The nominal mesh size selected for the model was 4 in. by 4 in. While this mesh was far more refined than required to simulate the intact response of the structural members, this level of refinement was desired so that the deterioration observed could be approximated with reasonable accuracy.

To construct a FE model of the Oceanic Bridge, the geometry was established in AutoCAD (using the geometric models previously discussed) and imported into SAP2000. Once the basic 3D geometry was imported, the model was meshed using the nominal mesh size. In addition, the model was examined to locate areas of stress concentrations (member connections, stiffeners, boundary conditions, etc.) and the mesh in these regions was further refined down to 0.5 in. by 0.5 in. to allow the expected complex stress distributions to be properly simulated. Once the meshing was completed, the material properties, boundary and continuity (where applicable) conditions were assigned and several simple analysis cases were conducted to error screen the model. The basic geometry of the north and south bascule leaf models are shown in .

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| (a) | (b) |
| Figure 2. 3D Finite Element Model is SAP2000 (a) North Leaf and (b) South Leaf | |

To refine the preliminary FE model two sources of information were employed. First, the results of the H&H condition assessment were directly incorporated to modify the primary and secondary structural members. Second, preliminary strain data was used to provide information about the shear transfer between spans and the performance of the live load bearings.

The traditional method of FE model calibration is conducted by manually minimizing the error between the experimental results and model output. Based on the initial discrepancies between results and model output, adjustments to the model are made, varying material properties, geometry, boundary/continuity conditions or part interaction to attempt to reduce the error. These adjustments are based on heuristic knowledge as well as the in-situ properties of the structure being calibrated. In the case of the Oceanic Bridge, uncertainty was present in regards to the (1) condition and activation of the span locks, (2) the performance of the live load anchors on both bascule leaves, and (3) the deterioration of primary and secondary members.

The deterioration of the Oceanic Bridge was established by H&H through visual inspection and provided to Pennoni and IIS via a series of member elevation views with areas of deterioration drawn by hand. In addition, H&H also provided an estimate of the percentage of section loss for each area of deterioration. These areas of section loss and corrosion were mapped onto a 3D CAD model to aid in the conceptualization of the current state of the bridge. Using this 3D CAD model, the locations of deterioration were transferred to the FE model.

To simulate the deterioration within the model, shells with decreased thickness equal to the section loss, based on the information provided by H&H, were used in areas deterioration was reported. For example, for 50% section loss on a 3/8 in. plate, a shell with 3/16 in. thickness is used. For areas where 100% section loss was noted, the entire shell element was removed from the model in an area approximately the size of the area noted in the field notes. shows the deteriorated sections as well as the elements that were removed from the FE model for the north leaf of the Oceanic Bridge.

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| DETERIORATED MODEL.bmp |
| Figure 3 - Deteriorated FE Model of North Leaf with Highlighted Corroded Areas |

The second modification made to the preliminary as-built model involved how the boundary conditions at the live load supports and the continuity conditions at the span locks were modeled. In the as-built model, one of the live load support conditions employed was a pin, which restrained translation in the x, y, z-directions but allowed rotation around these axes. The restraint in the x-direction induced large compressive forces into the bascule girder that could not be justified after inspecting the live load supports, and were not consistent with the results of the cursory load test. Removing the restraint in the x-direction alleviated the large compressive stresses and drastically reduced the bounds of the responses in the rear area of the bascule girders. Also, the preliminary analyses indicated that the bascule girder stresses were very sensitive to the level of shear transfer simulated between the two leafs. Based on the strains measured during the load test, the continuity conditions at the span locks were calibrated.

**Live Load Cases**

The truck configuration used in the analytical load cases is shown in . This configuration represents an AASHTO 72 Kips Tridem dump truck.

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| Figure 4 – Truck configuration used for analytical ratings |

Four live load cases were used in the analyses of different models. These four cases are as follows:

* FB1: Two 72 Kip dump trucks side by side with their rear axles located on Floor Beam 1 and facing toward Floor Beam 4
* FB2: Two 72 Kip dump trucks side by side with their rear axles located on Floor Beam 2 and facing toward Floor Beam 4
* FB3: Two 72 Kip dump trucks side by side with their rear axles located on Floor Beam 3 and facing toward Floor Beam 1
* FB4: Two 72 Kip dump trucks side by side with their rear axles located on Floor Beam 4 and facing toward Floor Beam 1

**H&H Priority Repairs**

The priority repairs performed in June 2010 which included adding sandwich plates to the most deteriorated panels (with areas of 100% section loss) on the North Leaf were incorporated in the model. Two different approaches were evaluated using a benchmark model. These two approaches were to (a) directly model the sandwiched panels with a gap between the plates and the web plate and use rigid links between to enforce continuity between the plates and the web, or (b) increase the thickness in the area of the sandwiched panels to account for the thickness of added the plates. The results for the benchmark model showed that both of these approaches yielded the same results. However, the first approach required significantly more modeling time and effort and thus increased the potential for modeling error. Consequently, the latter approach was selected to add the sandwich plates to the FE model. shows the panels in which the priority repairs were performed and the FE model of those panels. The different color panels in (b) represent different thicknesses for the added plates (except for dark green which indicates deterioration).

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| P:\Projects\MCED 0901 - Monmouth County\Photos\FE Matching Photos\H&H Emergency Repairs-2.JPG |  |
| (a) | (b) |
| Figure 5. (a) Priority Repairs Done in June 2010, (b) FE Model of these Panels | |

Results of the FE model with the priority repairs applied show an improvement (reduction) in the nominal stress levels. However, the overall rigidity of the reinforced section increased, which causes a distortion of the un-reinforced section and imposes a stress increase on the portions of the panels that are not reinforced. This could be avoided by covering the entire panel, or covering the entire width of a panel with sandwich plates. compares the results of the FE model for the panels on the Northwest girder for the deteriorated model and the one with priority repairs.

In addition to the bascule girders, the flexural and shear stress levels in the floor beams are considerable under different loading cases. The floor beams were supposed to be replaced in the Fall of 2010 but the repair activities have been postponed for at least one year, which raises concerns about the condition and on-going reliable performance of these elements.

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| (a) | (b) |
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| (c) | (d) |
| Ksi | |
| Figure 6. Flexural Stress Distribution on Northwest Girder in (a) Deteriorated FE Model and (b) FE Model with Priority Repairs, and Shear Stress Distribution on Northeast Girder in  (c) FE Deteriorated Model and (d) FE Model with Priority Repairs (results in Ksi) | |

**H&H Retrofit Plans**

The drawings submitted by H&H (H&H Progress Set August 6, 2010) have been carefully reviewed and integrated in the FE model with an appropriate level of detail. The same approach used for the priority repairs (discussed in the previous section) was used in modeling the sandwich plates. It was attempted to model the geometry of the plates as close to the repair drawings as possible. Also, Floor Beam 1 and Floor Beam 4 in the FE model were replaced with the new floor beams as noted in the H&H drawings. shows a sample of the drawings and the FE model of the retrofit plans.

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| (a) | (b) |
| Figure 7. (a) H&H Retrofit Plans for the Tip of Northeast Girder, and (b) FE Model of these Panels | |

The results from the FE model indicate decreases in both flexural and shear stresses compared to the deteriorated FE model. Figure 8 illustrates this comparison for a part of Northeast girder under load case FB3. One of the immediate findings from the comparison of these panels as well as the other panels subjected to retrofit is that although adding sandwich plates decreases the overall level of stress, stress increase is observed on the narrow uncovered strips on the panels which are not fully covered with the sandwich plates. This is due to the overall rigidity of the reinforced section which causes a distortion of the un-reinforced section and imposes stress increases on the portions of the panels that are not reinforced. The same phenomenon is observed on other panels which are not fully covered on the North and South Leaves. In general, and apart from the stress concentrations, the H&H retrofit plans help in increasing the load rating factors. It is recommended that if sandwich plates are to be added to any panel, these plates should cover the entire panel.

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| (a) | (b) |
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| (c) | (d) |
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| Figure 8. Flexural Stress Distribution on Northeast Girder in (a) Deteriorated FE Model and (b) FE Model with H&H Repairs, and Shear Stress Distribution on Northeast Girder in (c) Deteriorated FE Model and (d) FE Model with H&H Repairs (results in Ksi) | |

In addition to the bascule girders, H&H’s proposed repairs for the floor beams were evaluated and they have shown improvement (reduction) of stress levels for the floor beams under different loading cases.

**Pennoni’s Retrofit Concept (Diagonal Angles)**

As mentioned in the previous reports, Pennoni has developed the concept for the installation of diagonal truss members across the most deteriorated web panels of the bascule girders instead of adding two sandwich plates to the web plates. Different concepts have been considered and their constructability has been evaluated by Pennoni’s experienced field engineers. Finally, the concept of using diagonal angles along with filler plates, gusset plates and connecting angles was deemed the most feasible and effective concept. Details of this concept were developed in 3D drawings in Google Sketchup® and the members were sized using capacity design (more details were sent in the previous reports dated October 1, 2010 and December 7, 2010). illustrates the 3D presentation of the concept and the FE model for one of the panels. In modeling the gusset plates, the same approach of increasing the thickness is used, while the gap between the diagonal angles and the web plates is considered in the model. Body constraints are used to attach the diagonal members to the gusset plates.

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| (a) | (b) |
| Figure 9. (a) 3D Conceptualization and (b) FE Model for Pennoni’s Retrofit Concept | |

compares the results for the deteriorated FE model and the one with Pennoni’s concept diagonal members added to the FE model.

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| (a) | (b) |
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| (c) | (d) |
| Ksi | |
| Figure 10. Shear Stress Distribution on Northeast Girder in (a) Deteriorated FE Model and (b) FE Model with Pennoni’s Retrofit Concept, and Shear Stress Distribution on Northwest Girder in (c) Deteriorated FE Model and (d) FE Model with Pennoni’s Retrofit Concept (results in Ksi) | |

It appears from the FE model results that the diagonal member concept reduces the shear stress level on the panels and helps increase the load rating factors. However, this concept cannot be added to some of the panels in which the diagonals interfere with other bridge components (e.g. trunnion panels with rack bolts). For these panels the H&H retrofit plans were added to the FE model. Analysis results for the combined FE model (H&H and Pennoni retrofits) show good improvement in decreasing the level of stress on the panels. shows the suggested location for Pennoni’s retrofit concept and the panels for which the H&H retrofit plans are more constructible. Although it seems from the FE model results that diagonal members do not decrease the stress levels as significantly as the sandwich plates, they still appear effective in improving the stress level and distribution. In addition, the diagonal members weigh much less than the sandwich plates and require less field work for installation.

**Preliminary Conclusions and Recommendations**

From the discussions and results presented in the preceding sections the following preliminary conclusions and recommendations can be made:

* Priority repairs have improved the stress level and distribution on the panels they were applied.
* Shear and flexural stress levels are considerable on the deteriorated floor beams, which raises some concerns, expecially considering the fact that their replacement has been postponed an entire year.
* The H&H retrofit plans help reduce the stress level on the panels they are applied. However, in cases where the sandwich plates do not cover the entire panel, this approach also causes stress increases on the narrow strip of the height or the width of the panel which is left uncovered. It is recommended that if sandwich plates are to be added to any panels, these plates should cover the entire panel.
* The Pennoni diagonal member retrofit concept helps reduce the stress level and improve the stress distribution on the panels they are applied. Although this stress level reduction is not as much as the FE models with sandwich plates, these members are much lighter than sandwich plates and they are less labor intensive which makes this approach a more effective retrofit approach.
* For some panels, due to the interference with other bridge components (e.g. trunnion panels with rack bolts), the H&H sandwich plate approach appears more constructible. Therefore, a combination of Pennoni’s retrofit concept (diagonal members) and H&H’s retrofit plan (sandwich plates) is a reasonable retrofit plan.

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| Pennoni’s Diagonal Member Concept Instead of H&H’s Sandwich Plates on These Panels  H&H’s Sandwich Plates on These Panels |
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| Figure 11. Suggested Retrofit Scheme, A Combination of H&H’s and Pennoni’s Concepts |

The proposed retrofit concept design that includes bracing the panels of the main bascule girders is considered by our team as a preliminary design to prove the feasibility of the concept. The superior constructability of this concept relative to sandwiching web plates with additional plates has been verified. However, this or any other retrofit concept should not be applied unless a detailed design and failure-mode analysis is carefully performed and checked, and the impacts of the retrofit are carefully monitored before, during and after installation. We would further recommend that the County move forward with the anticipated long-term monitoring due to the delays that have surfaced regarding the temporary retrofit design. We had all anticipated the onset of retrofit construction immediately after the summer season, but now that the actual construction is being pushed back, it is essential that the bridge be instrumented so that we can monitor the continued health of the structure and become aware of intrinsic forces due to temperature changes, which may be far greater than live loads.

Pennoni Associates appreciates the opportunity of working with Monmouth County on this very exciting and important project. Should you have any questions or comments regarding the conceptual design or the results presented in this report, please do not hesitate to contact me. Thank you again for your consideration.

Sincerely;

**Pennoni Associates Inc.**

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David S. Lowdermilk, P.E.

Vice President