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Rigging and Bracing Stability: Considerations for Moving, Lifting and Placing a Non-Building Structural Module

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Abstract

The Westinghouse AP1000 pressurized water reactor is the safest and most economical commercially available nuclear power plant in the marketplace today. In order for the plant's design to provide an unequaled level of safety, economic competitiveness and more efficient and improved plant operations, the use of modularization during construction for both major structural portions of the Nuclear Island as well as for major mechanical systems and components has been employed. One of the major advantages of the AP1000 plant is that it uses modern, modular-construction techniques. The design incorporates vendor-designed skids and equipment packages, as well as large, multi-ton structural modules and special-equipment modules. Modularization has allowed construction tasks that were traditionally performed in sequence to be completed in parallel. The modular design promotes efficient site construction, including a shortened construction schedule; reduced field manpower, yielding reduced site congestion and increased site safety; and improved quality through off-site pre-testing and inspection, yielding less rework. This paper describes the challenges with the construction, rigging, and lifting stability of one of these large structural modules that will become the exterior wall of the In-containment Refueling Water Storage Tank.

1. Introduction

The In-containment Refueling Water Storage Tank located inside the Containment Building is one of the passive safety systems in the AP1000 design. Fig.1.1 shows schematically the IRWST available for use to assist in shutting down the reactor in case of an emergency. The portion of the IRWST that is of interest is the semi-circular exterior wall of the tank identified as the CA03 module. CA03 is comprised of 17 straight submodules that have been welded together as a large ground assembly creating the curved wall that will be rigged, lifted and properly positioned within the NI utilizing the heavy lift derrick (HLD). When this 'curved wall' was lifted for one of the AP1000 China plants under construction (see Fig. 1.2) the module experienced undesirable geometry distortion. Therefore, for the same module being installed in the AP1000 plants in the U.S. a new rigging and lifting plan was developed.

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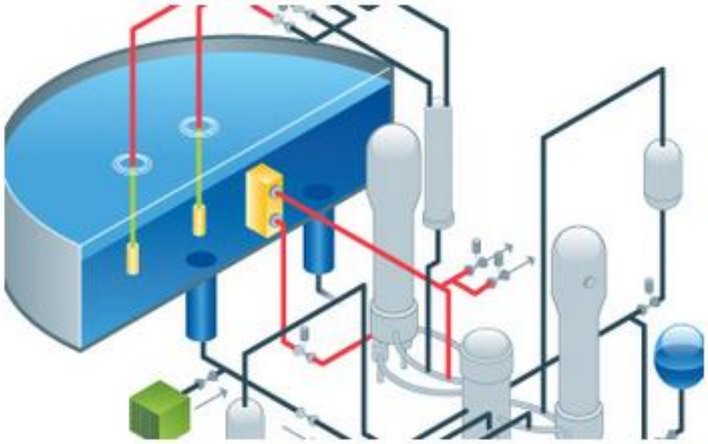


Figure 1.1: Schematic of In-containment Refueling Water Storage Tank (IRWST)

Figure 1.2: Original Rigging Design Utilized for IRWST in China

2. Detailed Description of Structure

The CA03 module is a combination of seventeen submodules assembled into one unit by complete joint penetration (CJP) welds. The inner fifteen submodules (submodules 02 through 16) are similar, having an overall height of 41 ft-10 in., a width of 9 ft-4 in., and a depth of 2 ft-6 in., measured from the outer faces of the flange plates. The typical submodules resemble double-tee beams, having a continuous, approximately 34 ft tall, 9 ft-4 in. wide by 5/8 in. thick (exterior) flange on one side, two 2 ft-4 in. deep by 3/4 in. thick webs at 4 ft-8 in. apart and 1 ft-4 in. wide by 1 in. thick flanges on the opposite side of the webs. Pairs of web stiffeners are located near the third points along the length of the web. The continuous flange plate is stiffened by angles having 4 in. or 6 in legs, welded to the plate at their toe. Above the flange plate is a curved plate resembling a hood. Below the continuous flange plate, the web tapers inward and individual exterior flange plates are used to form built-up wide flange sections resembling legs. These plates are studded to develop composite action after concrete is cast around them. Base plates located at the bottom of the legs have two holes to receive dowels/pins upon setting. While similar in most aspects, submodules 01 and 17 differ in that they each only have one web and the exterior flange is non-planar. When fully assembled, the overall dimensions of the CA03 module (not including the stiffening angles) are approximately 116’-5” x 47’-6” x 42’-6” (L x W x H) where the long direction is almost circular having a radius of nearly 120 ft. Overall dimensions of the CA03 module are shown in Fig. 2.1, and selected dimensions of Submodule CA03_08 are shown in Fig. 2.2.

The CA03 module is primarily made of ASTM A240 S32101 duplex stainless steel, which has an elastic modulus of 28,000 ksi, minimum yield strength of 65 ksi, and minimum ultimate strength of 94 ksi. The horizontal stiffening angles welded to the exterior side of the shell are made from ASTM A36 carbon steel, which has an elastic modulus of 29,000 ksi, minimum yield strength of 36 ksi, and minimum ultimate strength of 58 ksi.

The exterior (convex) side of the CA03 module supports various piping and other components; this outfitting is supported by brackets attached to the outstanding legs of the horizontal stiffening angles. After the CA03 module is set, a relatively narrow annular space exists between the exterior face of the module and the inside face of the Containment Building. To enable safe installation and inspection of the outfitting, the outfitting and supports are installed prior to lifting of the module.

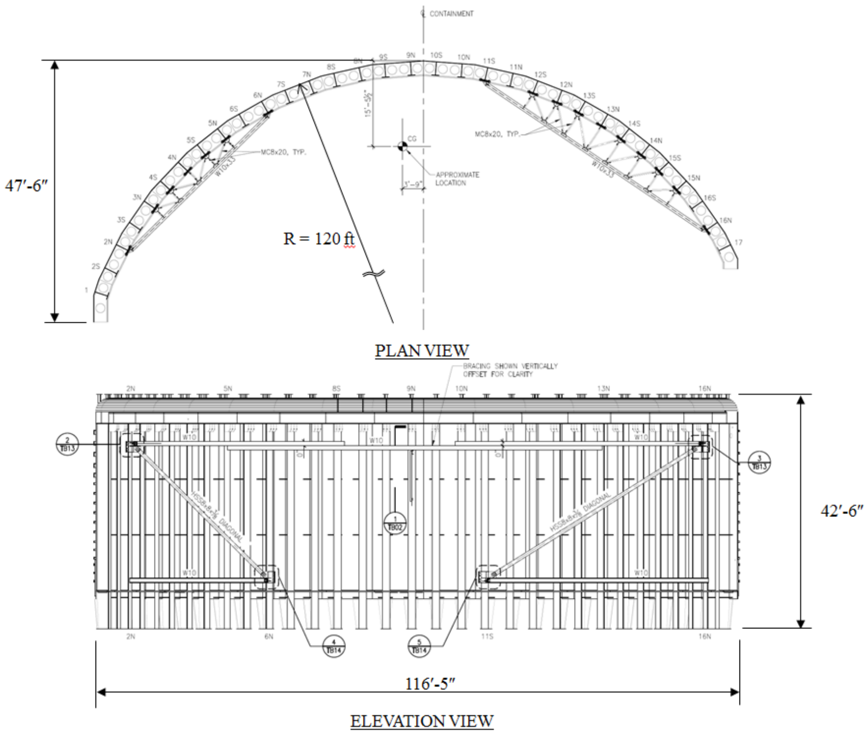


Figure 2.1: Overall Dimensions of CA03 Module with Anti-Deformation Bracing Utilized for IRWST in U.S.

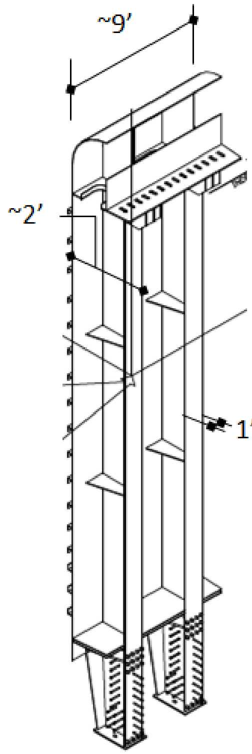


Figure 2.2: Submodule CA03_08

3. Summary from China

Construction of the first AP1000 unit began in China. The CA03 module was assembled and lifted into the Containment Building as part of the modular construction approach. The rigging arrangement included two levels of spreaders that resulted in a four-point lift. The vertical slings below the lowest level of spreader beams were relatively short. Chain falls were used between the hook and submodule 09 to help plumb the module. The CA03 module was lifted in one piece by a heavy lift derrick and was unbraced during the lift. A view of the CA03 module during the lift is shown in Fig. 1.2.

Observations of the CA03 module after setting within the Containment Building indicated the final dimensions were out of tolerance; permanent deformation had occurred, which was manifested by a curling of the module. Jacks were used to attempt to recover the original geometry, but a residual amount of permanent deformation remained after corrective action. After a thorough review, the final conditions were accepted, and lessons-learned were documented to improve assembly and installation at future sites. The lessons-learned included performing finite element analysis of the module under lifting conditions, and design and installation of multiple levels of anti-deformation bracing for the module prior to lifting. Subsequent lifts of the CA03 module at other nuclear sites utilized anti-deformation bracing to stabilize the model during lifting.

4. Case Study at US AP1000 Installations

To successfully navigate the modular construction approach, consideration must be given to preserve the integrity of the module throughout its life, from initial fabrication, through sub-assembly fabrication, full module assembly, lifting and setting and through any other means of transport from stage to stage.

The following sections of this paper will discuss how stability considerations were addressed during CA03 module assembly prior to lifting and as part of the rigging design and design of anti-deformation bracing for the module during lifting at AP1000 installations at two U.S. sites.

4.1. Module Assembly Prior to Lifting

As previously noted, the CA03 module is made from seventeen submodules. The geometry of each of these submodules is such that when standing upright on its feet, the distance from the base to the center of gravity is significantly longer than the width of the base. Global stability of an unanchored or unbraced submodule or even a small assemblage of submodules is a concern. Unless braced or otherwise anchored to supporting installed structures, each submodule or small assemblage of submodules is potentially subject to overturning, rocking, and/or sliding from wind forces (if exposed) and/or accidental contact with temporary construction equipment. Unstable or uneven/sloping base support conditions can contribute to stability concerns if these conditions exist.

A properly designed and installed temporary bracing system can be used to alleviate global stability concerns during construction. The bracing system must possess sufficient strength and stiffness to prevent sliding, rocking, overturning, or deformation of the assemblage in any way. Additionally, it must be configured to allow assembly of the module, addition of the outfitting and installation of the lift bracing with little or no rework. The system must fit within any temporary enclosures used for fabrication/assembly to allow safe access and mobility of equipment and personnel.

Strength and stability of the bracing components, the connections, and the structures to which the bracing attaches, must be considered. A summary of the design of temporary bracing for the CA03 module during construction at one of the AP1000 installations in the U.S. follows.

At one nuclear power station in the U.S., the submodules were fabricated and assembled inside several tents. However, to complete installation of the temporary lift bracing and rigging, the tents had to be opened. Concerns about module stability (sliding, rocking, and overturning) during potential wind events arose. To alleviate project risk, a temporary bracing plan was developed to help ensure stability of the CA03 module until it was ready to be lifted into place.

The project required temporary bracing be designed to maintain stability of the CA03 module during a 40 mph wind. Module assembly was performed on a reinforced concrete slab. The contractor’s work area inside the tents had insufficient clearance for bracing and equipment mobility on the exterior (convex) face of the module. To the extent possible, the contractor wished to use equipment and materials already available onsite.

The bracing designers computed the wind pressures using appropriate modification factors from ASCE/SEI 7-10 and shape factors that accounted for the curved geometry of the module. Finite element analysis showed that the unbraced module was expected to be stable for sliding and overturning, but local uplift or rocking could occur when the design wind blows against the interior (concave) side. The contractor decided to brace the module, so a design was developed.

Fig. 4.1 shows a plan layout of the temporary wind bracing design, which was implemented successfully. The bracing design included the use of Burke braces at submodules 01, 02, 16, and 17 to prevent rocking. The brace shoe was welded to a larger stiffened base plate that was anchored to the supporting concrete slab with expansion anchors. To prevent sliding and local uplift, the bracing design also included the use of fabricated hold down assemblies at each of the legs; the hold downs at the end two legs on each side were larger than the others. These hold down assemblies consisted of fabricated steel frames that were clamped to the module and anchored to the base slab by expansion anchors in the typical condition and by undercut anchors at the end frames.

During the design process, the following observations were made:

- Because no bracing was allowed on the convex face of the module, the bracing system was required to act in tension and compression depending upon the wind direction.
- The available pipe-type braces were much stiffer than any reasonable quantity and size of wire rope-type braces such that they could not effectively be used together.
- The Burke braces themselves had sufficient capacity in tension and compression, but the connections required modification/strengthening to transfer brace tension forces.
- The available post-installed expansion anchors were insufficient to resist the combined uplift and shear demands at some bracing bottom connections and required a different anchor (undercut anchor).

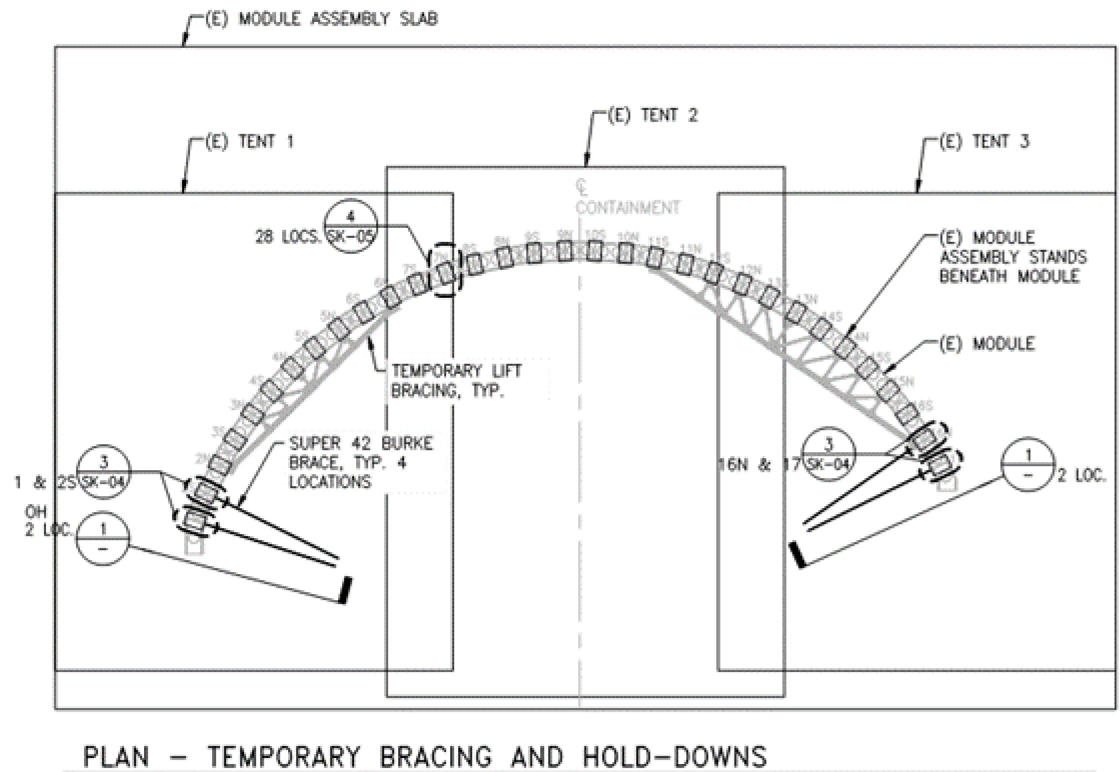


Figure 4.1: Plan Layout of the Temporary Wind Bracing Design

4.2 Rigging Design

Design of the rigging arrangement for the CA03 module needed to consider a number of factors to establish a stable and successful lift. The module had to be lifted by the HLD from its assembly area, flown above the Containment Building, properly oriented, and lowered in an upright condition between the cylindrical wall of the Containment Building and the CA01 and CA02 modules that had been previously installed. The rigging arrangement needed to possess appropriate levels of strength, stiffness and adjustability to allow this activity to occur successfully.

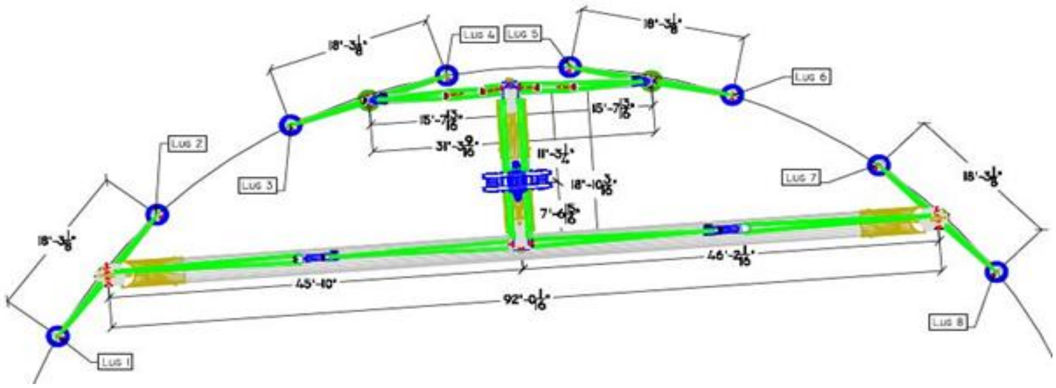
Initially, the CA03 module was to be lifted at four points positioned at the top of the module as was used in China. After review of the lift lug design and the demands imparted to the module at these concentrated locations, changes were made to the design of the lifting lugs and the number of lugs doubled to eight, located at the top of the module. This change required a new rigging arrangement, which was designed by the contractor's rigging engineers using computer software, their experience and expertise, and input from the lift bracing designers. Fig. 4.2 shows the location of the lift lugs in plan and elevation view.

A photo of the final rigging arrangement for the eight-point lift is shown in Fig. 4.3. The rigging arrangement included four levels of slings and three levels of compression members. The total height of the rigging arrangement approached 180 ft. TPXC/TPXCF Twin Path synthetic roundslings were used as tension members. Enerpac pull cylinders were used to provide adjustability in the top level of rigging, and Van Mechelen TR Series turnbuckles were used in line with the slings to provide the necessary adjustability in the second level of rigging.

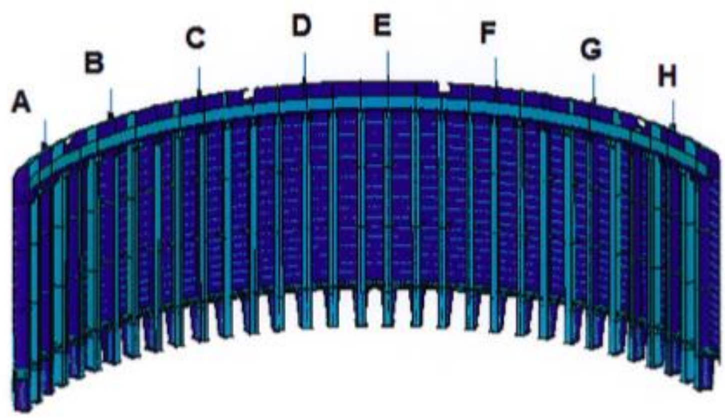
Tandemloc and Versabar pipe assemblies were used as compression members. The total weight of the rigging, including shackles, swivels and the above-mentioned parts, was approximately 127 kip, compared to the 474 kip estimated combined weight of the CA03 module, outfitting, and lift bracing.

The boom and hook height on the heavy lift derrick enabled the use of the 180 ft tall rigging arrangement, but other factors affected the design of the rigging. The mass of the total lifted load and the layout of the lift lugs necessitated the selection of certain components to ensure forces remained below the safe working loads (5:1 safety factor per ASME Standard B30.9) of each of the components. The design of the lift lugs required that the lowest level slings impart only vertical forces to them. The use of the 92 ft long compression member helped create a vertical pull on the lift lugs.

As the CA03 module was lifted, it rotated until the center of gravity was positioned vertically below the hook. Locating the lifting lugs above the center of gravity helped ensure a stable lift, and locating the lift points such that they box-in the location of the module center of gravity limited the amount of rotation and made it possible to adjust the rigging to plumb the module. Prior to making the actual lift, the module was raised slightly above the assembly location to verify proper rigging installation and inform the riggers as to which adjustments were required to allow the module to hang upright from the rigging. The pull cylinders and turnbuckles were adjusted as needed, and the process was repeated until proper conditions were realized.



(a) Plan View



(b) Elevation View
Figure 4.2: Eight-Point Lift Rigging Arrangement

Figure 4.3: Rigging Arrangement for CA03 Module Lift at Vogtle Unit 3

4.3 Design of Anti-deformation (Lift) Bracing

As previously noted, the CA03 module has a unique shape that is susceptible to deformation during lifting. Preventing yielding, buckling and significant elastic deformation throughout the lift was vital to its successful installation and mating with adjacent construction. In accordance with the lessons-learned from the initial CA03 module lift in China, finite element analyses were performed to analyze the unbraced module under lifting conditions and to help design anti-deformation bracing to maintain the geometry of the module during the lift.

4.3.1 Finite Element Analysis

ANSYS Mechanical APDL Release 15.0 was used to perform finite element analysis of the CA03 module with outfitting and bracing under lifting conditions. The overall geometry of the CA03 module and dimensions of the individual components were modeled based on the module design and fabrication drawings. The model is representative of the actual geometry and includes all components judged critical to the behavior of the module during lifting and setting. Fig. 4.4 shows an overall view of the model and rigging arrangement.

Material properties were assigned to elements based upon typical properties at expected ambient temperature. Weight of supported loads (outfitting) was included in the model using point mass elements. Weight of bracing members was increased to account for non-modeled end connection plates and hardware. Weight of the rigging was not included in the analysis model as it was judged not to have significant impact on the structural behavior of CA03 during the lift. Section geometry for the module was defined based on the design/fabrication drawings, and the bracing geometry was defined using dimensions for standard steel shapes as reported in the AISC *Steel Construction Manual*, 14th Edition.

Module flange and web plates were modeled with shell elements using ANSYS element type SHELL181. Angle stiffeners were modeled with beam elements using element type BEAM188 spanning circumferentially along the module outer shell nodes. Section offsets were used to properly locate the angle stiffener's cross section center away from the module outer shell centerline. Bracing members were modeled with BEAM188 elements. Multipoint constraint elements (element type MPC184) were used at bracing end connections to impose pinned conditions (no transfer of moments). Rigging members were modeled with beam and truss elements using element type BEAM188 and LINK180 elements, respectively. Outfitting loads were modeled with point mass elements using type MASS21 elements. Horizontal outfitting supports were modeled with BEAM188 elements, and diagonal outfitting supports were modeled with LINK180 elements. BEAM188 elements have full bending properties. LINK180 elements behave as truss members, transmitting only axial forces.

One node, restrained translationally in the global X, Y, and Z directions, was used at the top of the rigging arrangement to support the model. In addition, soft rotational springs (COMBIN14 elements) were used at the top of the rigging arrangement to stabilize the model against spinning about the global Z (vertical) axis. In reality, some frictional resistance to rotation exists at the crane hook and the module has rotational inertia, but those were not captured in the model.

The finite element model was created to capture important structural behaviors. The mesh of shell elements was relatively fine to capture local stresses, deformation and buckling modes. Fig. 4.5 shows part of the upper interior portion of the module, including some of the upper level bracing members. As seen in this figure, multiple beam elements are used along the bracing members to capture bending and buckling behaviors. Although it is not apparent in the model images, MPC184 elements are used to create hinges at each of the brace end connections (all brace-to-module connections, all web-to-chord connections).

At each of the eight lift lugs (Submodules 2, 4, 6, 8, 10, 12, 14 and 16), as shown in Fig. 4.6, the finite element model utilized the CERIG option, which defines a rigid region using constraint equations, to help distribute the concentrated demand at one node at the shackle to seven nodes at the top of the lug plate hole. This approach was intended to transfer bearing force to a region representing the pin bearing area at the top of the hole and to avoid loading a single node, which may cause unrealistically high local demands. The finite element mesh of the lift lug was intended to provide a proper load path between the rigging and the module only, and not intended to accurately calculate stresses in the lift lug. Hand calculations were performed to check the adequacy of the lifting lug design.

The module was analyzed for the following loadings:

- Self-weight of the module, outfitting and temporary bracing to determine the weight and center of gravity of the lifted load.
- Self-weight of the module, outfitting and temporary bracing with a 1.1 load factor on weight estimates and an additional 1.1 dynamic amplification factor.
- Wind pressures from 10 mph and 20 mph wind in the east-west direction, north-south direction and at a 45° plan offset.

It was important to capture the full weight of the structure in the model and to accurately represent the center of gravity. The unit weight of bracing elements was increased by 20% to account for non-modeled connection components, including hardware. As requested by the contractor, a load factor of 1.1 was used on the dead load to account for uncertainties in weight estimates.

A dynamic amplification factor (DAF) was computed based on the stiffness of the rigging design and potential initial and final line speeds. A DAF of 1.1 was applied to the suspended load to account for vertical acceleration of the module during lifting and setting. This value was calculated using the unfactored total weight of the lift excluding rigging weight and the average vertical displacement of the module extracted from the finite element model. The calculations account for the flexibility of the rigging and module, but exclude any flexibility of the crane and cables above the hook. Principles of structural dynamics (Chopra 1995) indicated that a DAF of 1.1 is achieved when the module weight was completely transferred from the ground to the hook after 4 sec. This translated to an initial lift velocity of 17 ft/min., which exceeded the maximum intended line speed and therefore a dynamic amplification of less than 10% was expected. Fig. 4.7 shows that the dynamic amplification will remain below 1.1 as the rise time (t_r) is increased, which is accomplished by decreasing the line velocity (v).

Wind pressures were computed based on provisions in ASCE/SEI 7-10 considering Exposure C conditions and the geometry of the module and treating the CA03 module as a solid sign with the bottom of the module elevated above the ground. Pressures were considered uniform across the entire projected area of the module.

A number of load combinations were analyzed to capture the combined effects of factored and amplified dead load and wind pressures. In addition to these load combinations, which were used to design the bracing members, the analyses included a simulation for unfactored dead loads to establish the total weight and center of gravity. In addition, a modal analysis was performed to check for proper element connectivity and behavior, and an elastic buckling analysis was performed to check for component buckling.

Geometric nonlinear static analyses, using element types capable of exhibiting large deflection behavior, were performed to check the stresses and deflections of the CA03 module and temporary bracing under the effects of gravity and wind.

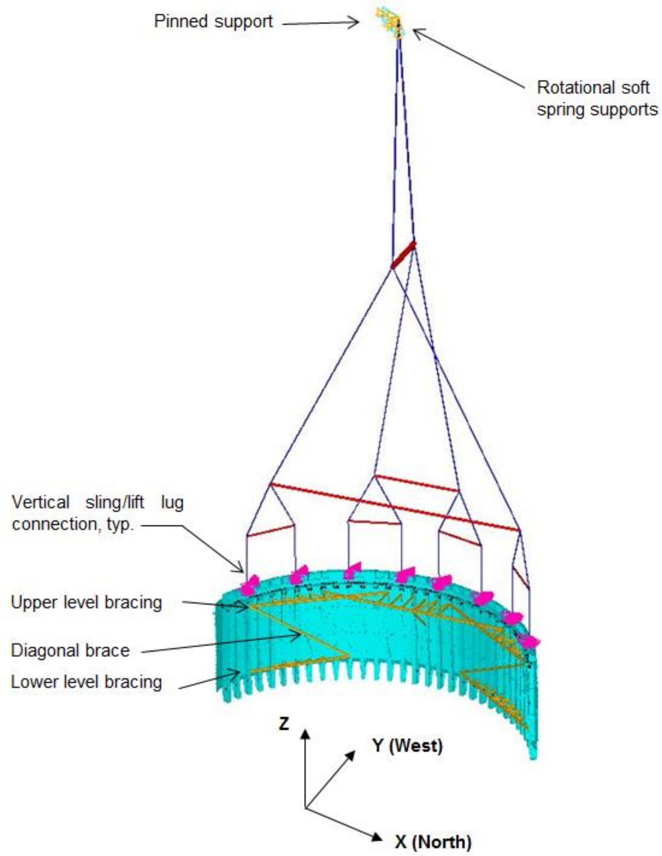


Figure 4.4: Overall View of the Finite Element Model Looking West Toward the Inboard Side

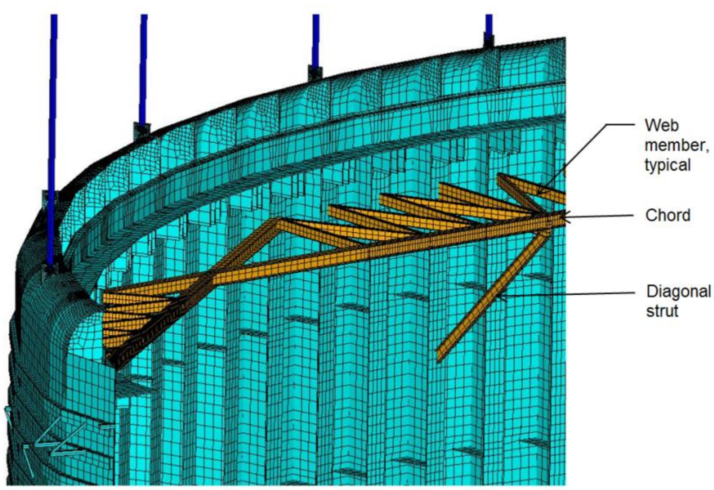


Figure 4.5: Close-Up of the Finite Element Model Showing Detail at Top and Upper-Level Bracing with Diagonal Support

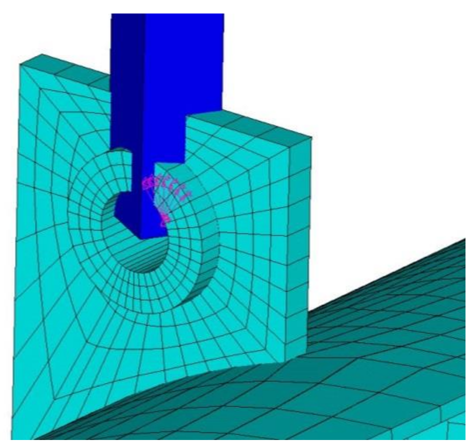


Figure 4.6: Close-Up of the Finite Element Model at the Lifting Lug

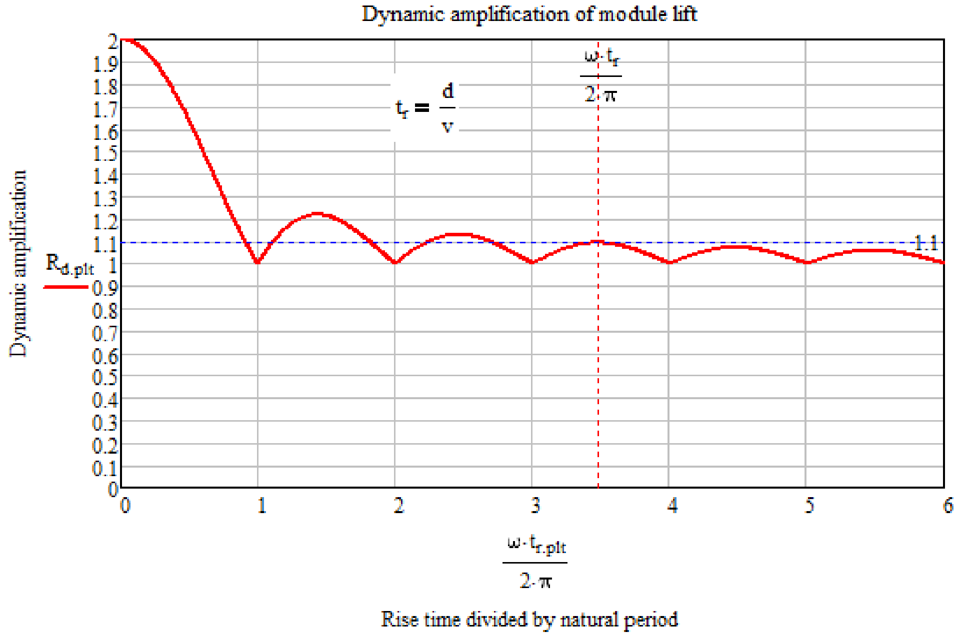


Figure 4.7: Evaluation of Dynamic Amplification Factor

5. Results

5.1 Rigid Body Motion

During lifting, the entire CA03 module will move as a rigid body relative to the hook, and certain components of the module will move relative to other module components. In nonlinear static analyses, ANSYS reports total displacements that include rigid body motion and any effects from the soft springs. The total displacements are useful to design rigging, but rigid body motion must be separated from the total motion to isolate structural deformations. In this paper, rigid body motion is separated into two categories: (1) displacement and rotation based on a pendulum-type mode, and (2) displacement and rotation based on a global torsional mode.

By performing nonlinear static analysis, large displacements caused by a misalignment of the hook (support point) and the center of gravity of the module are captured; this phenomenon is referred to herein as the pendulum-type mode. The module rotates such that the center of gravity and the support points align vertically. However, because the model is supported by a pin at the crane hook, and the rigging does not restrain the module from rotating about the vertical axis, soft springs are required at the top support point to provide the necessary resistance for stability.

The application of wind pressures, particularly at 45°, causes the module to spin about the vertical (global Z) axis; this phenomenon is referred to herein as the torsional mode. In the model, rotational soft springs resist this motion, but in reality this motion must be resisted by other means. Hand calculations were prepared to estimate the angular velocity of the CA03 module about the vertical axis about the crane hook due to wind loading.

The FEA results were post-processed to remove rigid body motion calculated by ANSYS. First, rigid body motion caused by translations about each global axis was computed and removed, and rigid body motion caused by rotations about each global axis was then computed and removed.

To highlight the ANSYS-computed rigid body portion of the total deflections, deflections are reported that include and also exclude rigid body motion.

Calculations were performed to estimate the angular velocity of the CA03 module about the vertical axis about the crane hook due to wind load (torsional mode). The approximate angular velocity was computed by using the unbalanced moment about the vertical axis about the center of rotation through the crane hook along with the mass moment of inertia of the module. The calculations considered constant wind 20 mph wind velocity, and neglected any damping or torsional resistance caused by friction or other rigging lines. The condition that produces the greatest spinning is wind at 45°; the module would rotate nearly 17°. The calculations showed that if four tag lines were used to prevent spinning, two at each of Submodules 1 and 17, forces of approximately 600 lbf would be required at each line if the bottom of the module is at 75 ft above grade.

5.2 Weight and Center of Gravity

Table 5-1 shows a summary of the total modeled mass and weight by general categories. The mass of the bracing elements includes a 20% increase to account for un-modeled connection plates.

Table 5-1: Weight Summary

Description	Weight (kip)
Base module	446.5
Outfitting	4.8
Bracing	22.5
Total	473.8

Table 5-2 shows a summary of the total modeled weight and location of the center of gravity (CG) based on the reference origin. The CG is shown in Fig. 2.1.

Table 5-2: Center of Gravity Summary

Description	Weight	CGX	CGY	CGZ
Module + Outfitting + Bracing	474 kip	11,955 in. (996 ft-3 in.)	12,572 in. (1,047 ft-8 in.)	1419 in. (118 ft-3 in.)

5.3 Reactions

The total lifted weight, including braces, 1.1 load factor and 1.1 dynamic amplification factor, is 574 kip. The total wind load is 5.3 kip for wind in the X-direction case. The total wind load is 7.3 kip for wind in the Y-direction case. The total wind loads in the X- and Y-directions are 4.2 and 4.2 kip, respectively, for wind in 45° cases. The soft rotational springs have little impact on the calculated stresses and distortion within the module, as the total wind load itself is less than 2% of the dead load.

5.4 Deflections

Analysis cases without wind loads showed little lateral and rotational movement, indicating that the crane hook was located properly above the module CG and that the rigging configuration provided adequate uniform lift stiffness at the rigging lifting points. Cases with wind loads show that at a 20 mph wind, the lateral displacements could be as high as 3.5 ft.

Most of the displacements were attributed to rigid body motion of the module, which must be removed to determine the distortions, or structural displacements, within the module. This was done by subtracting the three average translational displacements within the module and also three rotations (about the two horizontal and vertical axes located at mean nodal coordinates) to minimize the displacements.

A comparison of displacements for a case without and with wind load is shown in Fig. 5.1. For the case without wind load, the peak total displacement as indicated in the analysis is 0.3 ft, vs. 3.2 ft for the case with a 20 mph wind blowing toward the southeast. The displacements are not appreciably affected by the presence of the soft rotational springs.

Under factored self-weight, the maximum total structural displacement in the braced module is 0.3 in. The maximum structural displacement in the X, Y, and Z directions is 0.2 in., 0.2 in., and 0.2 in., respectively.

Under factored self-weight and wind load, the maximum total structural displacement in the braced module is 2.14 in. Maximum structural displacement in the X, Y, and Z directions is 0.3 in., 0.2 in., and 2.1 in., respectively.

The values noted above indicate that the temporary lift bracing design was effective in maintaining the shape of the module. All of these displacements were related to elastic behavior and disappeared once the CA03 module was set inside the Containment Building.

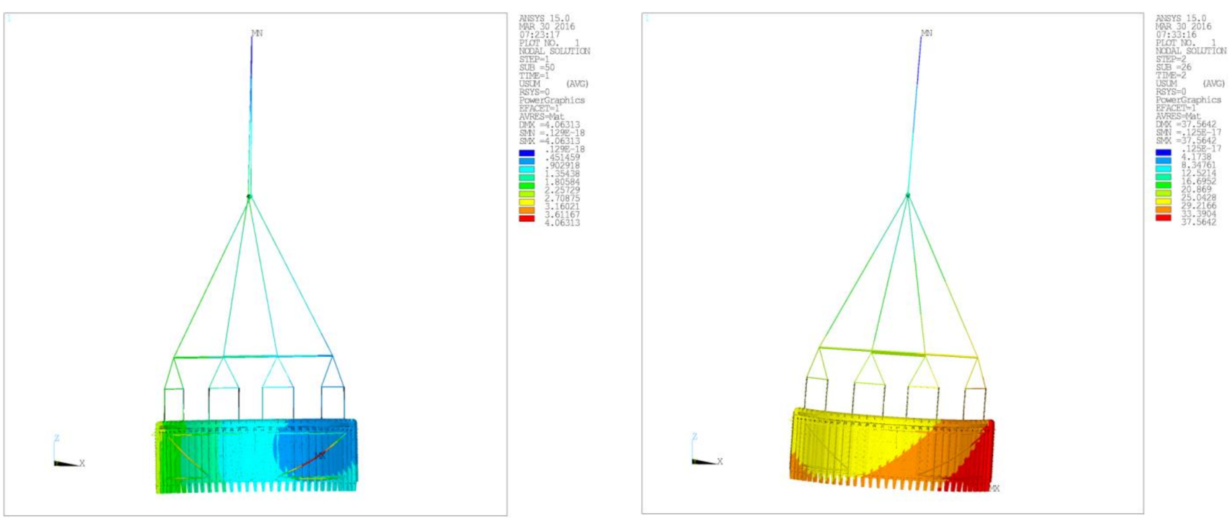


Figure 5.1: Deformed Shape (x10) with Total Displacement Contour (in.) Before Removing Rigid Body Motion (a) 1.1x1.1x (Self-Weight + Outfitting + Bracing) (b) 1.1x1.1x (Self-Weight + Outfitting + Bracing) + 20 mph Wind at 45°

5.5 Stresses

Fig. 5.2 shows von Mises stresses with the stress limit capped at 1 ksi. The allowable stresses in beams is 15.6 ksi. Note that the allowable stress for plates is higher, at 31.2 ksi. For all cases, all elements complied with the acceptance criteria for stresses, with the exception of some elements located at or near the lifting lugs. These overstresses were caused by stress concentrations at the rigid connection between the module and the rigging members and can be neglected. Excluding these overstresses, the maximum von Mises stress in the module is approximately 20.4 ksi, which occurs at the connection to the lifting lug attachment in Submodule 14. Away from lifting lug attachments, stresses in the CA03 module are less than 7 ksi, and typically much lower.

In comparison to the gravity loading, wind load contributes little to the stresses and deformations in module elements. The primary effect of the wind load is rigid body displacement. As shown in Figure 5.3, the highest stresses are at the lifting point region. For all cases the stresses are below the acceptable criteria.

The values noted above indicate that the temporary lift bracing design was effective in preventing overstresses in the module. All of these stresses were well below the yield stress of the particular material.

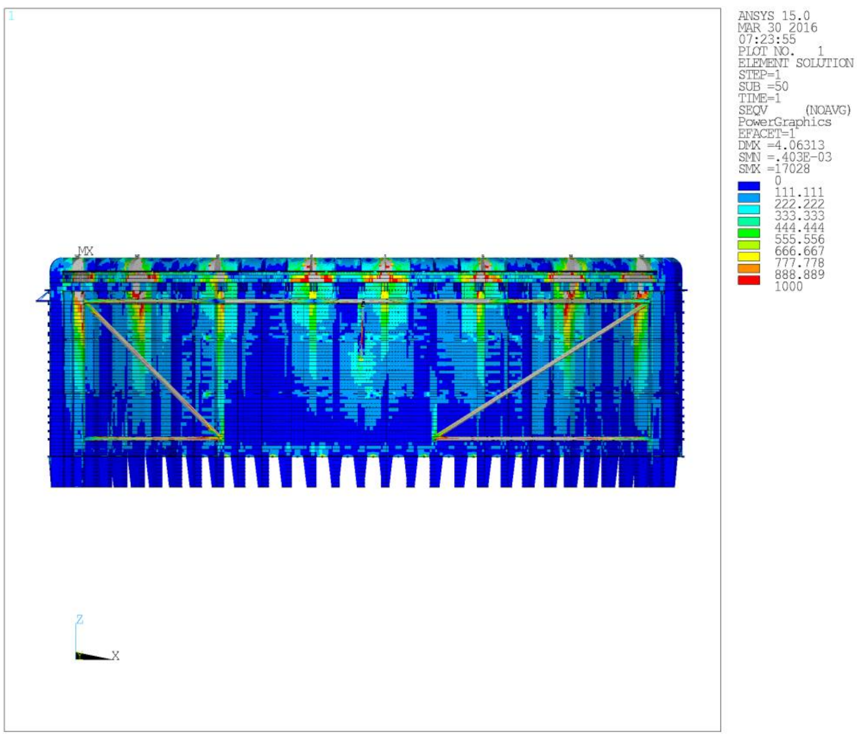


Figure 5.2: von Mises Stress Contour (psi) with 1 ksi Limit – Elevation View Looking along Y-Direction –1.1x1.1x (Self-Weight + Outfitting + Bracing)

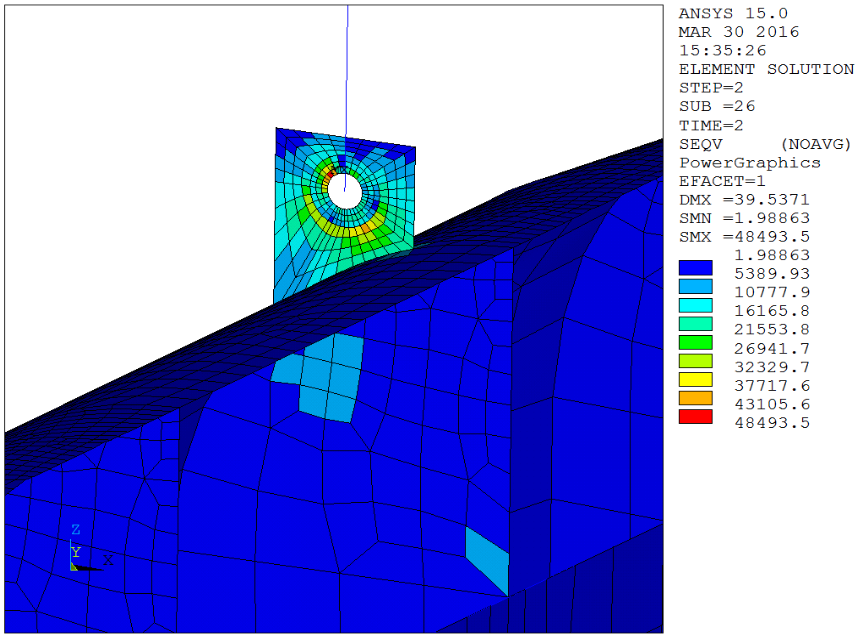


Figure 5.3: von Mises Stresses at Submodule 02 Lift Point for Factored Gravity + Wind Load Case

5.6 Elastic Buckling Results

The nonlinear analyses performed capture large deflection effects and structural instability, if any exist. In addition to those analysis cases, elastic buckling analyses were performed by rerunning the factored gravity load case for eigenvalue buckling analysis. Buckling analysis indicated that elastic local buckling of the CA03 module would not occur during the lift.

6. Lift Bracing Design

Dimensional stability of the CA03 module was critical since it needed to be lowered into a tight space, land in a designated location, and mate with adjacent construction already installed. Permanent deformation in the module was unacceptable, and excessive elastic deformation would complicate the lowering and landing processes. Therefore, an AISC allowable stress design (ASD) approach was used that would not permit yielding. To increase margin against plastic deformation, additional safety factors were incorporated into the design beyond those required by AISC ASD. In accordance with project criteria, typical AISC ASD allowable stresses in the module components were reduced by safety factors of 1.25 for plates, angles and beams and 2.0 for welds. This limited stresses in module plates to 31.2 ksi, module beams to 15.6 ksi and welds to 14.2 ksi. The limiting stress in stiffening angles was 17.3 ksi. The typical ASD allowable stresses were used in design of the temporary bracing elements. In the end, the stiffness and constructability of the bracing system significantly affected the design, possibly more so than the strength of the individual components.

The bracing layout used for the U.S. installations was based on the design used in China and refined to reduce weight, eliminate unneeded components and address contractor preferences. While the CA03 module is nearly symmetrical about one axis, the bracing layout was nonsymmetrical because it needed to avoid contact with the previously installed CA01 module. The lift bracing used in China used welded connections to the module and between bracing components. At one of the U.S. nuclear plants, the contractor requested that connections, at least connections to the module, be clamped in some fashion to minimize welding to the CA03 module. The design of this bracing utilized some creative solutions, which are summarized in the following paragraphs.

The temporary anti-deformation lift bracing design consisted of a row of bracing near the top of the module, a row of bracing near the bottom of the typical portion of the module just above the legs and two diagonal members that attached to the module at places where the upper and lower portions of the bracing connected to the module. An additional diagonal bracing member was used to provide vertical support to the upper level of bracing. The bracing is shown in Fig. 6.1.

The bracing chord members were W10x33 sections made of ASTM A992 Grade 50 steel. The web members were MC8x20 sections made of ASTM A36 steel. The long vertical diagonal members were HSS 8x8x0.375 sections made of ASTM A500 Grade B steel. Connection plates between bracing members were typically 1/2 in. thick sections made of ASTM A572 Grade 50 steel. To avoid all welding or contact between carbon steel and the inside face of the module, connection plates used to attach the bracing to the module were either ASTM A240 S32101 duplex stainless steel (same as the module) or ASTM A240 S3403 (304L) weldable stainless steel. Half-pipe sections used at connections were HSS 12.750x0.500 sections made of ASTM A500 Grade B. Bolts were 7/8 in. diameter ASTM A325 with associated washers and nuts.

Figure 6.1: Anti-Deformation Bracing: One row near the top of the CA03 module, and another row near the bottom portion just above the legs; two diagonal members are used between the top and bottom rows of bracings

6.1 Connection Details

All connections between module components were single shear plate connections. Slotted holes were provided in each of the members to allow for adjustability. All connections were designed and specified as slip-critical connections with carbon-carbon steel faying surfaces meeting at least Class A requirements (0.3 slip coefficient). Where multiple members attached to a chord or module flange, plates with standard holes were welded to round HSS sections that had been cut in half to provide clearance for the connections. At chord splice connections, MC8x20 sections were bolted to the top and bottom flanges to transfer forces between the W10x33 sections.

Lift bracing member connections to the module were developed to minimize welding to the module and to prevent direct contact between the carbon steel brace members and the duplex stainless steel module. A clamped connection was developed using a face plate, two back plates, spacers, and pretensioned A325 bolts to squeeze the module flange and therefore create sufficient friction to resist the demands on the connection. The size of shims/spacers could be modified as needed to accommodate fabrication tolerances or non-planarity of the module flange. A stainless steel seat angle was welded to the module flange to facilitate installation of the clamped connections and provide redundancy in supporting the weight of the bracing and any construction workers. Typically welded to the face plates were half-pipe sections with tabs or extended and stiffened half-pipe sections with tabs to create space for fit-up when multiple bracing members converged at one location. Fig. 6.2 shows some of these connections.

Connections to the module involving the vertical diagonal bracing members were somewhat challenging to design and detail. At these four locations, both a horizontal chord member and a vertical diagonal meet near the module flange, and the geometry was quite complex. To allow for assembly, the work points were offset 4 in. inboard from the face of the module flange, and the corresponding eccentricities were considered in the design. The connections to the module included a welded seat angle with an elongated version of the clamped connection as described above plus a welded angle located above the clamp plate as a secondary means to prevent the diagonal brace forces (compression) from sliding the clamped connection upward. Fig. 6.3 shows an installed clamped connection assembly prior to brace installation. Diagonal brace end connections consisted of a welded cap plate with a projecting plate having slotted holes to attach to the clamped assembly that has standard holes.

Figure 6.2: Connections at Top Bracing Row

Figure 6.3: Clamped Connection Assembly Prior to Brace Installation

6.2 Laboratory Testing

Parameters for the design of slip-critical (friction-type) connections using stainless steel bolts and/or faying surfaces are not well established (Baddoo 2013). The project team did not find any published values for slip coefficients with stainless steel plates as part of a connection assembly. Recognizing that slip coefficients when one or both faying surfaces is stainless steel would be lower than if both faying surfaces are carbon steel, the designers selected an expected-to-be conservative value of 0.2 as a slip coefficient compared to 0.3, which is typically used for Class A faying surfaces in AISC 360-10 for carbon steel. Under the allowable stress design methodology, Section J3.8 of AISC 360-10 requires a safety factor of 2.14 for bolts in long-slotted holes. To maintain the use of AISC 360-10 provisions, except for the slip coefficient, the design uses ASTM A325 bolts rather than high-strength stainless steel bolts.

To verify the appropriateness of 0.2 as a slip coefficient, Simpson Gumpertz & Heger Inc. conducted a series of slip tests in their in-house laboratory in Waltham, Massachusetts. The testing generally followed the approach used to determine the slip coefficient of coatings, which is presented in Appendix A of the *Specification for Structural Joints Using High-Strength Bolts* (RCSC 2009). The results of the testing confirmed that the use of a slip coefficient of 0.2 is acceptable. As expected, higher slip coefficients were achieved for the stainless steel-carbon steel plate configurations than for the stainless steel-stainless steel plate configurations. The testing showed that surface preparation by manual wire brushing and cleaning with water improved performance over the surfaces that were not fully prepared, and this instruction was provided on the temporary bracing design/installation drawings.

7. Conclusions

1) Modular design can be very beneficial to the construction of AP1000 units; however, care must be exercised to maintain the stability of submodules and modules throughout their construction life, from initial assembly through the lifting and setting processes.
2) The CA03 module has a unique shape that is subject to global stability during assembly and plastic deformation during lifting.
3) With the benefit of finite element analysis, temporary wind bracing was designed and then used to ensure safety and stability of the CA03 module prior to lifting.
4) Proper rigging design ensured safety during lifting and setting of the CA03 module.
5) With the benefit of finite element analysis, anti-deformation lift bracing was designed and then used to ensure safety and stability of the CA03 module during lifting and setting.

Acknowledgments

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