IRWST Sump Strainer and Trash Rack Structural Analysis

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ABSTRACT

This technical report describes the structural qualification of the floor/plenum mounted cartridges for APR1400 IRWST Sump Strainer and Trash Rack located in the entrance of HVT. The strainer design of Transco Products Inc. (TPI) is utilized and the structural qualification of APR1400 IRWST Sump Strainer was performed by Structural Integrity Associates, Inc. (SI), subcontractor of TPI. The structural analyses of IRWST Sump Strainer and Trash Rack were provided hereto.

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LIST OF ACRONYMS

APR1400	Advanced Power Reactor 1400
ASME	American Society of Mechanical Engineers
CAD	Computer Aided Design
CFR	Code of Federal Regulations
CQC	Complete Quadratic Combination
CSS	Containment Spray System
ECCS	Emergency Core Cooling System
FEA	Finite Element Analysis
IRWST	In-Containment Refueling Water Storage Tank
ISRS	In-Structure Response Spectra
KHNP	Korea Hydro & Nuclear Power Co., Ltd.
LOCA	Loss-of-Coolant Accident
NPSH	Net Positive Suction Head
NRC	US Nuclear Regulatory Commission
OBE	Operating Basis Earthquake
RG	Regulatory Guide
SI	Structural Associates, Inc.
SIS	Safety Injection System
SRP	Standard Review Plan
SSC	Structure, System and Components
SSE	Safe Shutdown Earthquake
TPI	Transco Products Inc.
US	United States of America
ZPA	Zero Period Acceleration

1. IRWST SUMP STRAINER STRUCTURAL ANALYSIS

1.1 INTRODUCTION

The APR1400 has four (4) Emergency Core Cooling System (ECCS)/Containment Spray System (CSS) trains with an independent 604.27 ft^2 [Reference 9] strainer for each train for a total of 2,417.08 ft^2 [Reference 5 and 9]. The design requires a minimum of three trains in operation (1812.81 ft^2, [Reference 5 and 9]) assuming one train with a single failure. The strainers prevent debris from being ingested into the Safety Injection System (SIS) and CSS in the event of a loss-of coolant-accident (LOCA) and are located within the IRWST.

If a LOCA inside the reactor building were to occur, it could generate debris that, if transported to and deposited on the recirculation sump strainers, could challenge the safety function of the recirculation sumps. Debris can block openings or damage components in the systems served by the IRWST pumps. Specifically, debris that could accumulate on the sump strainers would increase head loss across the resulting debris bed and sump strainers. This head loss might be sufficiently large such that it may exceed the net positive suction (NPSH) margin of the SIS and CSS pumps that draw from the sump. The IRWST sump (also known as the emergency or recirculation sump) is part of the ECCS. Every nuclear power plant in the United States of America (US) is required by regulation (i.e., 10 CFR 50.46, [Reference 13]) to have an ECCS to mitigate a design basis accident. The emergency core cooling system is one of several safety systems required by the US Nuclear Regulatory Commission (NRC). The IRWST sump collects reactor coolant and chemically reactive spray solutions following a LOCA. The IRWST sump serves as the water source to support long-term recirculation for the functions of residual heat removal, emergency core cooling, and containment atmosphere cleanup. This water source, the related pump inlets, and the piping between the source and inlets are important safety components.

The objective of this Technical Report is to provide the structural qualification of the floor/plenum mounted cartridges for APR1400 IRWST Sump Strainer developed by TPI. The analysis includes modal, response spectrum and static structural finite element analysis (FEA) conducted using ANSYS [Reference 1], and includes the calculation of the maximum stresses of the cartridge components at critical design conditions.

The strainers are evaluated for design basis conditions including seismic, and are capable of withstanding the force of full debris loading and hydrodynamic loads during an upset, emergency or faulted event. The structural qualification strategy that SI employs to address the TPI strainer configuration is to demonstrate that all of the load combinations including the worst-case loading (in this case the Service Level D load combination) meet specified acceptance criteria. The Specification provided by Korea Hydro & Nuclear Power Co., Ltd. (KHNP) [Reference 5] specifies four service level conditions for the evaluation of the sump strainers:

- Service Level A (Normal)
- Service Level B (Upset)
- Service Level C (Emergency)
- Service Level D (Faulted)

The loads for each combination are detailed in Table 1.1-1.

Table 1.1-1 Load Combinations [Reference 5]

Service Level	**Load Combination**
A	W+ΔP
B	W+ΔP+OBE
C	W+ΔP+SSE
D	W+ΔP+SSE+PDE

Where,

W = Dead Weight
ΔP = Differential Suction Pressure (Allowable Head Loss is 2 feet of water or 0.87 psig
OBE = Operating Basis Earthquake
SSE = Safe Shutdown Earthquake
PDE = Postulated Dynamic Load i.e. Hydrodynamic Load

The Service Level A load combination is evaluated in the submerged condition (wet) with added mass effects, and the Service Levels B and C/D load combinations are evaluated in identical submerged conditions. Service Level D is the most critical in terms of high stresses.

Specific documentation in Appendix A details the calculation of hydrodynamic mass values used in the Design Report.

A discussion of the perforated plates used in the strainer design, as well as information regarding the area reinforcement calculation used to justify the modeling of solid plates in the subject analysis is also provided.

1.2 DESIGN INPUT

The following design input has been provided by TPI for use in the qualification of the IRWST sump strainers.

1.2.1 Filter Cartridge CAD Geometry

TPI provided a shell model [Reference 6] for one of the four floor mounted filter cartridge assemblies. There are four trains (including Train A) which are mirror reflective image of the A train. Trains A through D are located at angular locations of 25°, 155°, 205° and 335° around the containment wall. Train A consists of twenty four (24) units of four tube filter cartridge sub-assemblies. A finite element model was developed for the filter cartridge assembly, in this case the TPI Train A Computer Aided Design (CAD) model, whose filename is as listed below.

- STRAINER ASSEMBLY.SLDASM [Reference 6]

1.2.2 Seismic Acceleration Response Spectra

The In-Structure Response Spectra (ISRS) curves as shown in Figure 1 of Reference 5 for the three orthogonal directions corresponding to different damping factors (as summarized in Table 1 of Reference 5) have been digitized. The strainer assembly is a welded and bolted steel structure with friction connections. A majority of the bolt holes in the strainer cartridge assembly are oversize in comparison to the bolt stud diameter. The US NRC Regulatory Guide (RG) 1.61, Rev. 1 states an acceptable structural damping value of 4% for SSE and 3% for OBE. The bolts used in the strainer assembly are used for high-load connections and obtain their total strength from the shear strength across the diameter of the bolt PLUS the friction developed between the nut and joined steel surfaces. In order to achieve the friction capacity, these bolts are tensioned to at least 70% of the ultimate tensile strength of the material according to the table below. It is noted here that 3/8" and ½" A193 Grade B8, Class 2 bolts are used in the strainer filter cartridge assembly and Reference 9 provides the bolt torque recommendations. The seismic response spectral accelerations vs. frequency at a 4% damping ratio for the SSE and 3% damping ratio for OBE, as stated in Reference 8, are applied to the finite element models in three orthogonal directions, namely, vertical and in the two horizontal axes. For the purpose of strainer dynamic qualification, one half of SSE values shall be used for OBE [Reference 5].

1.2.3 Hydrodynamic Drag Force

The strainer filter cartridge assembly is designed to withstand the hydrodynamic loads caused by the fluid discharged (water jet, air bubble transient, steam jet, etc.) into the IRWST water pool. The hydrodynamic load acts on the strainers concurrently with SSE. The total drag force of 54 kips [Reference 5] is applied in both the horizontal directions (Global X and Z directions).

1.2.4 Material Designations for Filter Cartridge Assembly Components

The mechanical properties and stress allowables were obtained from the ASME Code, Section II, Part D [Reference 2]. For the FEA, physical properties used include density and elastic properties, which include the modulus of elasticity (E) and Poisson’s ratio. The density of water at Service Level B temperature conditions was obtained from Table 1-8 of Reference 10.

The filter cartridge tubes, frame support, circular/rectangular plates, attachments and other miscellaneous hardware are made of either SA-240, Type 304 or Type 304L stainless steel [Reference 9].

The stress allowables for each component of the filter cartridge assembly are based on the ASME Boiler and Pressure Vessel Code, Section III, Division 1. The strainer structural frame components are evaluated per Subsection NF [Reference 4] and the stress allowables for the tube cartridges are evaluated per Subsection NC [Reference 3]. The stress allowable for Service Level A at 230 °F [Reference 5] for the limiting SA-240, Type 304L stainless steel material is conservatively used.

1.2.5 Hydrodynamic and Debris Loads

The finite element analysis includes the hydrodynamic "added mass" of the cartridge tubes and frame structure due to the disturbances generated in the fluid in motion, and the debris "added mass" accumulated in the cartridge. The mass moment of inertia due to the fluid inside the concentric tube pairs of the filter cartridge and dead weight of the inner tubes are accounted for as an effective density increase across the inner tubes. The mass moment of inertia due to the added mass and dead weight of the outer tubes are accounted for as an effective density increase across the outer tubes. The added mass due to the debris is conservatively applied as an effective density increase across the tube set pairs (5 inch inner tube and 6 inch outer tube) of the filter cartridge assembly. The analysis accounts for all estimated debris being clogged on one independent safety train, in accordance with Reference 5.

Table 1.2-1 shows the modified effective material density for various components of the filter cartridge assembly. Detailed representative calculations for the hydrodynamic mass and effective material weight densities are provided in Appendix A.

Table 1.2-1 Effective Material Densities for Various Components of the Filter Cartridge Assembly

Component Designation	Effective Material Weight Density (lbf/in^3)
Filter Module	0.29
Filter Tubes	0.6444
Structural Components	0.29

1.3 ASSUMPTIONS

The following assumptions are used for the evaluation:

1) Under Service Level B conditions, the submerged condition affects the mass weight due to the buoyancy effect. A buoyancy factor of 0.8817 was calculated, and this value is applied to the density of the structure.

   From equilibrium in the vertical direction, the resultant load R is:

   $$R = W - N$$

   Where, W = Weight and N = Buoyancy

   $$R = m_s \times g - m_w \times g = (\rho_s \times V) \times g - (\rho_w \times V) \times g = (\rho_s - \rho_w) \times V \times g$$
   $$= \left((\rho_s - \rho_w) \div \rho_s\right) \times \rho_s \times V \times g = \left(1 - \left(\frac{\rho_w}{\rho_s}\right)\right) \times m_s = (1 - d_r) \times m_s = \text{factor} \times m_s$$

   Where,
   m_s = Mass of the filter cartridge assembly structure
   m_w = Mass of the water displaced by the filter cartridge assembly structure
   g = Acceleration due to gravity
   ρ_s = Density of steel structure
   ρ_w = Density of water
   V = Volume of the filter cartridge assembly structure
   d_r = Density ratio
   factor = Buoyancy factor

2) The IRWST sump strainers will expand due to the elevated temperature of 230 °F for Service Level D. However, there are no significant dissimilar metal effects since all materials are similar in terms of thermal properties [SA-240, Type 304 and SA-240, Type 304L, Reference 2]. As a consequence, thermal stresses are negligible, and are not considered in the analysis.

3) All welds are full penetration, so that weld joint efficiency factors applied to the allowables for non-full penetration welds are not applicable in the analysis.

4) All welds are assumed to be volumetrically examined, so that the weld joint efficiency factor applied to the allowables is taken as 1.0 in the analysis.

5) All pump head loss (2 feet of water or 0.87 psig) related pressure loads acting on the flat faces of the cartridge assembly structure (for example, cross braces, formed channels, side channels, cross braces, etc.) are in equilibrium except for the bottom plate with weld studs that are in contact with the inner and outer filter tubes. A uniform static pressure load of 0.87 psig is applied on outer diameter of the outer tube, inner diameter of the inner tube and the bottom plate and the stress is accounted for in the Service Level A through D load combination.

6) The FEA includes the hydrodynamic “added mass” of the cartridge tubes and frame structure due to the disturbances generated in the fluid in motion, and the debris “added mass” accumulated in the cartridge. The mass moment of inertia due to the fluid inside the concentric tube pairs of the filter cartridge and dead weight of the inner tubes are accounted for as an effective density increase across the inner tubes. The mass moment of inertia due to the added mass and dead weight of the outer tubes are accounted for as an effective density increase across the outer tubes. The added mass due to the debris is applied as an effective density increase across the tube set pairs (5 inch inner tube and 6 inch outer tube) of the filter cartridge assembly.

7) The perforations in the filter tubes were not explicitly modeled. However, it can be shown that the requirements for area reinforcement are satisfied (per ASME Code, Section III, NC-3332, [Reference 3]) for all planes through the center of the 0.0938" [Reference 9] circular perforated holes and normal to the surface of the filter tube.

The total cross-sectional area of reinforcement, A (in^2), required in any given plane for a vessel under internal pressure shall not be less than:

$A = d \times t_r \times F$ per ASME Code, Section III, NC-3332.2 [Reference 3]

where,

d = Finished diameter of the circular opening = 0.0938" [Reference 9]
t_r = Required thickness of a shell under internal pressure
F = A correction factor which compensates for the variation in pressure stresses on different planes with respect to the axis of the vessel. A value of 1.0 is used for this analysis

$$t_r = \frac{P \times R_i}{\sigma_{allowable}}$$

where,

P = Internal pressure due to head loss loading across filter tubes
R_i = Internal radius of inner filter tube
$\sigma_{allowable}$ = Allowable membrane stress for inner filter tube [Reference 2]

$$t_r = \frac{0.87 \times 2.4375}{13850} = 0.0001531''$$

This implies that since the nominal thickness of the shell, 0.0625" is greater than 0.0003062", there is enough thickness available for area reinforcement.

$$A = 0.0938 \times 0.0001531 \times 1 = 0.00001436 \text{ in}^2$$

Per ASME Code, Section III, NC-3335.1 [Reference 3],

$$A = (t - F \times t_r) \times d$$

Therefore,

A_1 = Area in excess thickness in the vessel wall available for area reinforcement, in^2

.

$$\mathrm{A} = (0.0625 - 1 \times 0.0001531) \times 0.0938 = 0.005848\ \mathrm{in}^2$$

The reinforcement required for the perforated hole opening in the shell designed for internal pressure is 0.25% of the available area in the shell, and hence the requirements of area reinforcement are satisfied.

1.4 METHODOLOGY

The following steps are performed during the analysis of the GS-50873-GA filter cartridge assembly.

1) The analysis of the floor mounted cartridge of the IRWST sump strainers was performed using a response spectrum analysis approach in ANSYS [Reference 1].

2) The geometry was imported from SolidWorks 2012 as a shell model into ANSYS. As mentioned before, the CAD model included the filter cartridge assembly and the channels that the assembly is mounted on before being bolted down to the floor using Hilti anchor bolts [Reference 7]. Each component of the filter cartridge assembly is assigned a shell thickness as a real constant, and each component was assigned the respective physical material properties. The geometry is meshed in ANSYS Workbench using SHELL181 (4-Node Structural Shell) elements. Surface bonded contacts are manually created between tube/plate, top plate/middle plate, side channel/bracket, base plate/Hilti anchor Attachment and many more interfaces.

3) The free vibration response of the structure and the natural frequencies of the structure are calculated from modal analysis. An iterative Preconditioned Conjugate Gradient Lanczos solver was selected to calculate the eigenvalues and eigenvectors, which correspond to the natural frequencies and mode shapes, respectively.

4) ANSYS runs were executed to evaluate the boundary conditions at the base plate that is in contact with the floor and is held to the L-shape brackets through Hilti anchor bolts. In this case, only one node corresponding to the Hilti anchor bolt location was pinned in the vertical direction. All other degrees-of-freedom were released. The FEA results showed that the vertical tensile reaction force in the Hilti anchor bolts was lesser than the minimum preload on the Hilti anchor bolts (calculated from the installation torque [Reference 9]). Therefore, there would be no risk of uplift of the bolts or increased bending stresses at the web section of the C-channels in contact with the floor. The loading condition for the test run was an equivalent static acceleration corresponding to the guidance provided in Standard Review Plan (SRP), US NRC NUREG-0800 [Reference 12, Page 3.7.2-7] that states: To obtain an equivalent static load for an Structures, Systems and Components (SSC) that can be represented by a simple model, a factor of 1.5 is applied to the peak spectral acceleration of the applicable ground or floor response spectrum.

5) A single point spectrum analysis was performed to calculate the maximum response of the structure to seismic loading. In a single response spectrum, the structure is excited by a spectrum of known direction and frequency, acting uniformly on all fixed support points. Refer to Figures 1.5-5 for an example Input Response Spectrum (Vertical Global Y-Direction) for the GS-50873-GA Filter Cartridge Assembly. The fixed support boundary condition is considered conservative based on the ANSYS test runs explained above. Refer to Figures 1.5-7 for a pictorial representation of the boundary conditions.

6) When performing the spectrum analysis (both SSE and OBE) that takes into account missing-mass and rigid response effects, the following recommendations were implemented and in accordance with US NRC RG 1.92 [Reference 11]:

a. The Zero Period Acceleration (ZPA) frequency value is defined corresponding to the input spectrum [Reference 8]. This value is the beginning of the frequency range for which the acceleration remains constant and equal to the ZPA.
b. All modes in the frequency range 0-100 Hz have been included in the spectrum analysis.
c. The Complete Quadratic Combination (CQC) mode combination technique is used to correctly combine modes with closely spaced frequencies.
d. The missing mass effect was included in the simulation.
e. The rigid response effect using the Yindley-Yow method is also included.

7) A hydrodynamic drag force of 54 kips is applied in both the horizontal directions i.e. Global X and Z directions. The hydrodynamic load acts on the strainers concurrently with SSE. Figure 1.5-8 shows the pictorial representation of application of the total static drag force applied on the outer 6 inch tubes. This total static drag force translates to 562.5 lbf on each 6 inch outer tube. This loading condition is considered appropriate since as stated in Reference 5, the total volume occupied by the strainer is utilized in the computation of the acceleration drag force. Figure 1.5-9 shows the fixed support boundary conditions are conservatively used for all bottom faces of the C-Channels and the Hilti Anchor attachments.

8) A separate load case is analyzed in ANSY to simulate the 1G (386.4 in/s^2) gravity acceleration to satisfy the Service Level A load combination. The finite element model has all the hydrodynamic "added" mass, fluid mass inside the filter tubes and stainless steel component weight included in this analysis.

1.5 ANALYSIS

The following section describes the analyses performed to qualify the IRWST sump strainers.

1.5.1 CAD Geometry and Finite Element Model

As mentioned previously, ANSYS 12.1 was used to perform the finite element analysis of the floor-mounted cartridges. The geometry was imported from SolidWorks 2012 as *.SLDPRT and *.SLDASM files. The CAD model included the filter cartridge assembly and the channels that the assembly is mounted on before being bolted down to the floor using Hilti anchor bolts [Reference 7]. Refer to Figure 1.5-1 for the GS-50873-GA filter cartridge assembly. It should be noted that representative plots are shown for the GS-50873-GA filter cartridge assembly in the main body of this report.

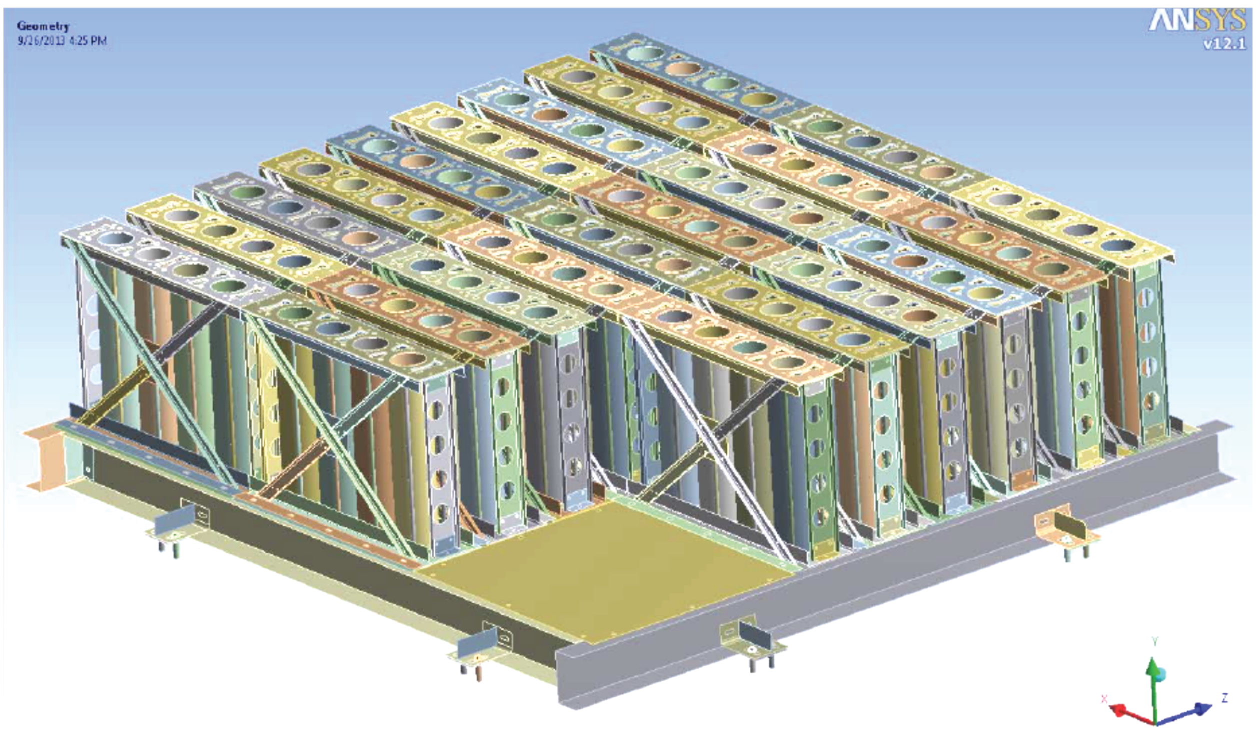

Figure 1.5-1 Geometry of GS-50873-GA Filter Cartridge Assembly

A Uniform Quad method in ANSYS 12.1 was selected to produce a uniform mesh of quadrilateral elements over the entire part of the selected body, depending on the values of element size specified for the selected geometry. Figure 1.5-2 shows the finite element model of the GS-50873-GA filter cartridge assembly.

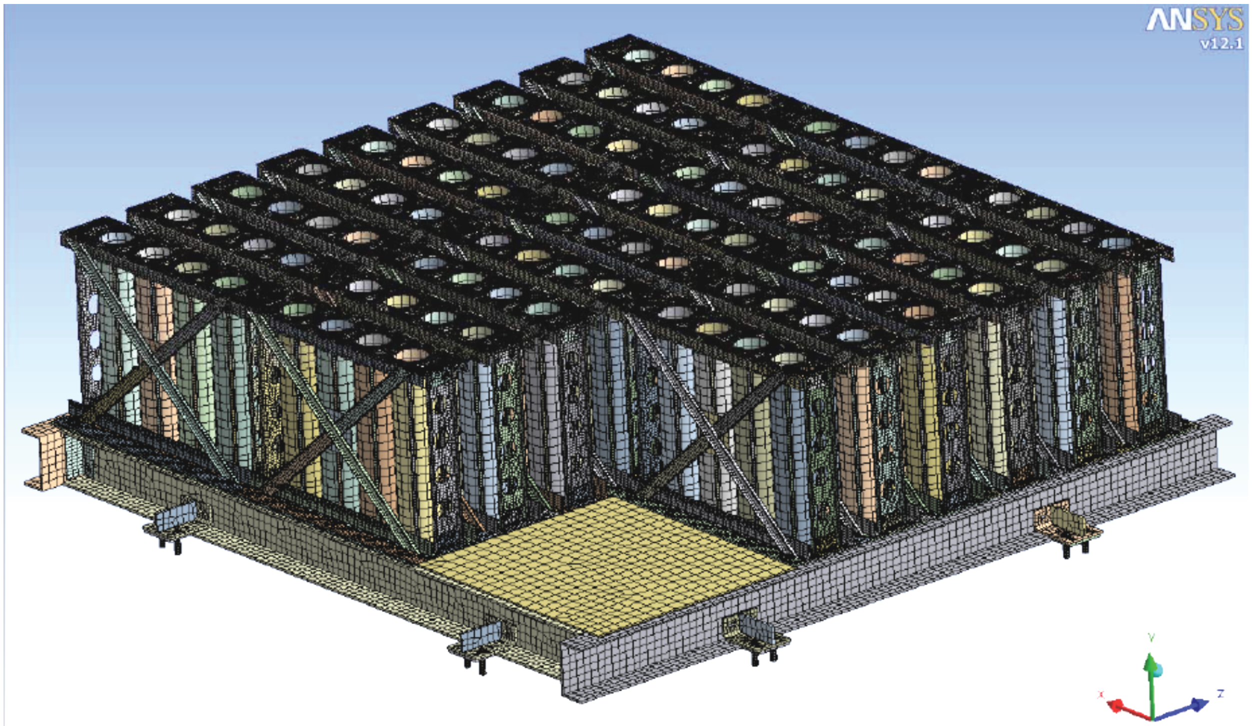

Figure 1.5-2 Finite Element Model of GS-50873-GA Filter Cartridge Assembly

The finite element model has 1,078,286 nodes which amount to approximately 6.5 million degrees-of-freedom. Figures 1.5-3 and 1.5-4 show an example of bonded Contact-Target surface connections in ANSYS [Reference 1].

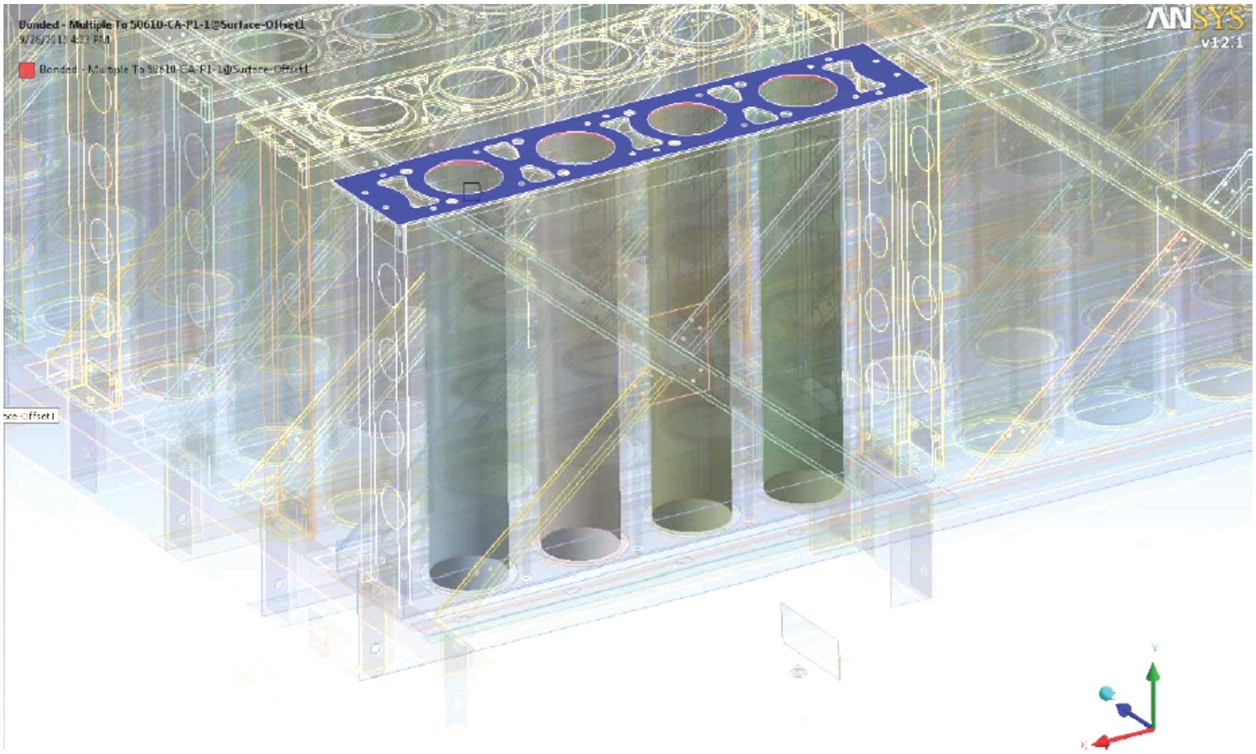

Figure 1.5-3 Example Bonded Surface Contact Interface of Tube/Top Plate for GS-50873-GA Filter Cartridge Assembly

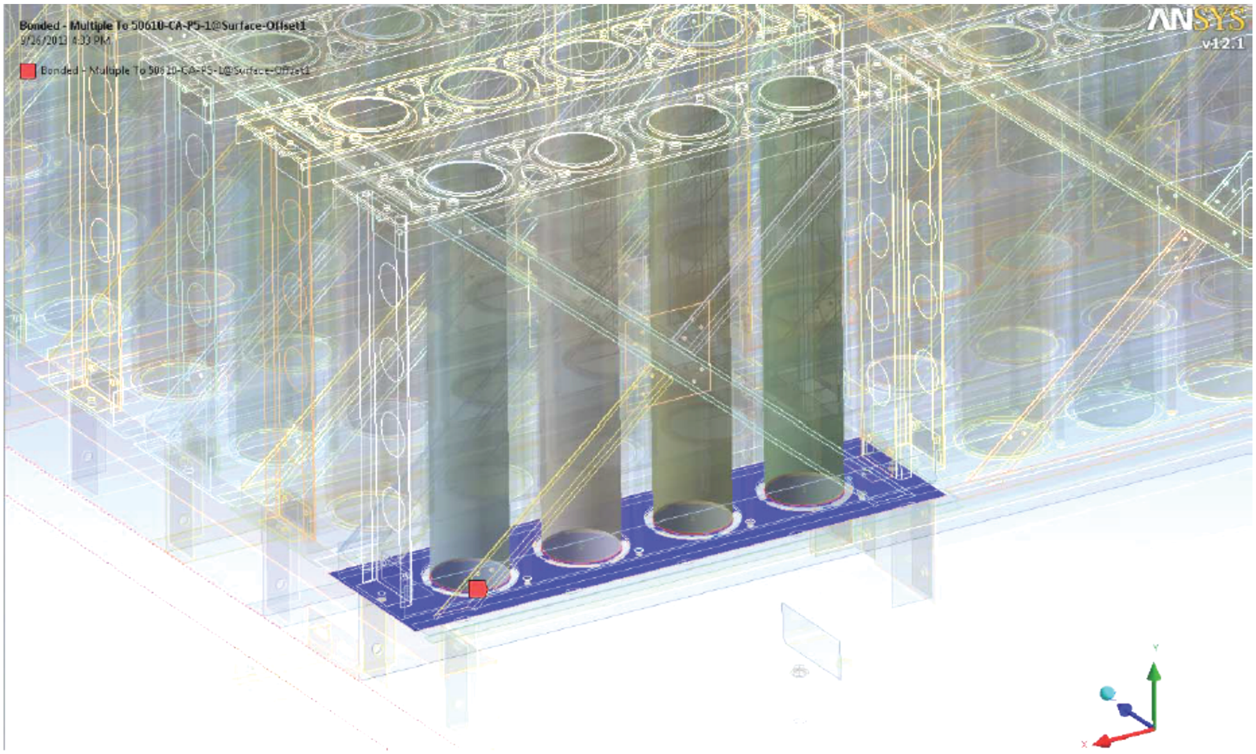

Figure 1.5-4 Example Bonded Surface Contact Interface of Tube/Bottom Plate for GS-50873-GA Filter Cartridge Assembly

1.5.2 Loads and Boundary Conditions

1.5.2.1 Single Point Input Response Spectrum Analysis

The inertial loads acting on the floor mounted cartridges are proportional to the masses in motion and acceleration. The dry steel masses are directly calculated by ANSYS as a function of volume and density of the material. A summary of the total effective weight densities of individual components of the filter cartridge assembly, that includes the hydrodynamic and debris “added” mass effects are shown in Table 1.2-1.

Figures 1.5-5 and 1.5-6 provide the representative input response spectrum in vertical and two horizontal directions (ANSYS Global Y, Z and X) to excite the GS-50873-GA Filter Cartridge Assembly structure and components in the case of a SSE event. These spectral acceleration loads act uniformly on all fixed support points. The modes are combined in a separate solution phase using the CQC method. Reference 5 provides guidance that for the dynamic qualification of the strainer, one half of SSE values shall be used for OBE. In this case the ISRS curve with 3% damping is digitized and the seismic acceleration magnitudes are divided by two across the 0-100 Hz frequency range. The resulting seismic acceleration vs. frequency is used as input for the OBE event.

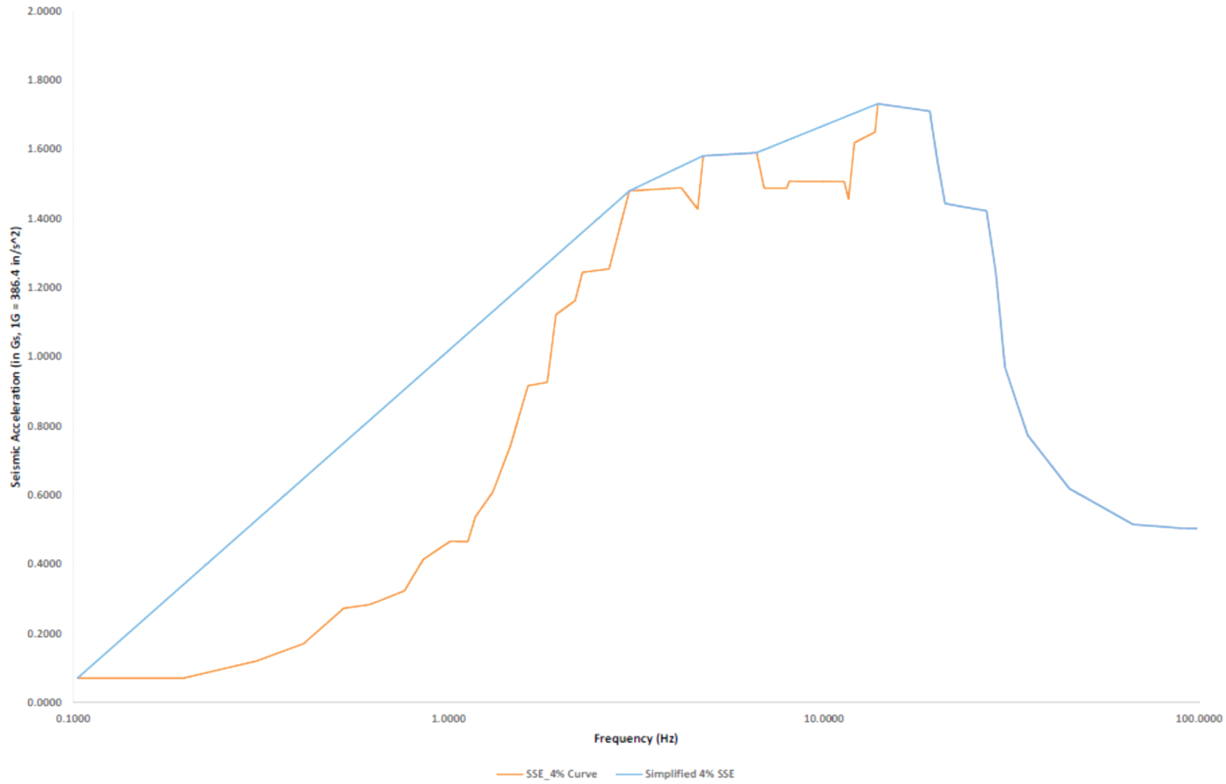

Figure 1.5-5 Input Response Spectrum (Vertical Global Y-Direction) to GS-50873-GA Filter Cartridge Assembly

Note:

1. The X-Axis in the above chart represents frequency in Hz and the Y-Axis in the above chart represents seismic acceleration in G's; 1G = 386.4 in/s^2. The X-axis is a logarithmic scale.

2. A bounding simplified 4% SSE curve is conservatively developed as shown by the blue line in the above graphic. This is the input response spectrum curve used for the stress analysis.

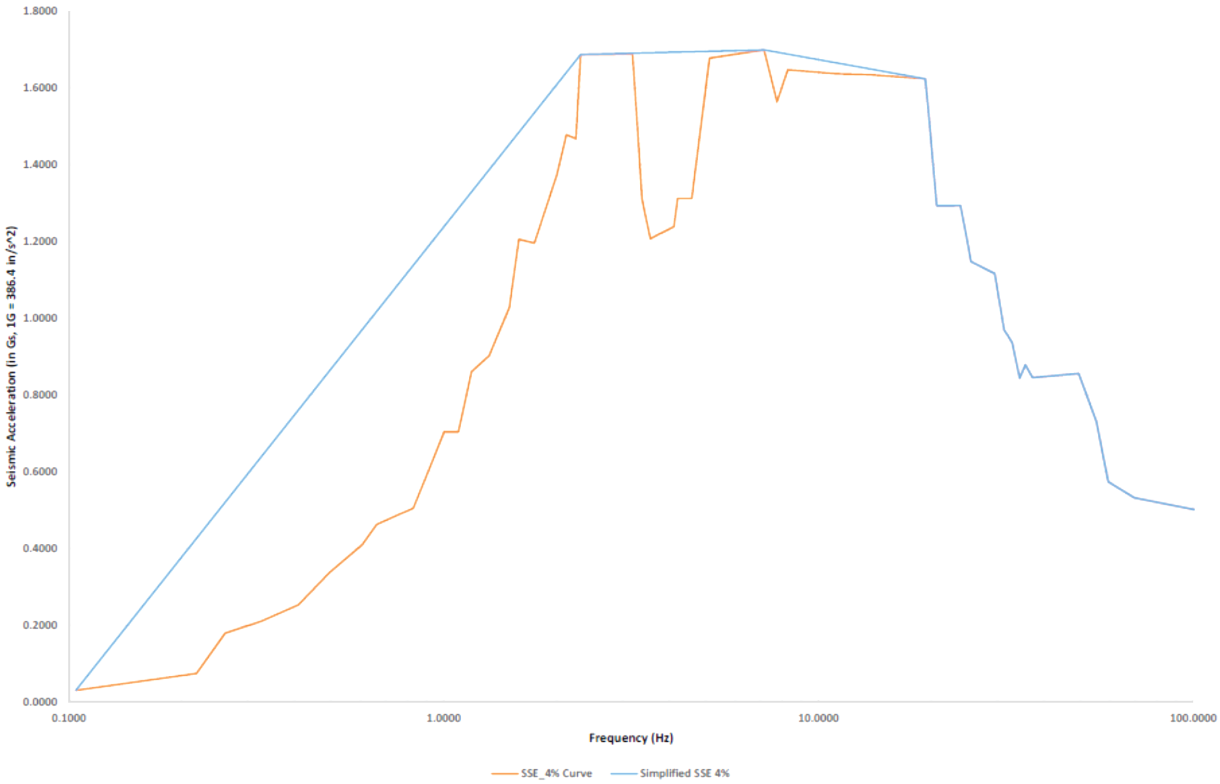

Figure 1.5-6 Input Response Spectrum (Horizontal Global X and Global Z-Direction) to GS-50873-GA Filter Cartridge Assembly

Note:

1. The X-Axis in the above chart represents frequency in Hz and the Y-Axis in the above chart represents seismic acceleration in G's; 1G = 386.4 in/s^2. The X-axis is a logarithmic scale.

2. A bounding simplified 4% SSE curve is conservatively developed as shown by the blue line in the above graphic. This is the input response spectrum curve used for the stress analysis.

Fixed support boundary conditions are used for all bottom faces of the C-Channels and the Hilti Anchor attachments as shown in Figure 1.5-7. As described earlier in Section 4.0, ANSYS test runs proved that there was no risk of uplift of the Hilti Anchor bolts or increased bending stresses in the web section of the C-Channels.

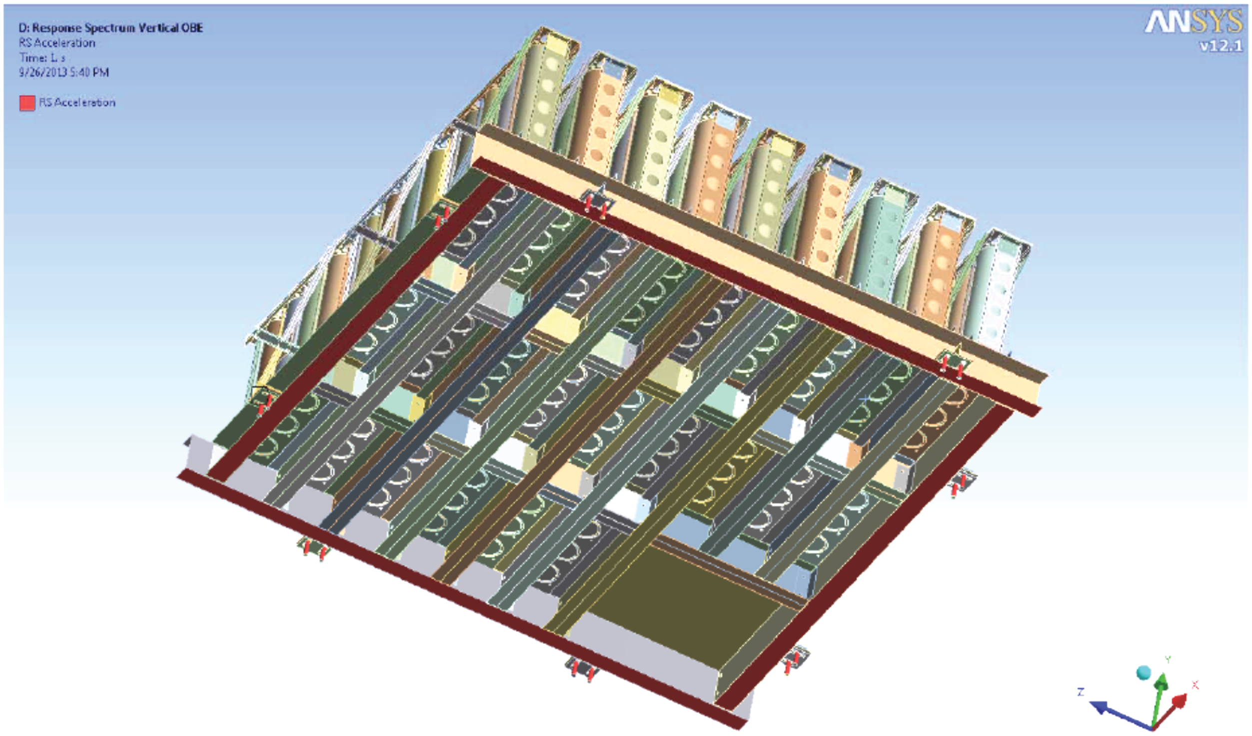

Figure 1.5-7 Fixed Support Boundary Conditions Applied to GS-50873-GA Filter Cartridge Assembly - Response Spectral Analyses

1.5.2.2 Hydrodynamic Drag Force Analysis

The strainer filter cartridge assembly is designed to withstand the hydrodynamic loads caused by the fluid discharged (water jet, air bubble transient, steam jet, etc.) into the IRWST water pool. The hydrodynamic load acts on the strainers concurrently with SSE. The total drag force of 54 kips [Reference 5] is applied in both the horizontal directions (Global X and Z directions). Figure 1.5-8 shows the pictorial representation of application of the total static drag force applied on the outer 6 inch tubes. This loading condition is considered appropriate since as stated in Reference 5, the total volume occupied by the strainer is utilized in the computation of the acceleration drag force.

Figure 1.5-9 shows the fixed support boundary conditions used for all bottom faces of the C-Channels and the Hilti Anchor attachments.

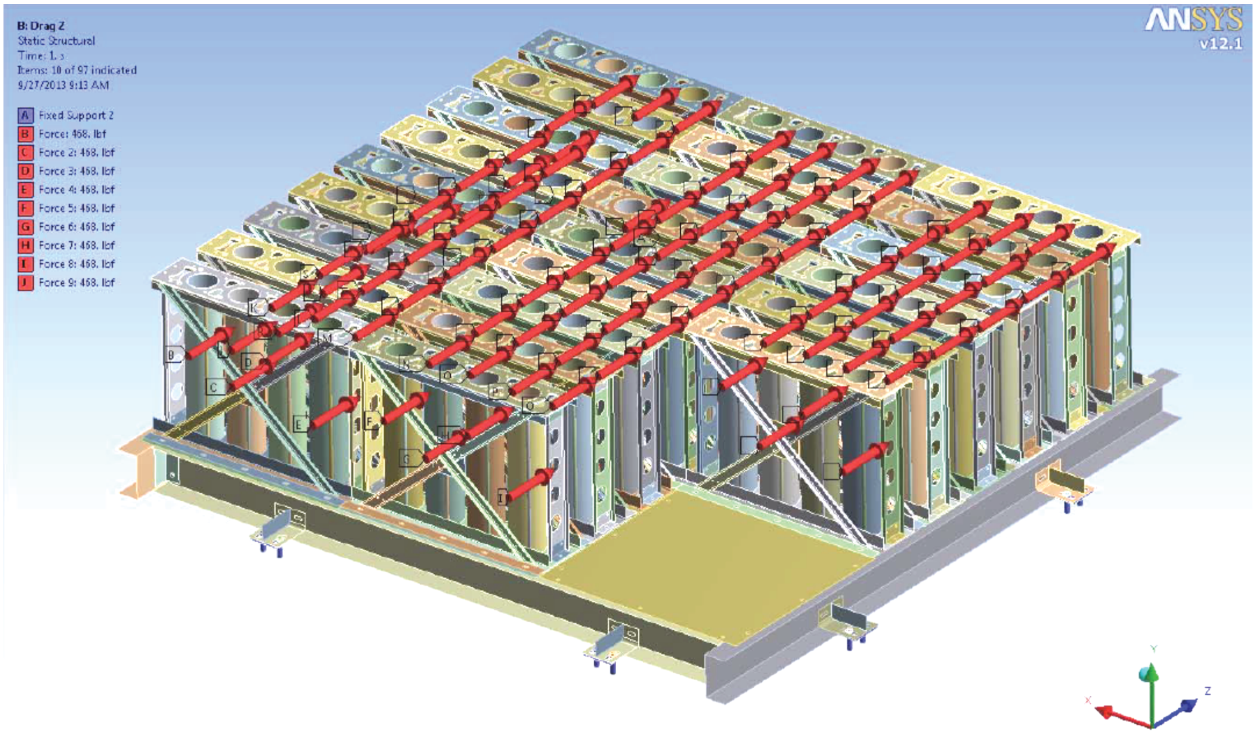

Figure 1.5-8 Fixed Support Boundary Conditions Applied to GS-50873-GA Filter Cartridge Assembly - Response Spectral Analyses

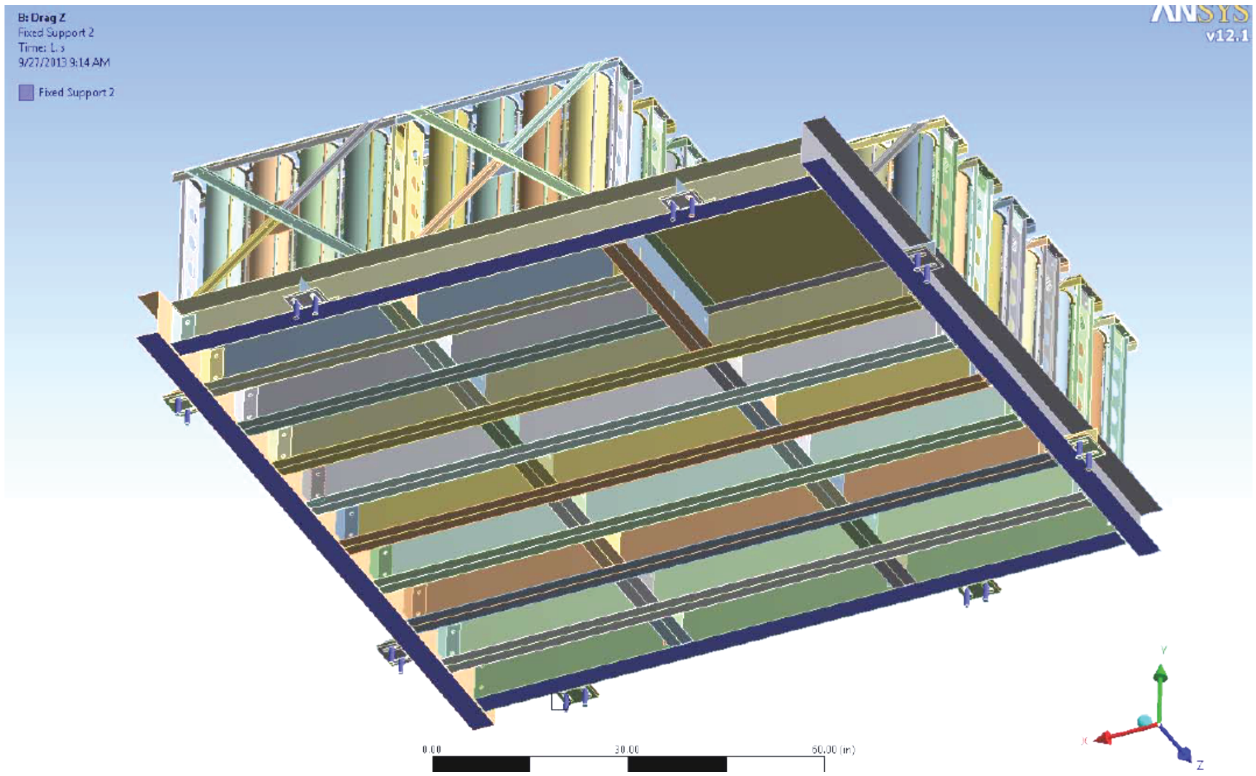

Figure 1.5-9 Fixed Support Boundary Conditions Applied to GS-50873-GA Filter Cartridge Assembly - Response Spectral Analyses

1.5.3 Material Properties

The cartridge tubes, frame support and anchor attachments are made for either SA-240, Type 304 or SA-240, Type 304L Stainless Steel [Reference 2]. The elastic and physical material properties at an elevated temperature of 230 °F (Service Level D) used in FEA are as follows:

- Elastic Modulus, E = 2.735E7 psi [Reference 2]
- Poisson's Ratio, μ = 0.31 [Reference 2]
- Weight Density, ρ = 0.29 lb/in^3 [Reference 2]