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# Determination of Deflection Requirements for BSC Support Beam Bellows

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**Abstract**

Worst case BSC support beam bellows deflections in axial and shear directions are calculated by combining actuation ranges (coarse and fine), deflections of facility floor and vacuum chamber due to vacuum load imbalance, and manufacturing and positioning tolerances of the chamber and support structure. The shear and axial bellows deformations obtained from this calculation are large and define critical selection/design requirements for the support beam bellows.

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LIGO PROJECT

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## 1. Problem Description

The purpose of this calculation is to evaluate the axial and shear deflection requirements on the BSC support beam bellows. These bellows connect the internal support beams of the SEI to the corresponding ports on the BSC vacuum chambers. Their large diameter and the limited axial space available makes shear deflection capacity a very critical requirement for the selection and/or design of these bellows.

Figure 1 shows a layout of the support system and defines the axis system used throughout this note.

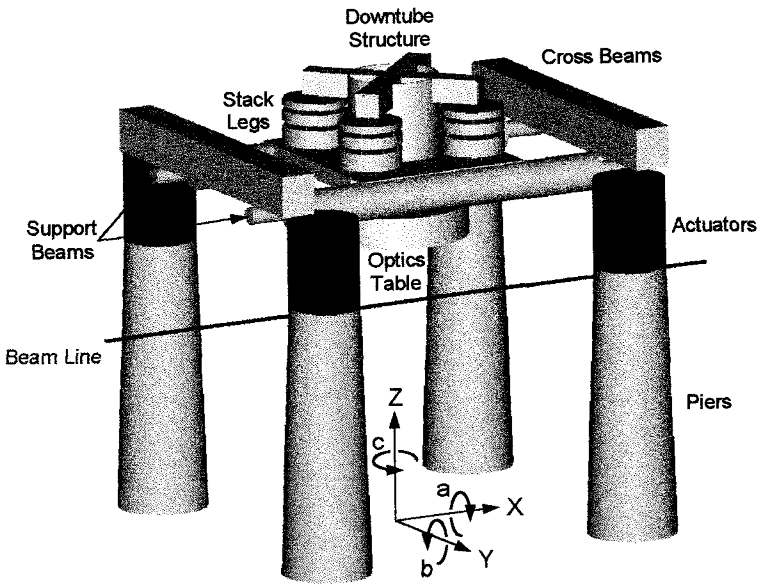



**Figure 1: BSC SEI layout, axis system definition.**

Several factors contribute to the total shear and axial deflections in the bellows; they are detailed in the sections 2 to 4 of this document:

- Coarse and fine actuation requirements (see Section 2): The actuation systems move the support beams relative to the vacuum chambers, deforming the support beam bellows.
- Deflections of the vacuum chambers due to unbalanced vacuum loads (see Section 3): because of the layout of vacuum tubes and caps around the BSC chambers, some chambers are subjected to asymmetric vacuum loads. These loads lead to deflections of the chambers which must be absorbed by the support beam bellows. These deflections are analyzed with FEM models of the chambers.
- Deflections of the facility floor in response to unbalanced vacuum loads (see Section 3): the vacuum loads mentioned above create significant forces and moments on the concrete slab supporting the chambers. slab deflections in response to those loads lead to non negligible motions of the support beam ports.
- Manufacturing and alignment tolerances (see Section 4): both the vacuum chambers and the support structure suffer small manufacturing imperfections; in addition, the vacuum chambers are aligned with the theoretical optical axis of the detector with

finite accuracy. Because in operation the support system will brought into alignment with the optical axis, these imperfections will again be absorbed by the support beam bellows.

The next 3 sections describe calculations and assumptions that lead to estimates of the magnitude of these various effects.

## 2. Actuation Ranges

The required ranges of actuation[1] are ±5 mm in the *X*, *Y*, and *Z* directions and ±4 mrad in the *C* direction (rotation around *Z*) for the coarse actuation (drift compensator) and ±0.1 mm in the *X* direction for the fine actuation (on-line) with a maximum allowable roll motion (*A* direction) of ±0.5 mrad. With the lever arms shown in Fig. 2, the ±4 mrad coarse yaw range leads to additional linear ranges of ±5.75 mm in the *Y* direction and ±3.35 mm in the *X* direction. The ±0.05 mrad roll tolerance (reduced from 0.5 mrad in [1]) gives an additional ±0.04 mm range in the *Z* direction.

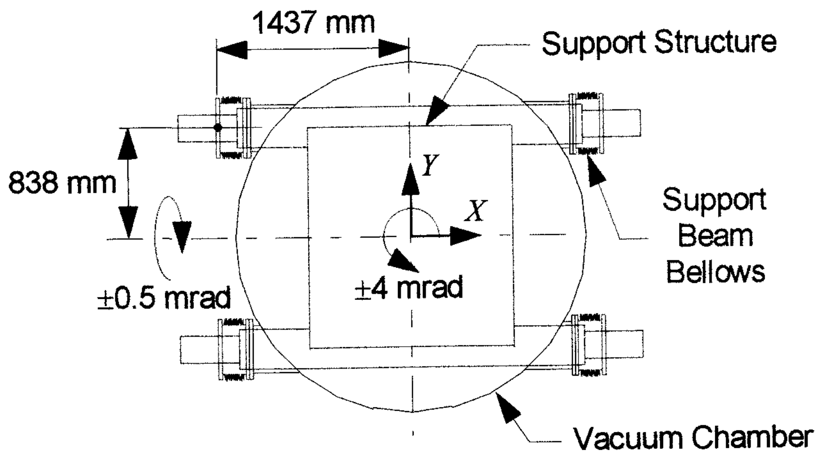



**Figure 2: BSC support beam bellows.**

These ranges combine together to lead to the values listed in Table 1 at the end of this note.

## 3. Vacuum Chamber Deflections

### 3.1 Worst Case Chamber and Load Cases

Various calculations[2,3] performed by PSI International, Inc. clearly show that both concrete slab and vacuum chamber deflections are largest for BSC 7 and 8 of the Washington corner station[4]. Conditions at BSC 7 mirror those of BSC 8 so that only BSC 7 will be considered.

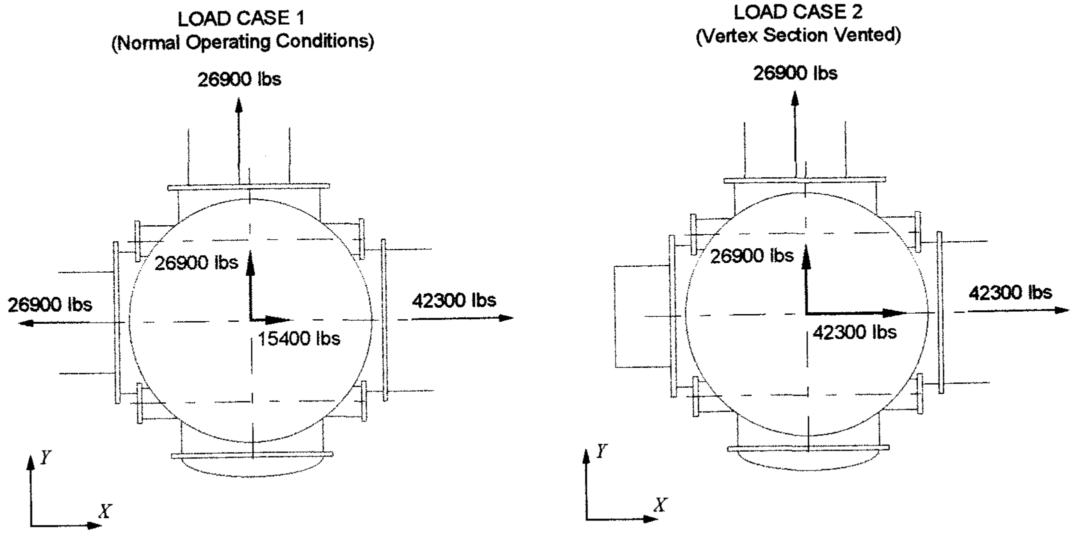



**Figure 3: Washington corner station, BSC 7, worst load cases for imbalanced vacuum loads; vacuum loads at each port are shown in green, resultants in red.**

Two distinct load cases are considered and illustrated in Fig. 3 (other cases considered in PSI studies are thought to be less severe):

1. Under normal operating conditions (detector completely evacuated), the chamber is acted upon by unbalanced atmospheric pressure loads due to the presence of a cap on one of the 4 large diameter (60") ports and also to differences in the diameters of the vacuum tubes connected to opposite sides of the chamber. The resultants in the *X* and *Y* directions are approximately equal to $F_x$= 68499. N (15400. lbs) and $F_y$= 119651. N (26900. lbs). The *Y* resultant is offset in the negative *X* direction by 14.9 cm (5.9")[5]
2. When the vertex section is isolated from the rest of the detector by the valves WGV2 and WGV1 and vented, the load imbalance in the *X* direction is further increased by atmospheric pressure on WGV2. Resultants in the *X* and *Y* directions are then approximately $F_x$= 188150. N (42300. lbs) and $F_y$= 119651. N (26900. lbs).

## 3.2 Chamber Deflections on Stiff Floor

### *3.2.1 FEM Modeling and Assumptions*

Two views of the finite element model are shown in Fig. 4 (with caps and adaptors corresponding to load case 1).

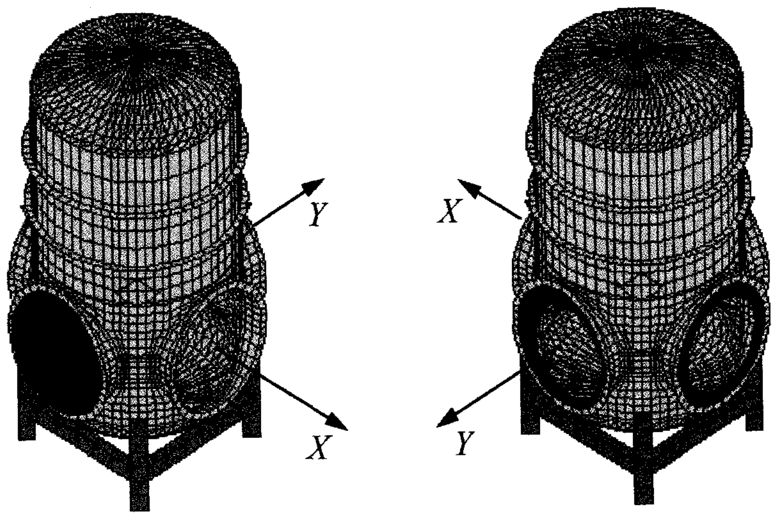



**Figure 4: FEM model of the complete BSC vacuum chamber. The chamber itself is shown in grey, the support feet in blue, and the attachments (adapter rings and covers) in red. Load case 1 is shown (normal operating condition)**

All dimensions were extracted from the latest chamber drawings[5]. The thickness of each 60" flange in the model reflects its own material plus that of the mating flange (adaptor or cover). The portions of vacuum tube that connect the chamber flanges to the closest bellows are not included in the models (results from FEM models with and without those sections of tubes have shown that their effect is negligible: a few percent difference in chamber deflections). The support feet extend to the top of the 3" of grout[5]. All stiffeners are modeled. For simplicity, none of the small ports are modeled.

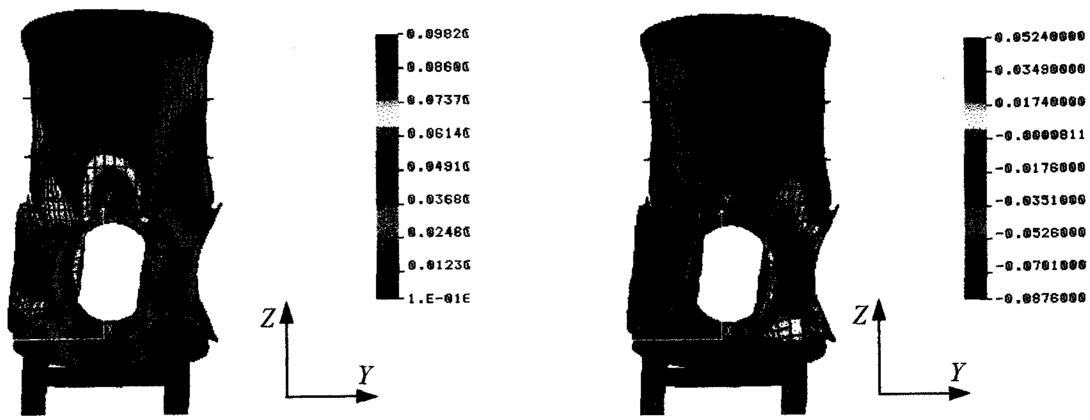
To facilitate extraction of the results, an extra node was created at the location of the center of each support beam flange. Each of these nodes is connected to 3 neighboring nodes on the shell via 3 beam elements. The modulus of elasticity of those beam elements is arbitrarily made equal to one thirtieth of the modulus of the housing, to avoid any artificial stiffening.

Atmospheric pressure equal to 101348 Pa (14.7 psi) is applied to all outside surfaces of the chamber, covers, and adapters.

### *3.2.2 Finite Element Results*

3.2.2.1 Case 1:

FEM deflections for load case 1 are shown in Fig. 5, looking down the beam line. Consistent with PSI results, the largest deflections occur around the large 60" openings. Deflections measured at the support beam flanges are listed in Table 1 at the end of this document.



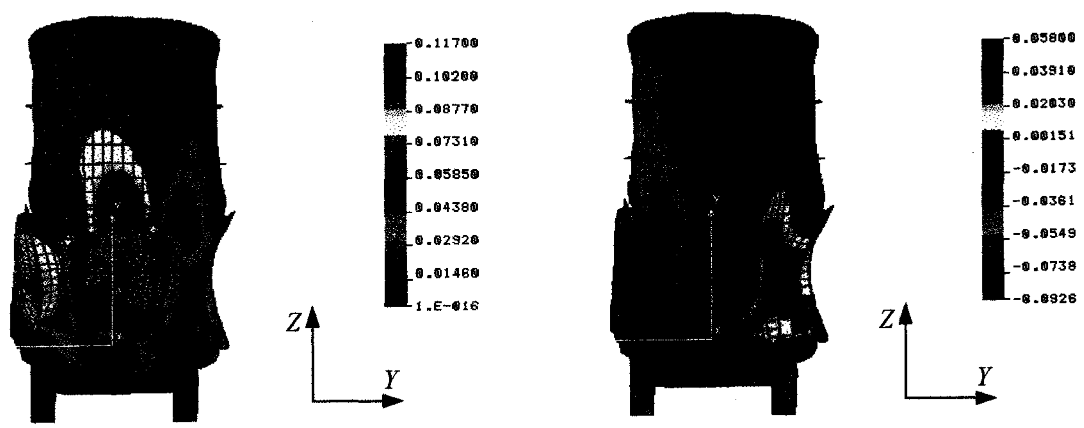

Resultant of $X$, $Y$, and $Z$ displacements

$Y$ component of displacements

**Figure 5: FEM Results for load case 1, WBSC7 (normal operating conditions); resultant displacements (in) are shown on the left and Y component on the right (with a sign change due to axis system definition in the FEM model).**

3.2.2.2 Case 2

Results are displayed in Fig. 6 for this load case. Displacement values at the support beam flanges are listed in Table 1.




Resultant of $X$, $Y$, and $Z$ displacements

$Y$ component of displacements

**Figure 6: FEM Results for load case 2, WBSC7 (vertex section vented); resultant displacements (in) are shown on the left and Y component on the right (with a sign change due to axis system definition in the FEM model).**

## 3.3 Effect of Facility Floor Deflection

The portion of the concrete slab directly under the chamber was assumed to behave rigidly (its 30" thickness should be large enough to make wave lengths of slab deformations large compared to vacuum chamber diameter). With this assumption, the local slab deflection is reduced to rigid body translations in the $X$ and $Y$ directions and rigid body rotations around those same axes (vertical deflection of slab is neglected). Stiffnesses associated with these deflections were extracted from Parson's FEM calculations[3], using the results for BSC 7, load cases 1 and 2. These lead to floor stiffnesses $K_h = 2.84\ 10^9$ N/m ($16.2\ 10^6$ lb/in) in both horizontal directions ($X$, $Y$) and $K_r = 2.71\ 10^9$ N.m/rad ($24.0\ 10^9$ lb.in/rad) in the roll and pitch directions ($A$, $B$). These stiffnesses are then used in conjunction with the loads of Fig. 3 (offset 73" above the floor) to evaluate the total motion at the support beam port flanges due to slab deflection only. These values are listed in Table 1, in the summary section at the end of this note.

# 4. Manufacturing and Alignment Tolerances

## 4.1 Vacuum Chamber Alignment Tolerances

The 60" main ports of the BSC vacuum chambers will be positioned and aligned in the facility with reference to the theoretical beam line. Tolerances on this alignment are ±2 mm in directions transverse to any beam line and ±25 mm in axial directions[6].

## 4.2 Vacuum Chamber Manufacturing Tolerances

Manufacturing tolerances on the position of the support beam port flanges with respect to reference (centerline of main 60" beam ports) were listed on PSI drawings[5] as ±0.38 mm (0.015 in). The LIGO vacuum equipment specifications[7] gives upper limits on those tolerances of ±2.54 mm (0.1 in). Recent measurements performed by PSI on a first article reveal imperfections up to 1.52 mm (0.060 in) [6]. A value of ±2.54 mm (0.1 in) is adopted here.

## 4.3 Support Structure Manufacturing and Alignment Tolerances

Manufacturing tolerances on the support structure must also be taken into account. For axial deformation of the bellows, the critical dimension is the axial distance between the mating surfaces for the bellows flanges that are machined into the support beams. A tolerance of ±1.52 mm (.060") was adopted on this dimension. In addition, assuming no shimming, the separation between the two support beams is fixed by the machining of the support beams/platform interfaces; a tolerance of ±1.52 mm (.060") was adopted on this dimension.

# 5. BSC Support Beam Bellows - Requirement Summary

Table 1 summarizes and combines bellows deflections from all effects considered. It shows that the support beam bellows must be able to sustain about ±14 mm axial deflection and ±18.1 mm shear deflection. These requirements are **extremely severe**, even for welded diaphragm bellows, in view of the large diameter required to provide sufficient clearance around the support beams and the little axial space available (6 to 7 inches maximum for convolutions) within the stay clear zone around the BSC chambers. In addition, the twist requirement of 1.32 mrad is a concern because of the risk of twist buckling of the convolutions.

| Source | Twist | Axial | Shear | |
|---|---|---|---|---|
| | a | X | Y | Z |
| | (mrad) | (mm) | (mm) | (mm) |
| actuation systems<br>Coarse: drift compensator, ± 5 mm X,Y,Z & ± 4 mrad Yaw<br>Fine: on-line, ± 0.1 mm X range, 0.05 mrad Roll tolerance | ± 0.05 | ± 8.45 | ± 10.75 | ± 5.04 |
| *Vacuum chamber deflection at support beam ports due to vacuum load imbalance (on stiff floor) (case 1 / case 2)* | *-1.17/-1.19* | *+0.70/+1.46* | *+0.97/+0.98* | *-0.34/-0.44* |
| *Deflection at support beam flange due to horizontal and rocking deflections of facility floor (case 1 / case 2)* | *-0.08/-0.08* | *+0.17/+0.45* | *+0.29/+0.29* | *±0.13/±0.23* |
| Total deflections from unbalanced vacuum loads (max) | + -1.27 | + 1.91 | + 1.27 | - 0.67 |
| *Vacuum chamber positioning tolerance (wrt beam reference)* | - | *± 2.00* | *± 2.00* | *± 2.00* |
| *Vacuum chamber manufacturing tolerances (distance from 60" port to support beam ports and support beam ports separation)* | - | *± 2.54 (100 mil)* | *± 2.54 (100 mil)* | *± 2.54 (100 mil)* |
| *Support structure manufacturing tolerance (axial distance between bellows flanges)* | - | *± 1.52* | *± 1.52* | *± 1.52* |
| Total deflections from tolerances (RMS) | - | ± 3.57 | ± 3.57 | ± 3.57 |
| | | | **≤ ± 15.59** | **≤ ± 9.28** |
| **TOTAL** | **≤ ± 1.32** | **≤ ± 13.93** | **≤ ± 18.14** | |

**Table 1: Deflection requirements for BSC support beam bellows.**

## 6. References

1. F. Raab and N. Solomonson, *Seismic Isolation Design Requirements Document* (draft and early corrections), LIGO draft document LIGO-T960065-02-D, California Institute of Technology and Massachusetts Institute of Technology, April 15, 1996.
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5. *LIGO Vacuum Equipment Final Design Report: Volume V, Drawings - Mechanical*, contract # PC175730, CDRL 03, May 1996.
6. Dennis Coyne, E-mail communication, August 15, 1996.
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