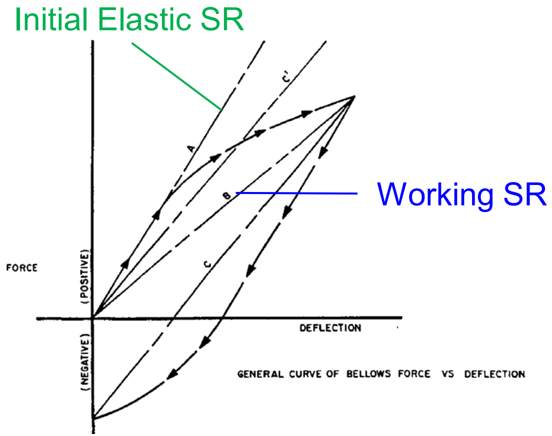
running update on LIGO beam tube dynamics analysis

- For CEBEX (Cosmic Explorer Beam Tube Experiment), pursuing discrepancy between previous dynamic analysis of the LIGO BT and measurements
- The following pages are excerpts from running CEBEX team log (G2500320)
  - 29-Oct-2025
  - 5-Nov-2025
  - 19-Nov-2025
- See also:
  - Original dynamic analysis: LIGO-T1400698, “Vacuum Beam tube FEA notes”
  - BT dynamic measurements: LHO Logbook entry #6418
  - BT anchor stiffness estimates: LIGO-T2500383, “LIGO Beamtube Support Anchors”

Modal and Dynamic analysis of the beamtube

- Last week Mike mentioned that Fabrice had done some extensive FEA of the LIGO BT but couldn’t match Robert’s frequency response measurements - see T1400698 and LHO Logbook entry #6418
  - FEA computed bellows axial spring rate was much stiffer than CBI measurements
  - Refined FEA first mode frequency of 12.4 Hz compared to 8 Hz from measurements
- Bellows axial spring rate discrepancy:

Initial Elastic SR Source	Axial Spring Rate	
	(lbf/in)	(MN/m)
EJMA calculation (this memo)	10,679	1.87
CBI EJMA calculation (LIGO-E950010-00-B)	10,202	1.77
Ansys FEA (this memo)	11,670	2.04
Ansys FEA (LIGO-T1400698)	21,127	3.7

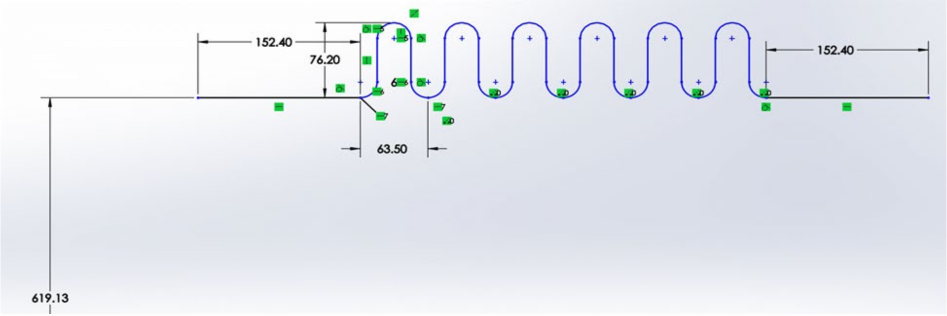


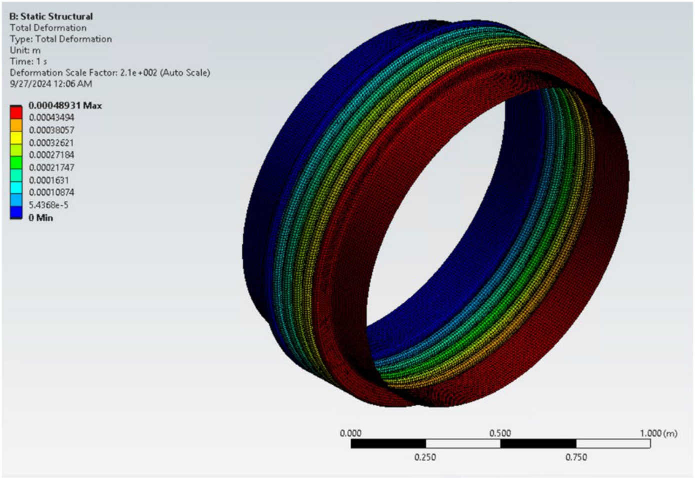
Modal and Dynamic analysis of the beamtube (continued)

- Working spring rate:

$$f_w = \begin{cases} f_i \; for \; S_t \leq 1.5 \, S_y \\ 0.67 \, f_i \; for \; S_t > 1.5 \, S_y \end{cases}$$

- Stress range, S_t, for bakeout far exceeds yield strength, S_y
- Calculated working SR = 0.67 x 1.8 MN/m = 1.2 MN/m
- Measurements of the spring rates of the first 125 bellows = 0.845 MN/m ± 10%
- Closer agreement between analysis and SR measurement … and not the reason for the modal frequency disagreement





48.75 in ID

0.105 in thick

U-shape corrugation

2.5 in pitch

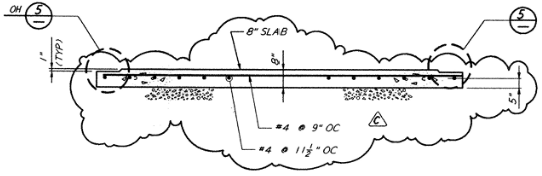
3 in depth

6 corrugations

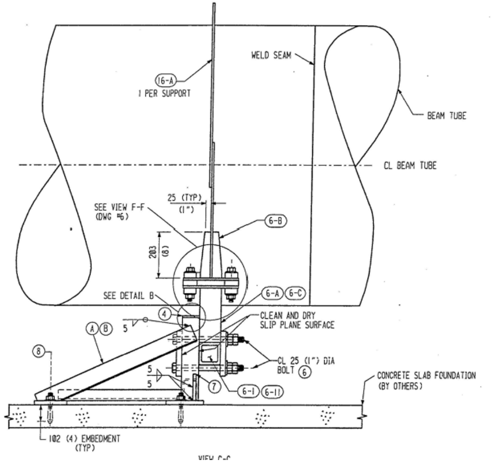
15 in convolution length

Modal and Dynamic analysis of the beamtube (continued)

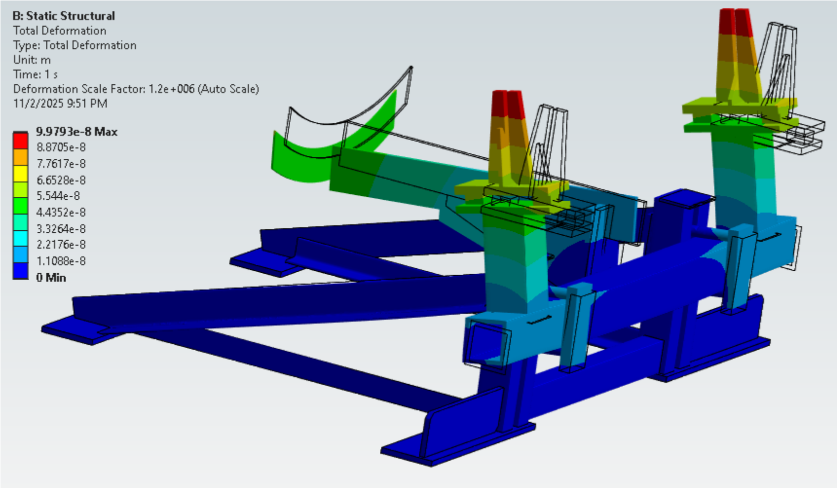
- T1400698 FEA boundary condition is for the bases (bottom faces) of the Fixed Support and Guided Support to be clamped (fixed)
- The bases are in fact bolted to the cement slab which rests upon the ground
- The embedded bolts and the cement slab, supported by the ground (semi-infinite, elastic half-space), may have significant compliance relative to the steel tube and its supports
    - → I plan to include this in a revised FEA …

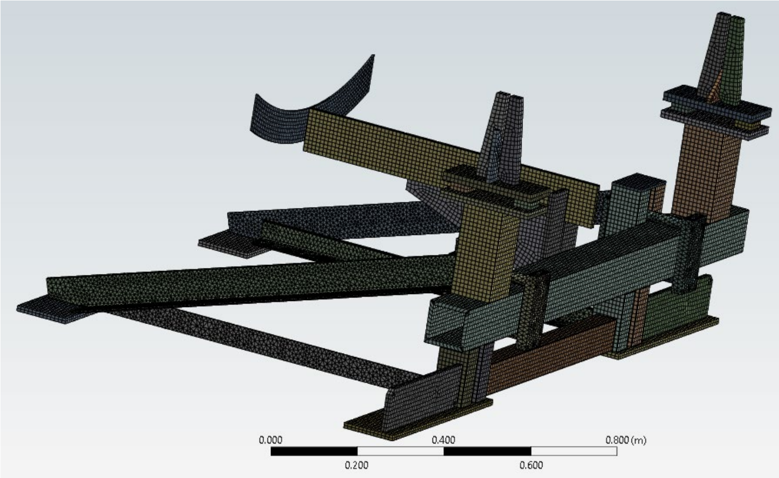


TYPICAL BEAM TUBE ENCLOSURE SLAB
SECTION A
½" = 1'-0"
REF LA-S-505 LA-S-506



Match LIGO Vibration Measurements with FEA

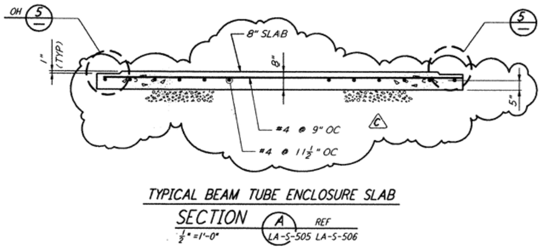




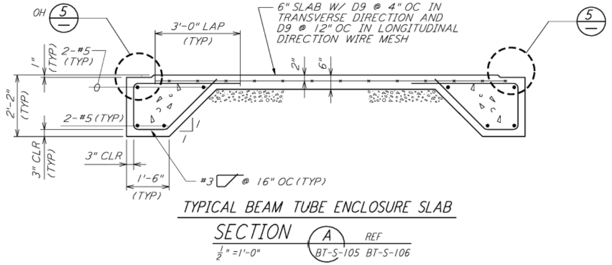
- Revisit the dynamic FEA in LIGO-T1400698
- Repeated fixed support stiffness analysis in T1400698 as first step
- Modeled using CBI drawings D950035, D950036, D950037
- Same result, k = F/x = 1.00e7 N/m
- Next step is to add reinforced concrete slab to model

Reinforced concrete slab model

- Hanford Final Design Report, C960774 (Vol. III-A-2)
  - Volume II, section 10, Concrete Slabs on Grade
    - Modulus of subgrade soil reaction, K=100 #/in^3 (conservative based on soil reports)
  - Volume II, section 9, Strip Footing Design
    - Soil
      - Ks = 190.1 kcf (modified for rectangular shape of footing/pad, see pg. 56 of 222)
      - Qa = 3 ksf ?
    - Concrete
      - Ec = 3122 ksi
      - ν = 0.250
- LHO Geotechnical Survey (aka soil report), C930032 (see pg. 14 of 204)
- ACI-318-99:
  - "For nonprestressed slabs, it is normally appropriate to reduce slab bending stiffness to between one-half and



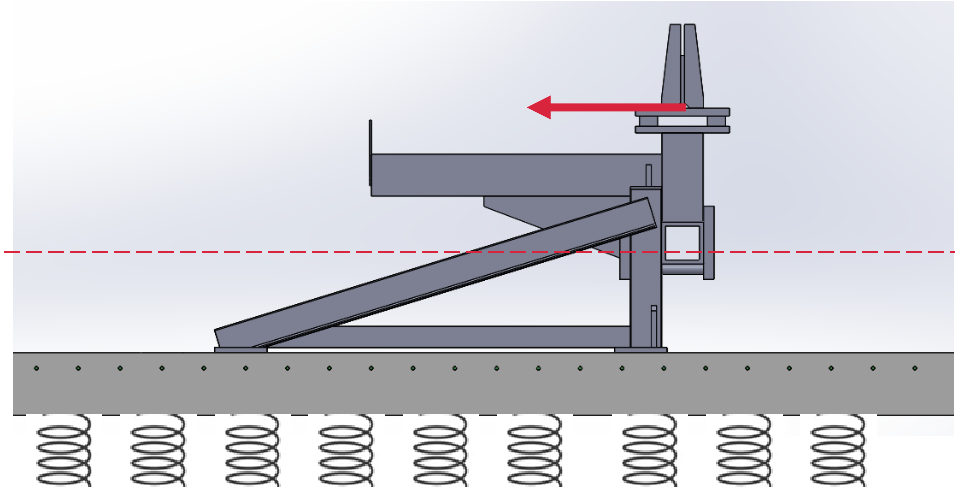
D961240-C, Parsons LA-S-505
LLO issued for bid



D961582-A, Parsons BT-S-105
LHO issued for as-built

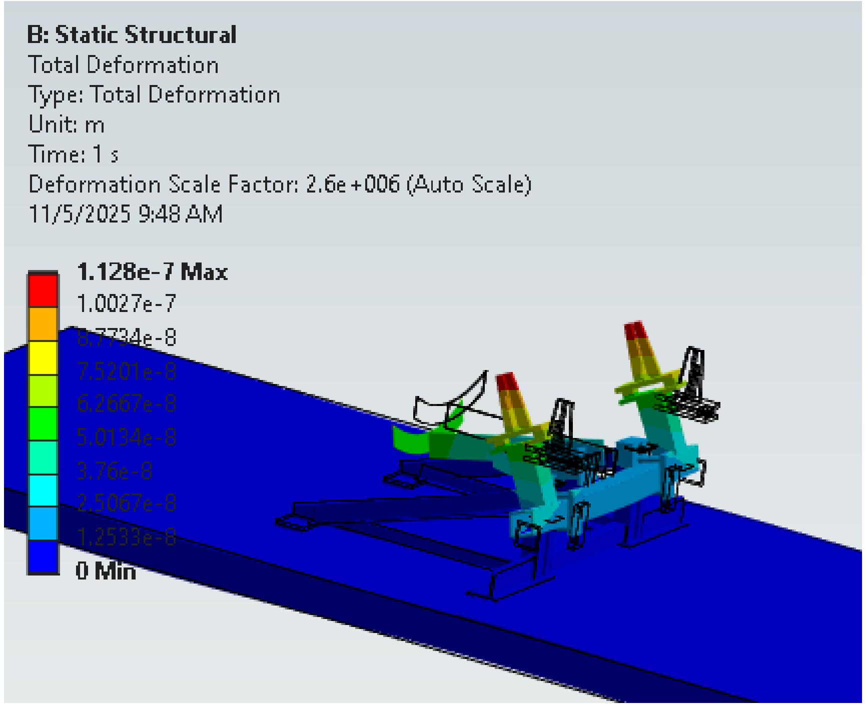
Reinforced concrete slab model

- Transformed section method
  - composite beams/slabs (e.g. reinforced concrete) transformed into a single, homogeneous cross-section by converting one material (rebar) into an equivalent area of the other material (concrete)
  - Modular ratio, $n = E_{steel}/E_{concrete} = 9.3$
  - Reinforcing wire mesh is small diameter: D9 = 0.338” diameter (8.58 mm)
  - Longitudinal spacing is large: 12” (0.305 m)
  - Bending is not about the slab neutral axis
  - Effective increase in slab thickness due to wire mesh is trivial (1.6 mm)

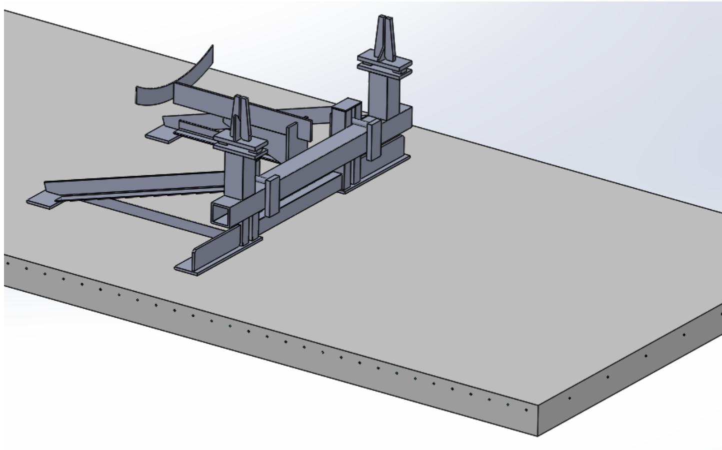


Reinforced concrete slab model

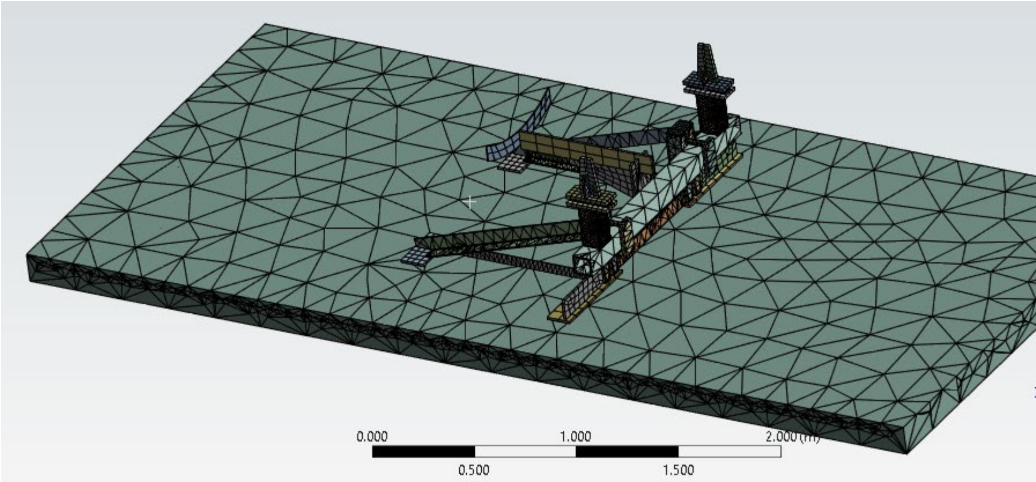
- k = F/x = 0.887E7 N/m
- transformed slab & elastic soil foundation
- ¼ cement modulus for nonprestressed, cracked slab
- Not enough to explain the T1400698 predicted 12.4 Hz vs 8 Hz measurement



Reinforced Concrete with Reinforcement Mesh Explicitly Modeled & Elastic (Soil) Foundation



- Insufficient memory on pleione … need to try again on eng10 when available
- Can also do more explicit/detailed modeling of the bolted joints in the fixed support



Expansion anchor preload (torque) relaxation & spring rate

- See E2500383 for details
- In search for reason that finite element modeling of the LIGO beam tube dynamics (T1400698) didn't match measurements (LHO Logbook entry #6418), discovered:
  - CBI may not have specified a quantitative torque value to be applied at the time of installation
    - Important to "set" the expansion wedge
  - The preload (torque) declines to between 40% and 50% of the initial value over a period of a few months to a year
    - However, Hilti strength values are based on 50% relaxation of pre-load, so not a problem
- Anchor spring rate
  - Hilti software PROFIS:
    - does not directly provide a single output value for the spring stiffness, but rather incorporates these proprietary, test-based stiffness values into its internal calculations to determine load distribution on the anchors
    - Will attempt to "reverse engineer" anchor stiffness from load distribution calculations
    - Does not include the LIGO 1990s model of the expansion anchor (KB-II)
  - Found Hilti value for current generation expansion anchor (Kwik Bolt TZ2) and will use in updated LIGO BT dynamic analysis to determine first modal frequency