



U.S. DEPARTMENT OF
ENERGY



**UNIVERSITY OF
CALIFORNIA**



BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY



Mechanical Vibrations of the ATLAS ITk Structures Under Transportation Loads

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Forum on Tracker Detector Mechanics 2023

01 June 2023

Outline

- Introduction
- Transportation Loads
- FE Modeling
- Measurements
- Conclusion

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Introduction



- There are many **shipments** planned for the ITk global mechanics:
 - **Outer Cylinder** (OC) from Applied Composites – San Diego (ACSD) to LBNL, LBNL to CERN
 - **Strip Barrels** (Layer 3 and 2) from ACSD to LBNL, LBNL to CERN, CERN to Oxford, back to CERN
 - Strip Barrels (Layer 1 and 0) from LBNL to CERN, CERN to Oxford, back to CERN
- Loads of interest: **truck**, **plane**, and **handling**
- Correct evaluation of **loads** and **box design** crucial to protect our structures

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Transportation Loads

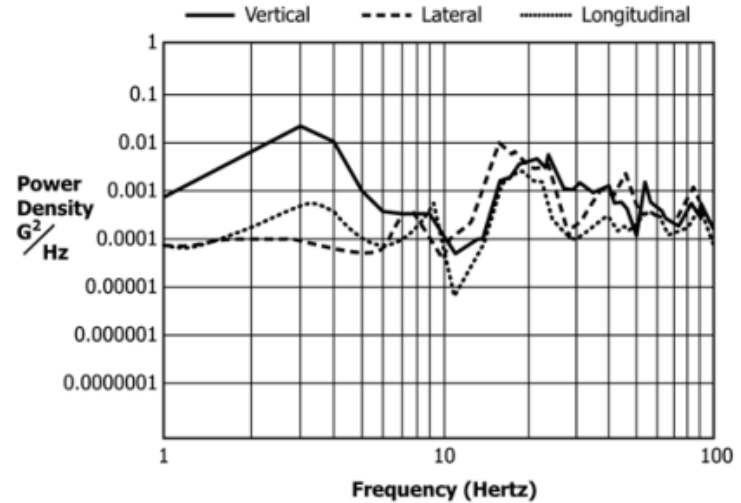
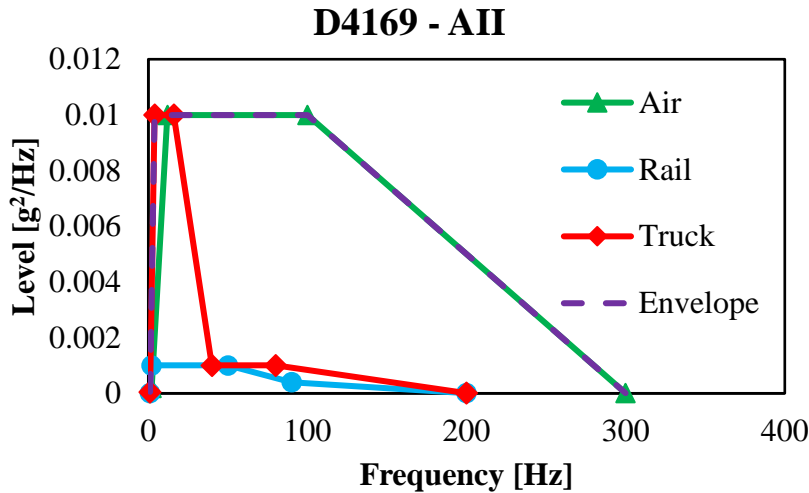
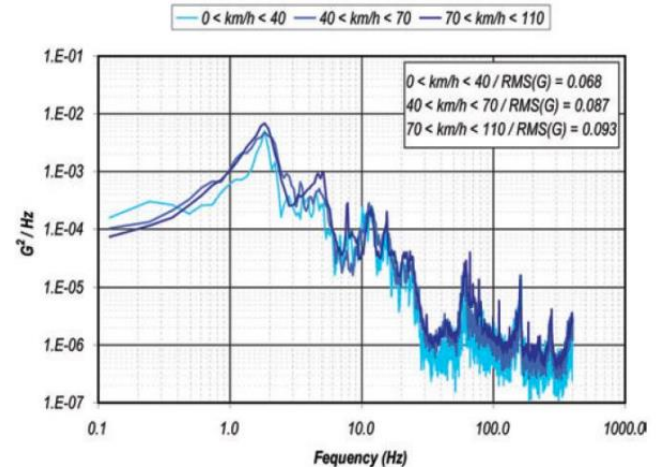


FIG. X2.1 Sample Truck Vibration Data

- **Standard** transport loads:
 - ASTM-D4169-16
 - ASTM-D4728 (Sample truck vibration data)
- **Measured** data for air ride truck from: 'Design Report for the DUNE APA shipping frames'
 - Air truck significantly damped
 - Only vertical loads available, can use lateral loads from ASTM-D4728



Transportation Loads - Fitting

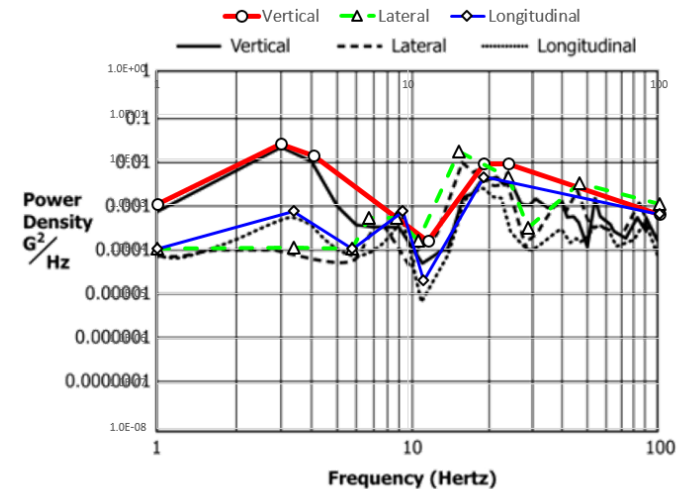
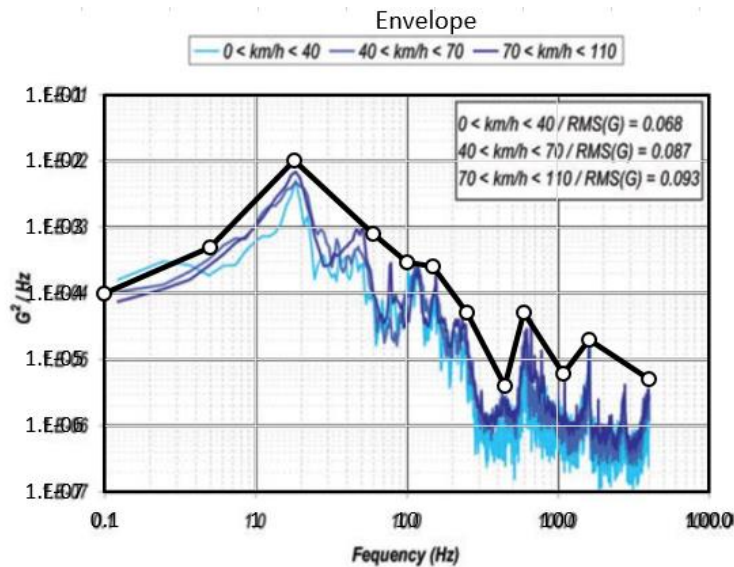
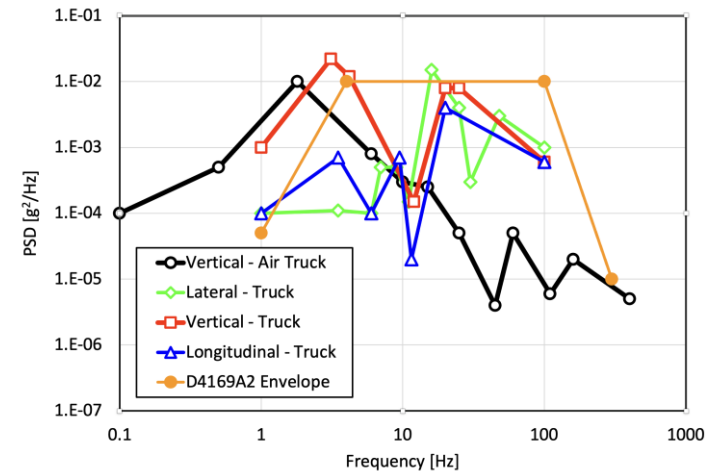


FIG. X2.1 Sample Truck Vibration Data

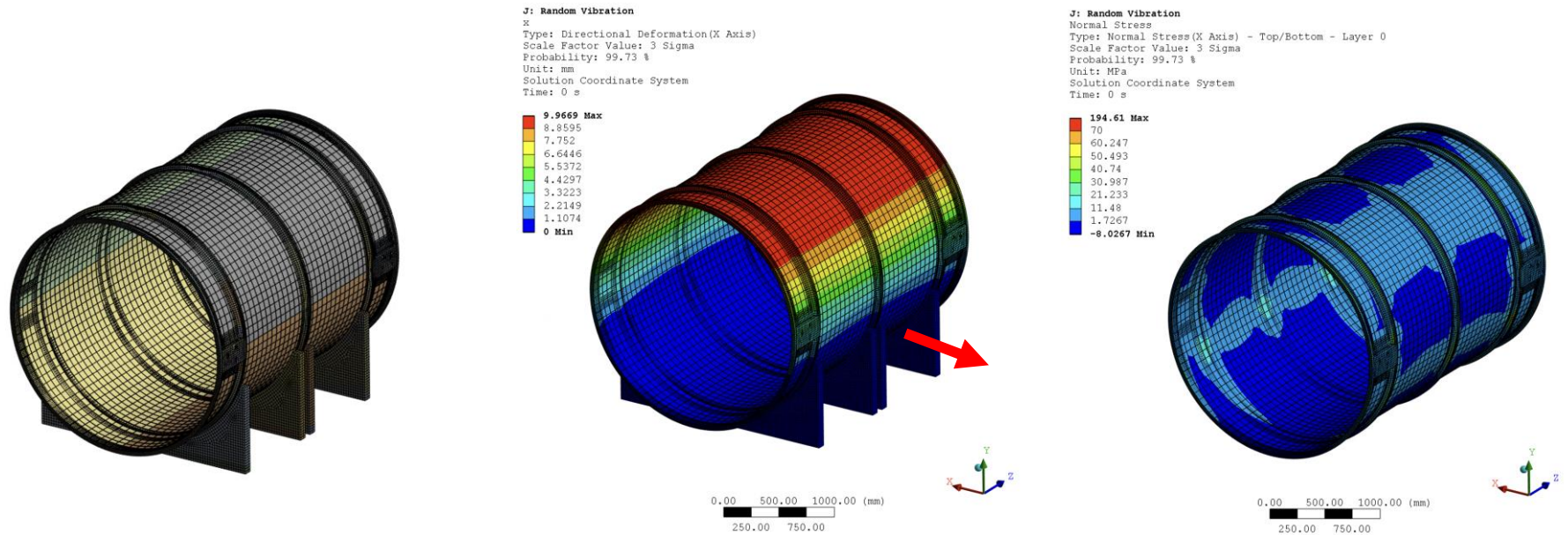
- **Conservative fitting** of the available data
- Another option could be to agree with the transportation firm for limits
- **Vertical peak** at ~ 2 Hz, **lateral** at 15 Hz, **longitudinal** at 3 Hz and 25 Hz



Outline

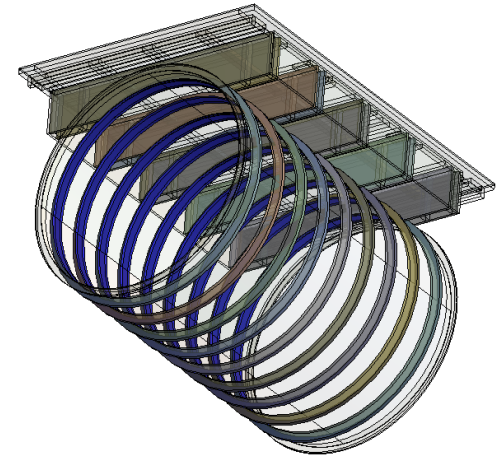
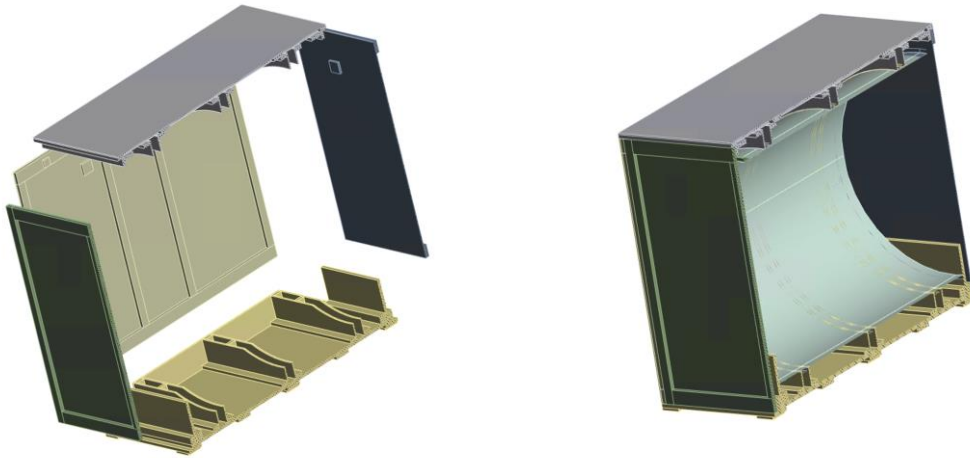
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Box Design - Preliminary

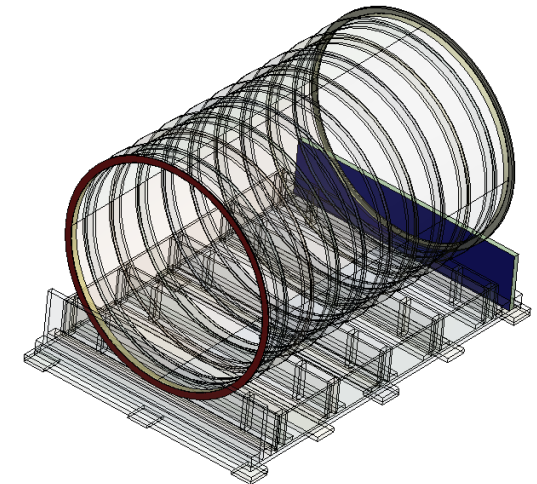


- Preliminary analysis performed with the OC supported only on the bottom
 - **High** (but **not dangerous**) **stresses** (~ 200 MPa)
 - Significant **displacements** (~ 9 mm in the horizontal plane), which could lead to 'impacts' against the box sides
 - Reinforcing the OC ends with stiffening crosses does not solve the problem

Final Box Design - Model Description

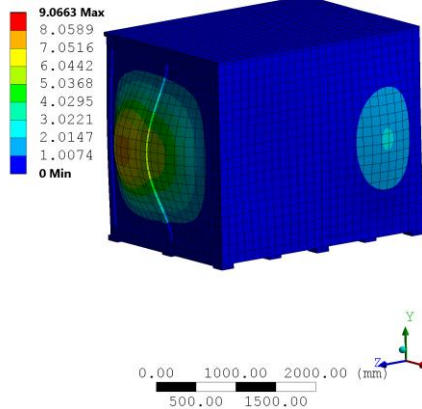


- **New design** with 'tight' fit between box and shell
- Connections:
 - Top, bottom against the hat stiffener flat
 - Flange against longitudinal plates
 - All simulated as **bonded**, which should be realistic for prestressed contacts and **small vibrations**
- Model results presented only for the OC, same considerations apply to SB

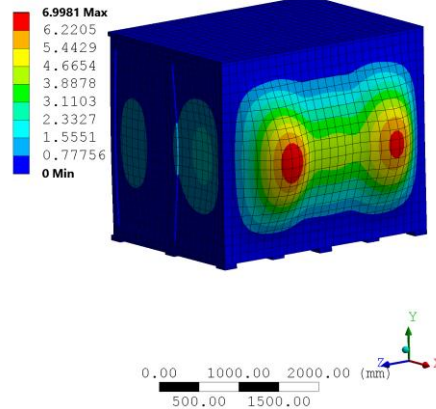


OC – Results – Box Modes

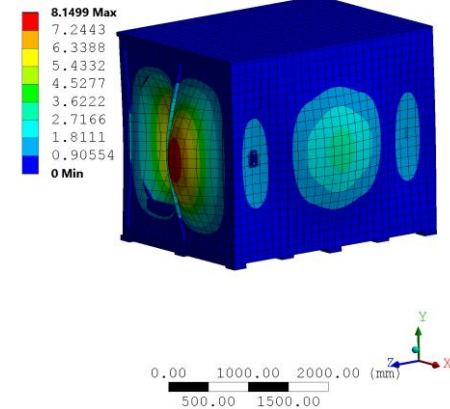
G: Modal
Total Deformation
Type: Total Deformation
Frequency: 29.123 Hz
Unit: mm



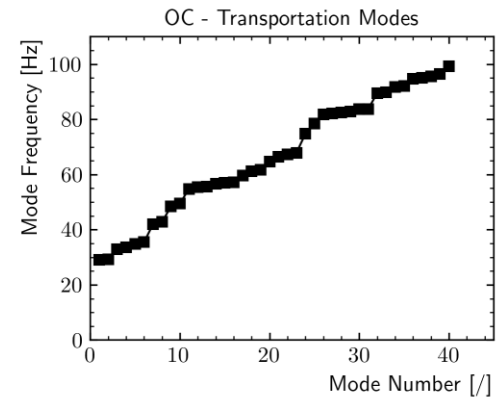
G: Modal
Total Deformation
Type: Total Deformation
Frequency: 32.893 Hz
Unit: mm



G: Modal
Total Deformation
Type: Total Deformation
Frequency: 42.005 Hz
Unit: mm



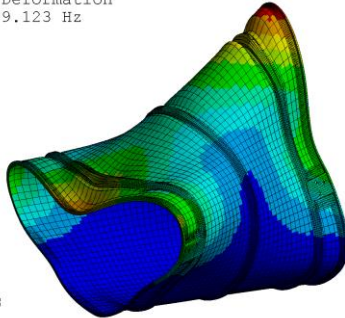
- **First mode** $f = 29$ Hz
 - This is **above** the **peaks** in the **PSD** data
- All modes mainly move the box
- Mode cut at 100 Hz, 40 modes found



OC – Results – OC Modes

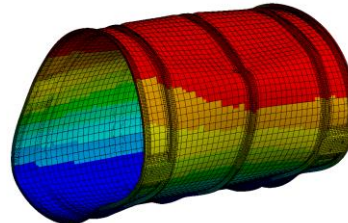
G: Modal
Total Deformation
Type: Total Deformation
Frequency: 29.123 Hz
Unit: mm
Custom
Max: 9.0663
Min: 0

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0.14458
0.12417
0.10376
0.083344
0.062932
0.04252
0.022108
0.0016958



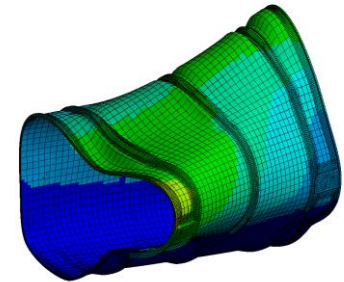
G: Modal
Total Deformation
Type: Total Deformation
Frequency: 32.893 Hz
Unit: mm
Custom
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Min: 0

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0.14406
0.12375
0.10343
0.083117
0.062803
0.042489
0.022174
0.0018598



G: Modal
Total Deformation
Type: Total Deformation
Frequency: 42.005 Hz
Unit: mm
Custom Obsolete
Max: 8.1499
Min: 0

0.1854
0.16499
0.14458
0.12417
0.10376
0.083344
0.062932
0.04252
0.022108
0.0016958



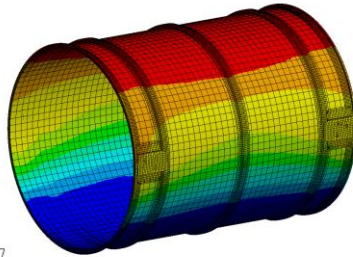
- All modes mainly move the box, but the OC follows
 - Motion ~1 or 2 **orders of magnitude smaller** with respect to the box
 - Box hidden, deformations scaled for display purposes

OC – Random Vibration Results

H: Random Vibration

X
Type: Directional Deformation(X Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
Custom
Max: 2.7114
Min: 0

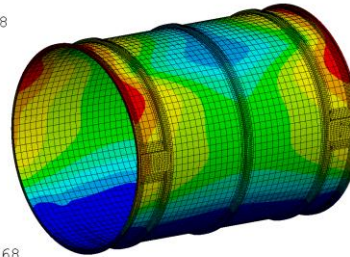
0.52354
0.46548
0.40742
0.34937
0.29131
0.23326
0.1752
0.11715
0.05909
0.0010347



H: Random Vibration

Y
Type: Directional Deformation(Y Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
Custom
Max: 0.26798
Min: 0

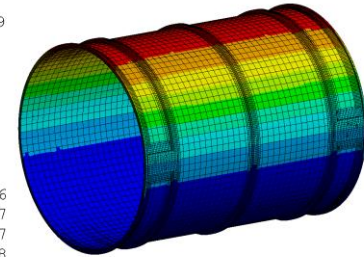
0.26798
0.23822
0.20846
0.1787
0.14893
0.11917
0.089411
0.05965
0.029888
0.00012668



H: Random Vibration

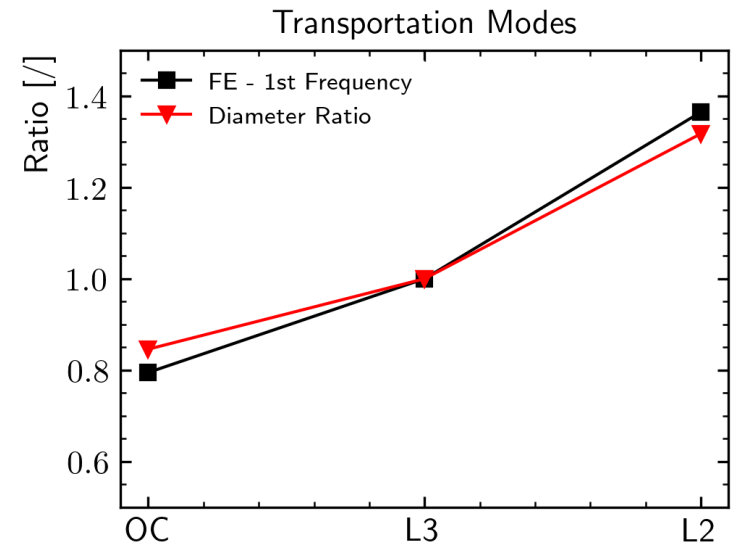
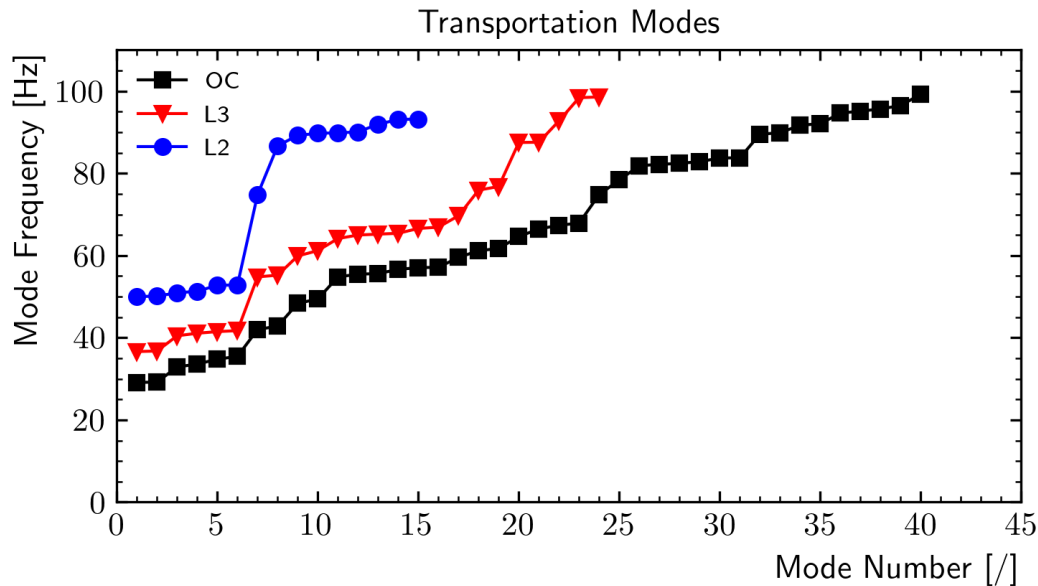
Z
Type: Directional Deformation(Z Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
Custom
Max: 4.1599
Min: 0

0.24394
0.21858
0.19322
0.16786
0.14251
0.11715
0.091786
0.066427
0.041067
0.015708



- **Envelope PSD** (shipping loads), 3 sigma **displacements** on the OC:
X: 0.52 mm Y: 0.27 mm Z: 0.24 mm
- Vibration on the box significantly larger in the XZ plane (sides and ends):
X: 2.7 mm Y: 0.27 mm Z: 4.16 mm
- OC is adding a constraint on the vertical displacements (top and bottom)
- OC stresses (not shown) negligible (<10 MPa)

Transportation Modes - Summary



- Same approach for **Layer 2** (L2) and **Layer 3** (L3) transportation modeling
- Similar box design for all shells, first mode **frequency scales** with **size**

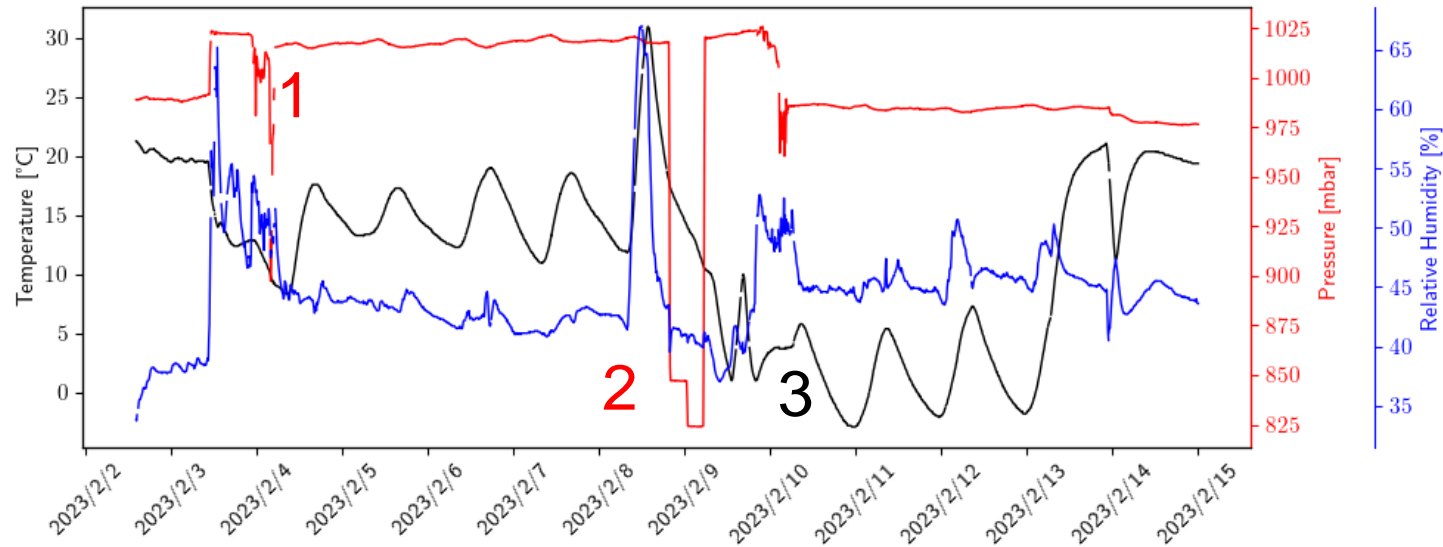
$$f \sim \sqrt{\frac{\beta/L_0 R}{\rho L_0 R t}} \rightarrow \frac{f_i}{f_j} \sim \frac{R_j}{R_i}$$

- Error within $\pm 5\%$, approach might be good for scaling to different shell sizes

Outline

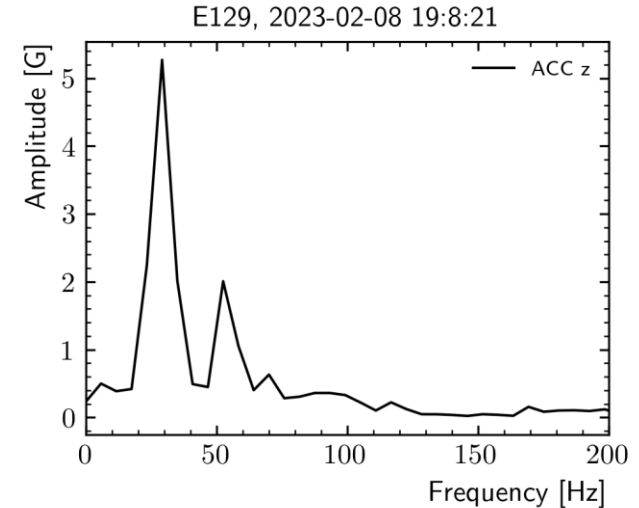
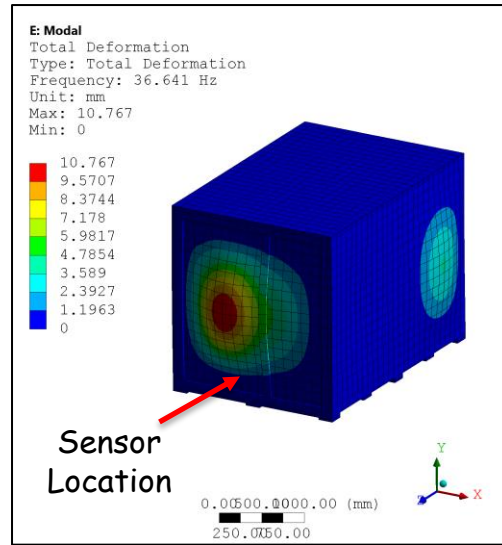
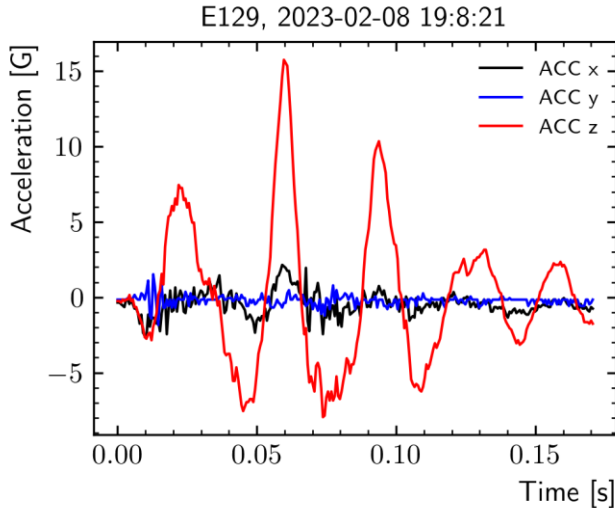
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SB L3 – LBNL to CERN



- Accelerometers record **environment** data at fixed time intervals, and **acceleration** 'events' if triggered (acceleration>threshold)
- Environment data example:
 1. Mountain outside of Los Angeles
 2. Drop in pressure: plane to FRA
 3. Pretty cold in Germany

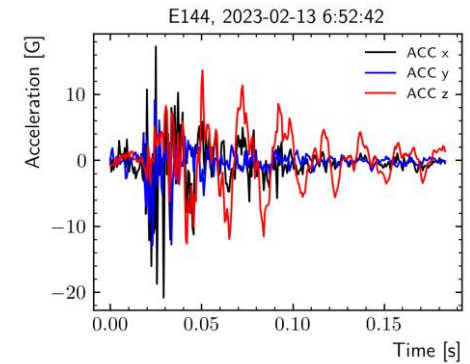
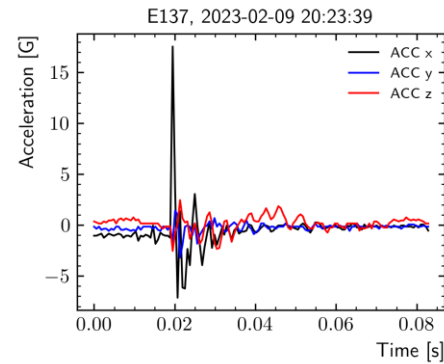
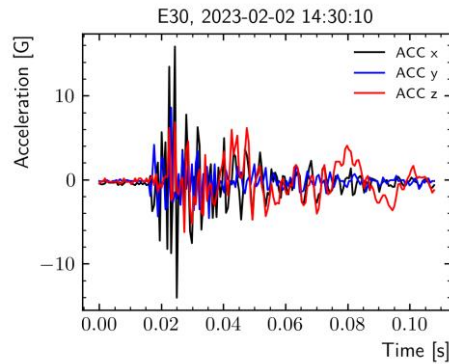
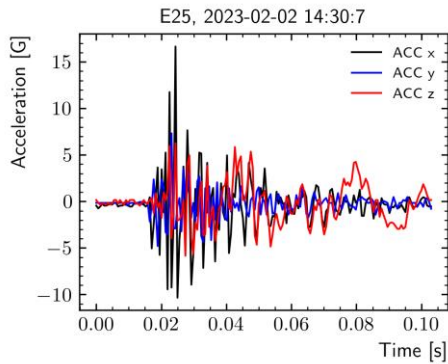
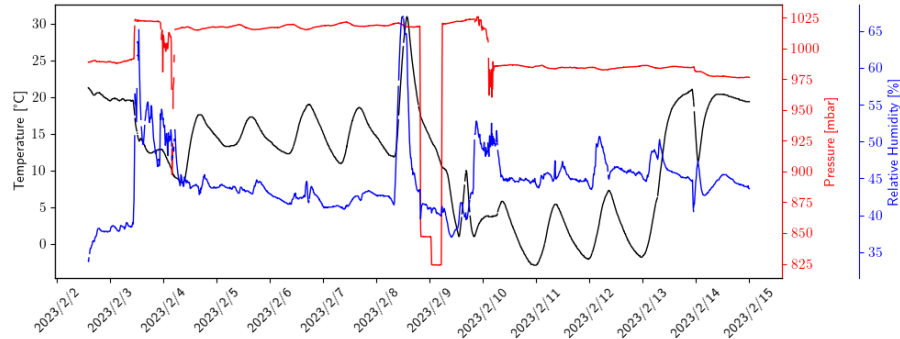
SB L3 – LBLN to CERN – Longitudinal



- Scripts automatically isolate and plot events
 - Events with **acceleration** above **10 g** are **flagged**
- Many events with **large vibrations** in z (**longitudinal**)
 - Sensor close to an antinode of the first vibration mode
 - **Model** predicted 36 Hz, reality is 29.2 Hz
 - Not too bad considering that box model was '**bonded**', reality is **bolted** (less stiff)

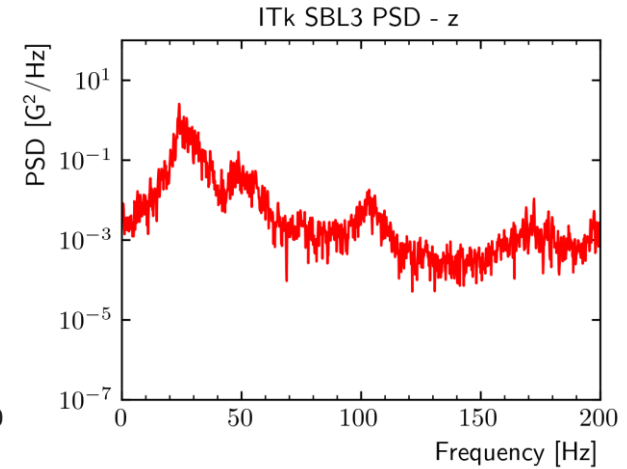
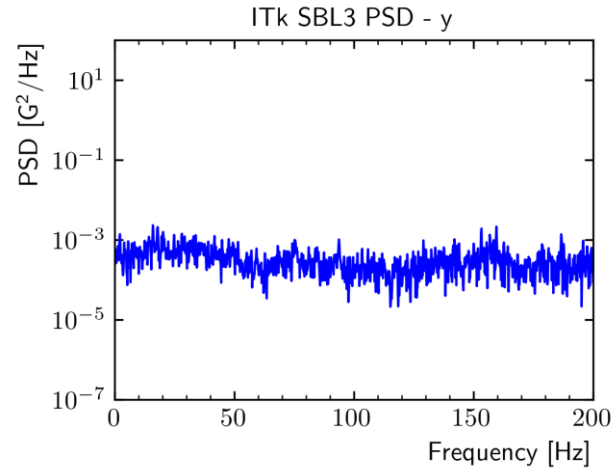
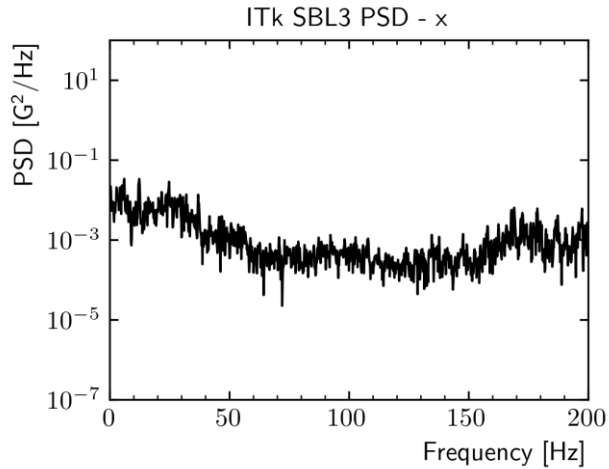


SB L3 – LBLN to CERN – X



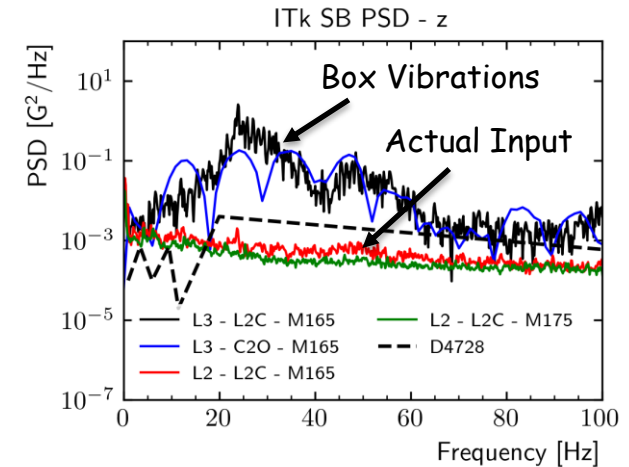
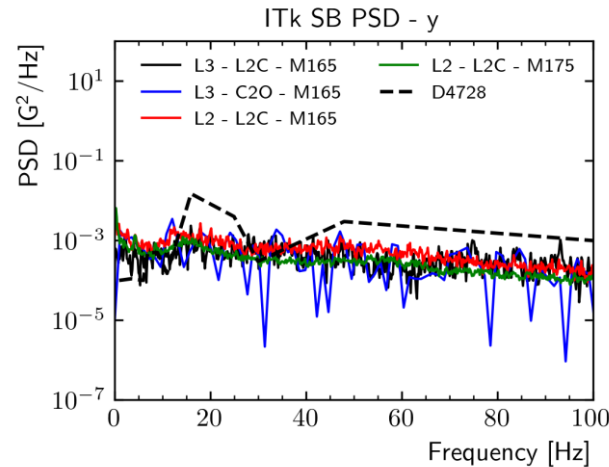
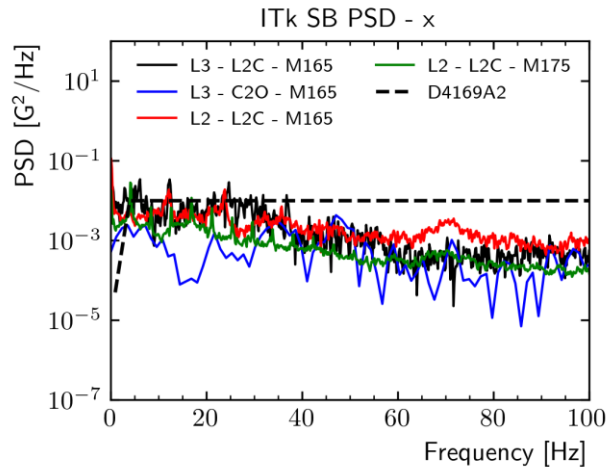
- **Typical** recordings: flagged events ($a > 10$ g) in the vertical direction
 - Accelerations on 02/02: **truck**
 - Acceleration on 02/09: **airplane landing**
 - Acceleration on 02/13: **handling**

SB L3 – LBLN2CERN – PSD



- **PSD** from all recorded events
- Only significant energy is in **longitudinal (z) motions**
 - Comparison with FE results suggest that this vibration is **contained within the box**

All Transportation Data



- PSD from all transportation data available
 - Legend: L-LBNL, C-CERN, O-OXFORD
- Sensor moved on the bottom of the crate for **L2**:
 - Measurement ~ input acceleration
 - Bump in **longitudinal** motions **disappeared**
- **Peak** values **similar** to available data from **standards**
 - **Higher** than expected values on the **low end** of the spectrum



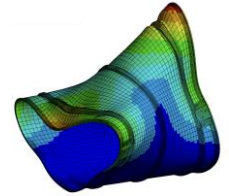
L2 Sensor Location

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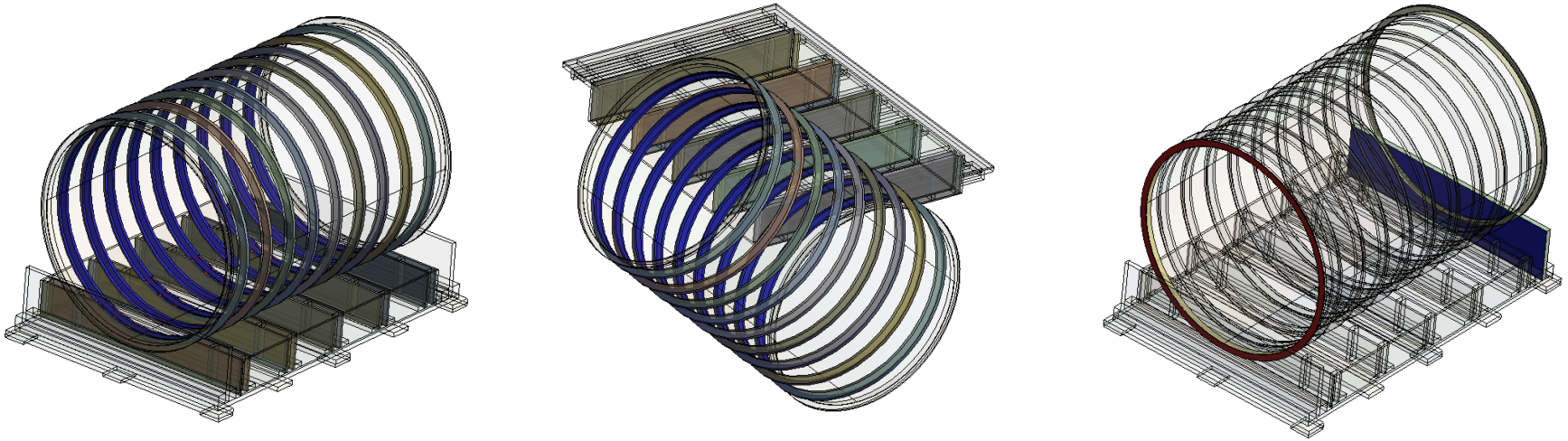
Conclusion



- **Loads** from **literature** review:
 - Conservative approach considering '**envelopes**' of the available data
 - Might not always be feasible for more fragile items
- **Box design**:
 - Supporting only the bottom leads to excessive displacements
 - Optimized box design allows for reduced displacements and stresses
- **Shipping** data **analysis**:
 - Some significant **vibrations** in the **longitudinal** direction (z) for L3
 - FEA suggests that these are only local **vibrations** of the **box**
 - They disappeared when the sensor was moved, as predicted
 - **Sensor placement** can either validate the models or retrieve the input accelerations – both important
 - Measured **PSD seems** larger than expected at lower frequencies
 - Acceleration peaks over 10 g due to airplane landings, handling

Extra

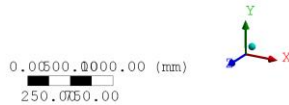
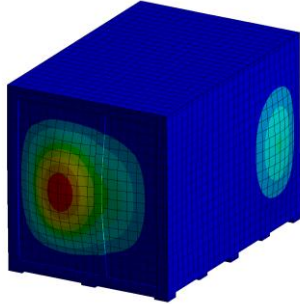
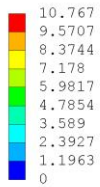
SB Design



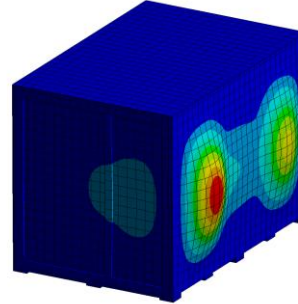
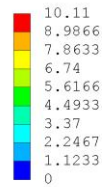
- Box in plywood: 0.5 g/cc^3 , 8 GPa modulus
 - Should add steel parts, might improve results
- Connections:
 - Top, bottom against the hat stiffener flat
 - Flange against longitudinal plates
 - All glued, which is true if fit precisely and vibration is small

SB L3 – Results – Box Modes

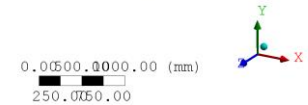
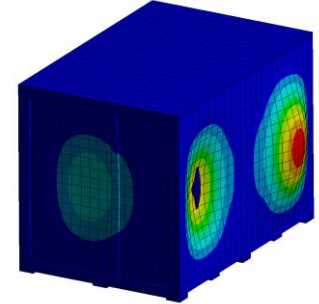
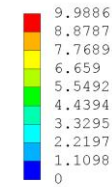
E: Modal
Total Deformation
Type: Total Deformation
Frequency: 36.641 Hz
Unit: mm
Max: 10.767
Min: 0



E: Modal
Total Deformation
Type: Total Deformation
Frequency: 40.478 Hz
Unit: mm
Max: 10.11
Min: 0



E: Modal
Total Deformation
Type: Total Deformation
Frequency: 41.734 Hz
Unit: mm
Max: 9.9886
Min: 0

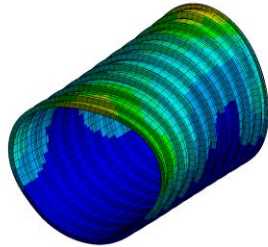


- First mode $f = 36$ Hz, does not change with finer box mesh
 - This is above the peaks in the PSD data and will probably be better with steel stiffeners
- All modes move mainly the box
- Mode cut at 100 Hz, 24 modes found

SB L3 – Results – SB Modes

E: Modal
Total Deformation
Type: Total Deformation
Frequency: 36.641 Hz
Unit: mm
Custom Obsolete
Max: 10.767
Min: 0

0.21814
0.194
0.16985
0.14571
0.12156
0.097416
0.073271
0.049125
0.02498
0.00083439

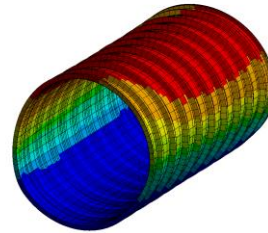


0.0500, 0.000.00 (mm)
250.0x50.00



E: Modal
Total Deformation
Type: Total Deformation
Frequency: 40.478 Hz
Unit: mm
Custom
Max: 10.11
Min: 0

0.21814
0.194
0.16985
0.14571
0.12156
0.097416
0.073271
0.049125
0.02498
0.00083439

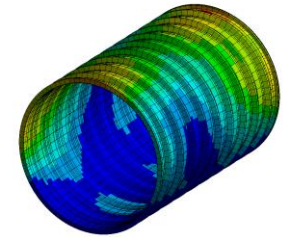


0.0500, 0.000.00 (mm)
250.0x50.00



E: Modal
Total Deformation
Type: Total Deformation
Frequency: 41.734 Hz
Unit: mm
Custom
Max: 9.9886
Min: 0

0.089379
0.079636
0.069893
0.060149
0.050406
0.040663
0.03092
0.021176
0.011433
0.0016898



0.0500, 0.000.00 (mm)
250.0x50.00



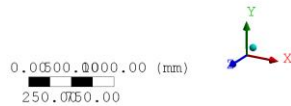
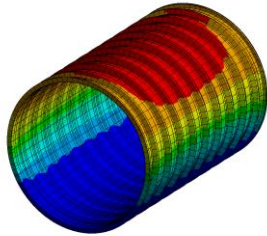
- All modes move mainly the box, but the SB L3 follows
 - Motion ~2 orders of magnitude smaller

SB – L3 - PSD Results

F: Random Vibration

ux
 Type: Directional Deformation(X Axis)
 Scale Factor Value: 3 Sigma
 Probability: 99.73 %
 Unit: mm
 Solution Coordinate System
 Time: 0
 Custom
 Max: 2.838
 Min: 0

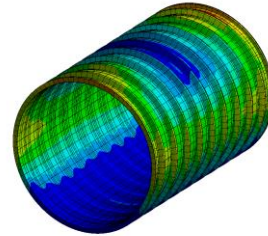
0.37355
 0.33213
 0.29071
 0.24929
 0.20788
 0.16646
 0.12504
 0.083619
 0.0422
 0.00078117



F: Random Vibration

uy
 Type: Directional Deformation(Y Axis)
 Scale Factor Value: 3 Sigma
 Probability: 99.73 %
 Unit: mm
 Solution Coordinate System
 Time: 0
 Custom
 Max: 0.13213
 Min: 0

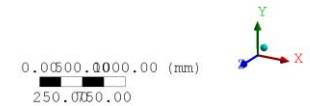
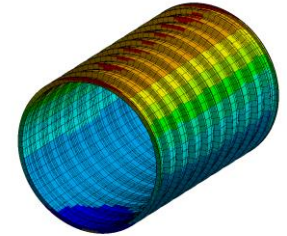
0.13213
 0.11745
 0.10277
 0.088091
 0.073411
 0.05873
 0.04405
 0.02937
 0.01469
 9.4805e-6



F: Random Vibration

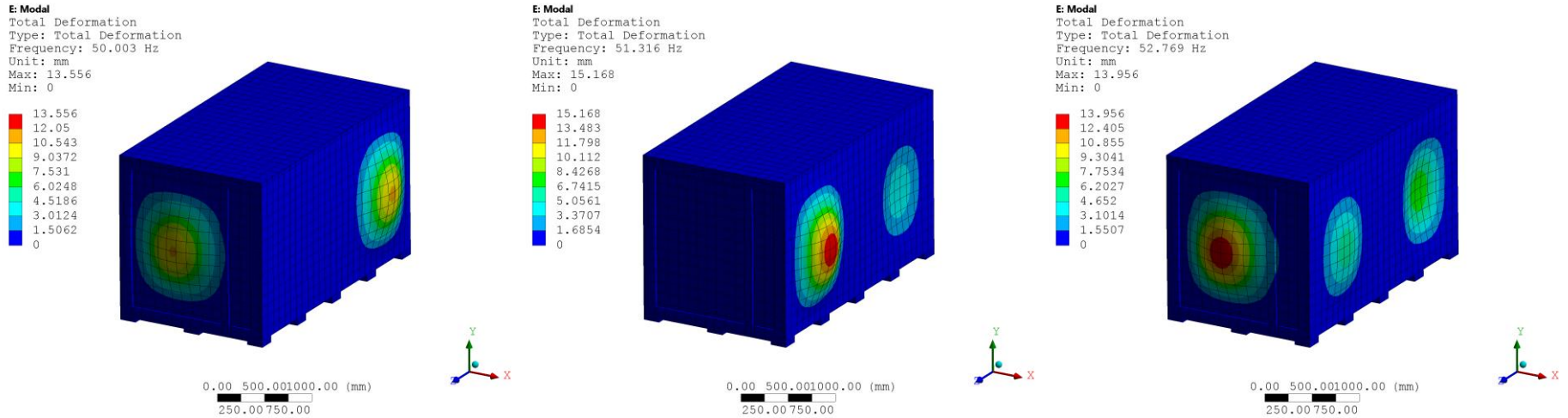
uz
 Type: Directional Deformation(Z Axis)
 Scale Factor Value: 3 Sigma
 Probability: 99.73 %
 Unit: mm
 Solution Coordinate System
 Time: 0
 Custom
 Max: 2.909
 Min: 0

0.11283
 0.10117
 0.089513
 0.077852
 0.066191
 0.05453
 0.042869
 0.031208
 0.019547
 0.0078855



- Results, 3 sigma displacements on the SB L3:
 X: 0.37 mm Y: 0.13 mm Z: 0.11 mm
- Vibration on the box significantly larger:
 X: 2.8 mm Y: 0.13 mm Z: 2.91 mm
- L3 is adding a constraint on the vertical displacements

SB L2 – Results - Box Modes

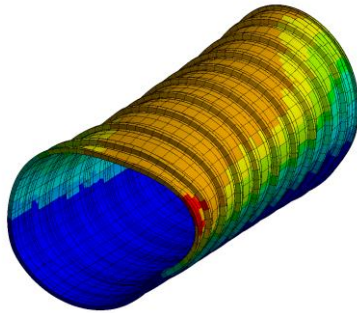


- First mode $f = 50$ Hz
 - All modes move mainly the box
- Mode cut at 100 Hz, 15 modes found

SB L2 – Results - SB Modes

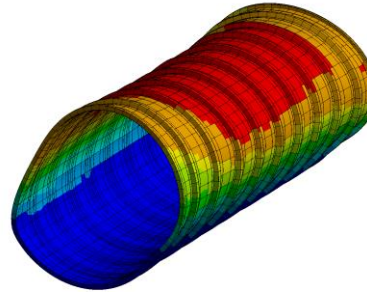
E: Modal
Total Deformation
Type: Total Deformation
Frequency: 50.003 Hz
Unit: mm
Custom
Max: 13.556
Min: 0

0.19101
0.17034
0.14967
0.12901
0.10834
0.087673
0.067005
0.046338
0.02567
0.0050029



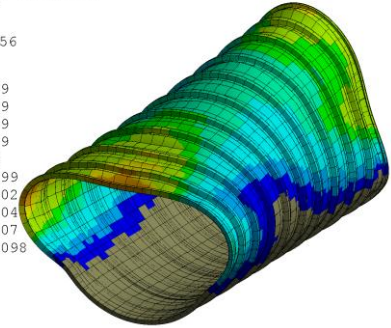
E: Modal
Total Deformation
Type: Total Deformation
Frequency: 50.927 Hz
Unit: mm
Custom
Max: 14.952
Min: 0

0.23054
0.20509
0.17963
0.15418
0.12872
0.10326
0.077809
0.052354
0.026898
0.0014424



E: Modal
Total Deformation
Type: Total Deformation
Frequency: 52.769 Hz
Unit: mm
Custom
Max: 13.956
Min: 0

0.17839
0.15939
0.14039
0.12139
0.1024
0.083399
0.064402
0.045404
0.026407
0.0074098



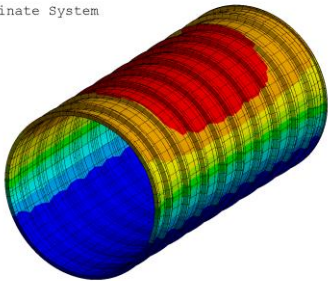
- All modes move mainly the box, but the SB L3 follows
- Motion ~2 orders of magnitude smaller

SB – L2 - PSD Results

F: Random Vibration

ux
Type: Directional Deformation(X Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
Custom
Max: 2.7133
Min: 0

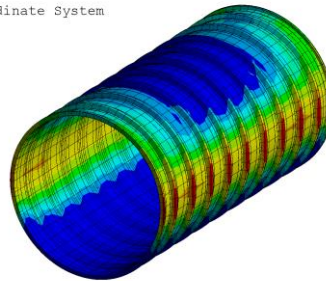
0.36737
0.32656
0.28576
0.24495
0.20414
0.16333
0.12252
0.081711
0.040902
9.3615e-5



F: Random Vibration

uy
Type: Directional Deformation(Y Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
Custom
Max: 0.094206
Min: 0

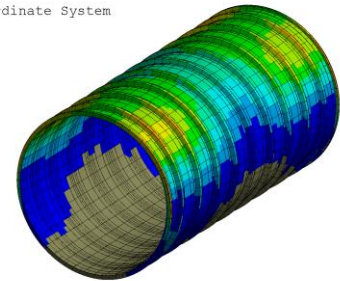
0.070721
0.062868
0.055015
0.047162
0.039309
0.031456
0.023603
0.01575
0.0078975
4.4528e-5



F: Random Vibration

uz
Type: Directional Deformation(Z Axis)
Scale Factor Value: 3 Sigma
Probability: 99.73 %
Unit: mm
Solution Coordinate System
Time: 0
Custom
Max: 1.6086
Min: 0

0.016873
0.01512
0.013367
0.011614
0.0098611
0.0081081
0.0063551
0.004602
0.002849
0.001096

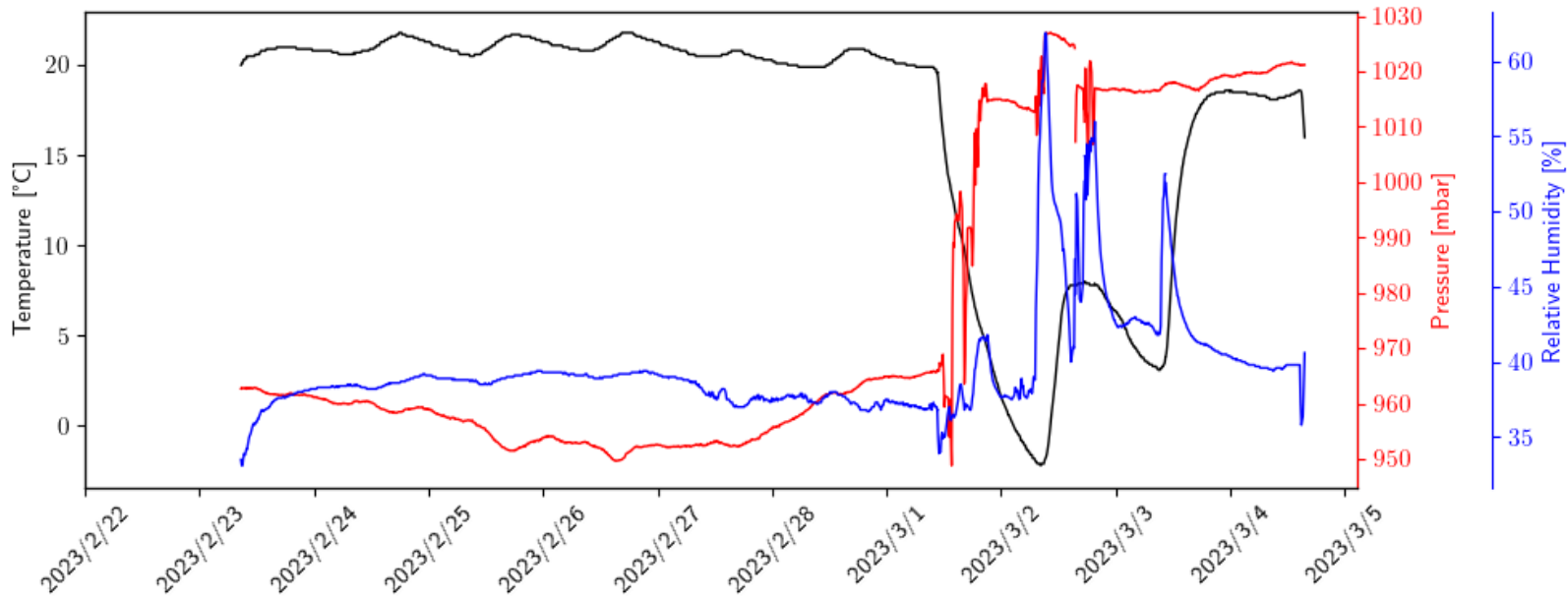


- Results, 3 sigma displacements on the SB L2:
X: 0.37 mm Y: 0.07 mm Z: 0.017 mm
- Vibration on the box significantly larger:
X: 2.7 mm Y: 0.09 mm Z: 1.68 mm
- L2 is adding a constraint on the vertical displacements

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L3 – CERN 2 OXFORD

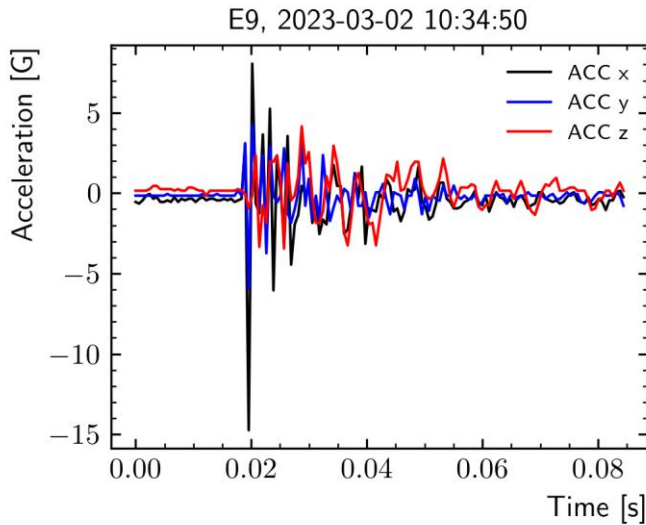
SB L3 – CERN to OXFORD



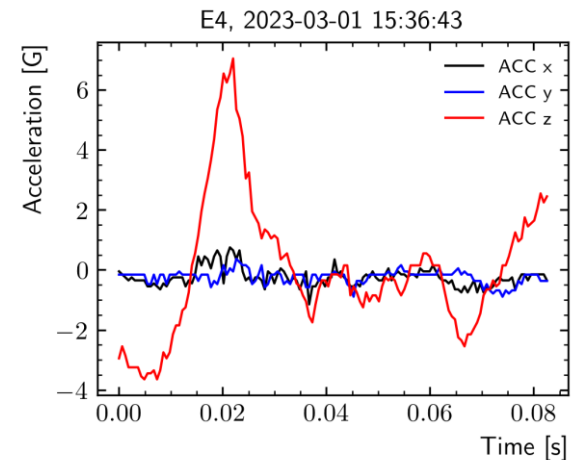
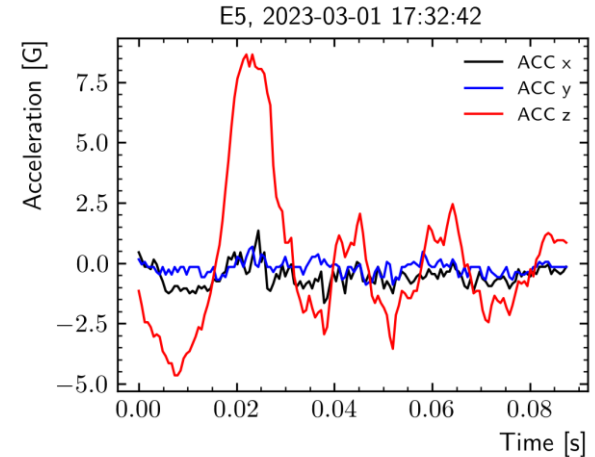
- Sequence:

1. Accelerometers loaded into crate and sealed 22/02
2. Crane lift to B180 entrance + Forklift onto truck + drive to UK – 28/02 →02/03
3. Forklift off truck at oxford + install casters+ move to lab 02/03 10:00am →10:40am
4. Opening crate and removal of accelerometer 03/03 15:00

Flagged Events



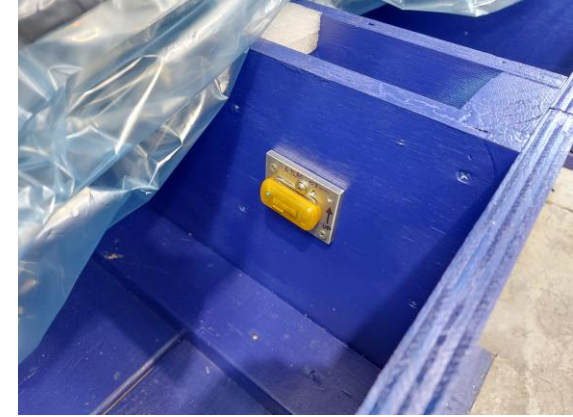
- Only one event (E9) flagged (>10 g)
 - Likely forklift operation
- Couple of loads with some energy content measured on the truck (E4, E5)



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L2 – LBNL 2 CERN

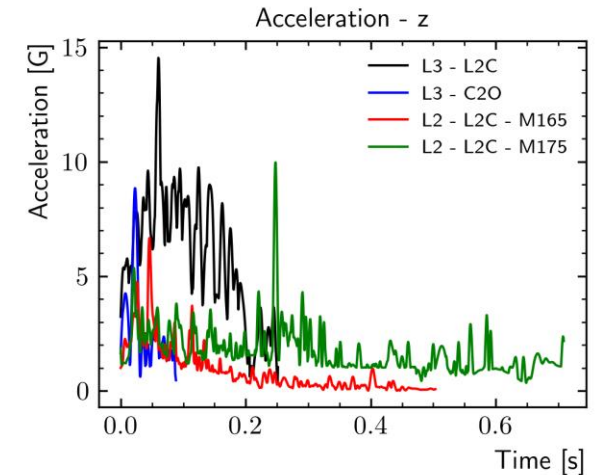
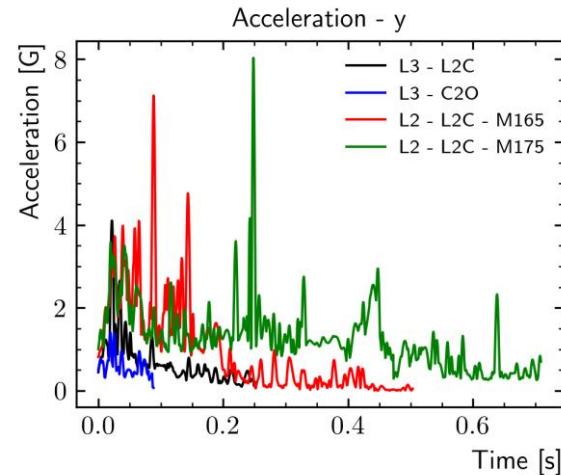
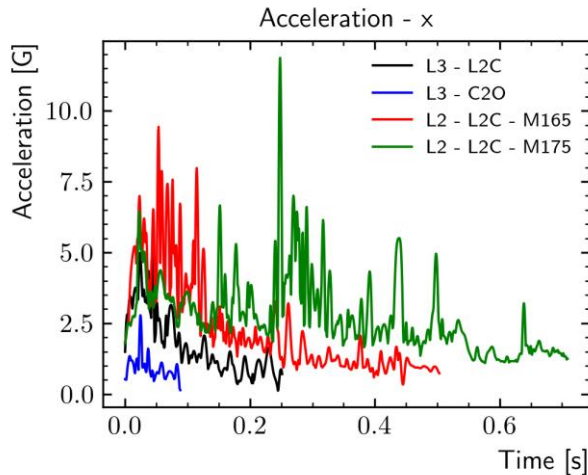
SB L2 – LBLN2CERN



Different sensor installation:

- Additional sensor used (M175, yellow). Should allow better resolution w.r.t. M165 (blue)
- Sensors now moved on the bottom of the crate
- Should allow to monitor more closely the 'input' accelerations

Acceleration Envelope



- Envelope of the worst accelerations as function of time
 - Maximum time window length depends on the actual data as the sensor can get 'retriggered' during an event