T060059-00-K

Finite Element Analysis of Advanced LIGO SUS ETM Structures

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Introduction

There is a large discrepancy between the finite element results performed on the quadruple pendulum controls prototype structures and the actual modal results done at Caltech, reference LIGO-T050237-00-D. There are two prototype structures referred to as upper and lower, the upper is a welded structure and the lower is piece part structure bolted together. The reason for the discrepancy is most likely the bolted joints in the lower structure and the bolted seams connecting the two structures together.

I have been talking to ANSYS support in the UK about our bolted joint problem. To limit the scope of the problem the initial analysis is done on the bolted connection between the upper and lower structures. The problem can be described as a cantilever made up of two sections, upper and lower, the two sections are bolted together. The ANSYS support recommendation would be to drop the stiffness between the contacting surfaces (surface between upper and lower structure, that of the bolted seam) this avoids having to model all the bolts. Dropping the contact stiffness factor makes the joint more flexible, so our model becomes a cantilever with a hinge that has a rotational stiffness (to do this click on contact area, go to advanced, click on normal stiffness, set it to manual, then change the normal stiffness factor). Alternatively you can model the actual bolts, the easiest way to do this is to literally model the bolts. With the bolts in the model you can then suppress the bonded connection between the contacting surfaces of the structure.

Analysis work

Below is some work done on a simple structure which is similar in principle to a cantilever in two sections, the cantilever has a stiff upper structure connected to a comparatively less stiff lower structure, at the connection of the two sections is a flange. The analysis has been run three different ways, firstly as a bonded structure, similar to the way our previous structural models have been run, so that the contacting faces of the flange are bonded (see definition Settings of contact regions in ANSYS described in the appendix). Secondly with varying contact stiffness on the flange faces and thirdly with the actual bolts modelled.

Results

Table 1. Simplified structure

	Bonded structure Contact surface Program controlled	Contact stiffness set to 0.01	Contact stiffness set to 0.001	Bolts, contact surface suppressed Modulus of bolts 2e11 Pa	Bolts, contact surface suppressed modulus of bolts 2e15Pa
Frequency Hz	424	402	328	224	356

	Screws, contact surface suppressed Modulus of Bolts 2e11Pa	Screws, contact surface suppressed Modulus of Bolts 2e15Pa	Bolts, contact surface frictionless, modulus of bolts 2e15 Pa	Screws, contact surface frictionless, modulus of bolts 2e15 Pa	
Frequency Hz	298	350	405	408	

Analysis of complete structure

To take the previous analysis one step further, the full structure has been modelled with particular attention to the upper and lower structure interface. The controls prototype design has what is known as an implementation ring as the interface between the upper and lower structures that incorporates three bolted seams. Models were run exploiting two different designs of the implementation ring and as previously described bonded and screwed connections.

Table 2. Implementation ring

	Complete structure with implementation ring bonded together.	Complete structure with implementation ring having 3 screwed seams, no contact between flange surfaces.	New idea for implementation ring bonded together.	New idea for implementation ring with bolted connection no contact between flange surfaces.
Frequency Hz	77,85 (fig 7)	72,81 (fig 8,9,10)	77,85	67,70 (fig 11)

	New idea for implementation ring with bolted connection, contact between flange faces set to frictionless.	Complete structure with implementation ring having 3 screwed seams, contact between flange faces set to frictionless.
Frequency Hz	73, 80	

Conclusion

Modifying the contact stiffness offers a simple way of approaching the bolted joint problem rather than having to model all the bolts. However the results are entirely dependant on the stiffness factor you use. The problem comes when determining whether the chosen system for modelling bolted connections, either contact stiffness or the actual bolts, works for every configuration. In order to prove you have a universal system you would have to match FE models with actual modal tests of various configurations. The simple structure shows a reasonable discrepancy between the bonded connection and the bolted or screwed connection, however this has not been repeated on the actual structure.

Analysis of simple cantilever structure.

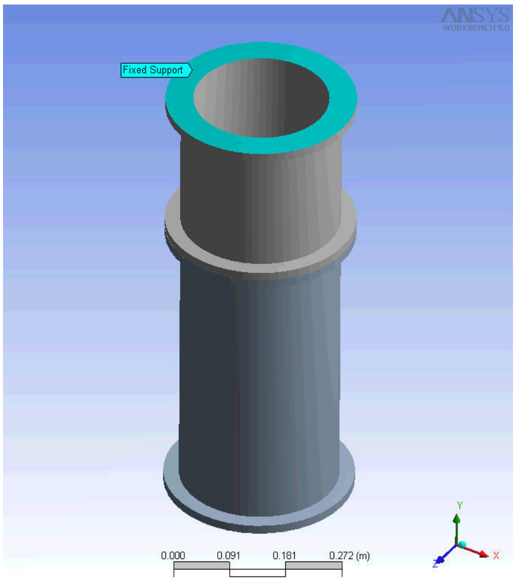

Fig 1. Flanged cylinders showing rigid fixed support.

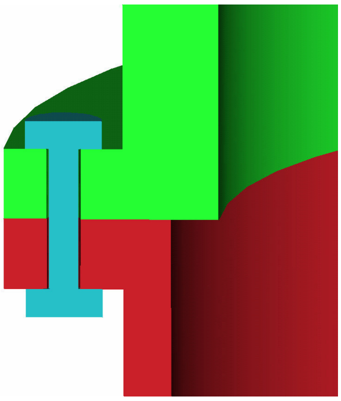

Fig 2. Flanged cylinders showing bolted connection.

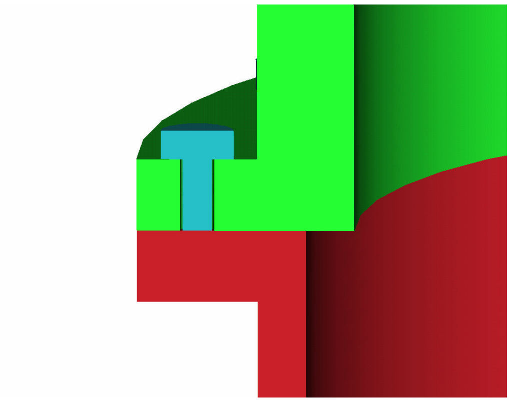

Fig 3. Flanged cylinders showing screw connection.

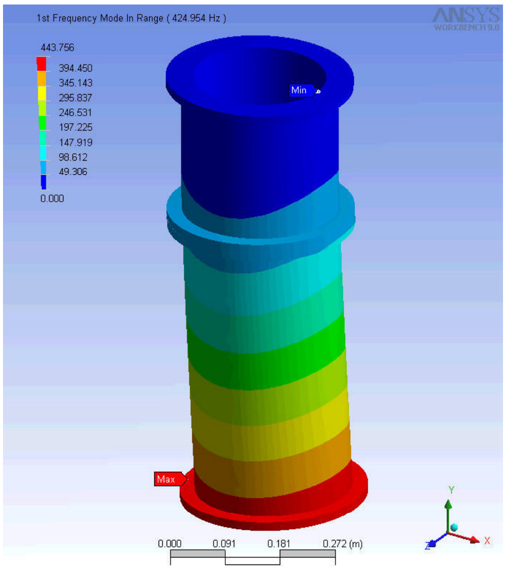

Fig 4. First frequency 424Hz. Contact stiffness set to program controlled (bonded).

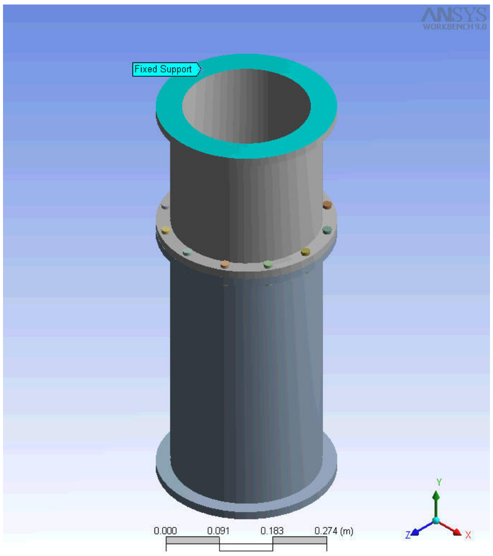

Fig 5. Flanged bolted cylinders showing rigid fixed support.

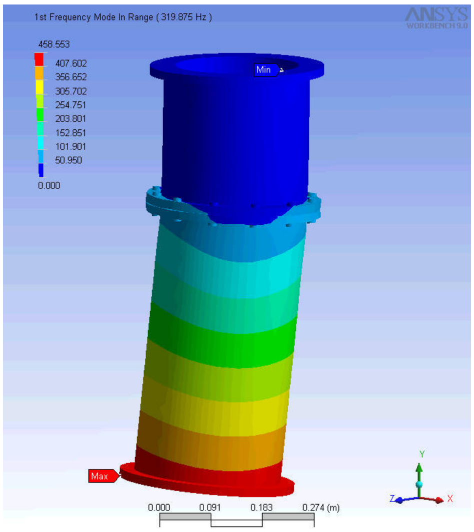

Fig 6. Flanged bolted cylinders with contact surface between cylinders suppressed. Steel bolts Young's modulus set to 2e11 Pa, First frequency 320Hz.

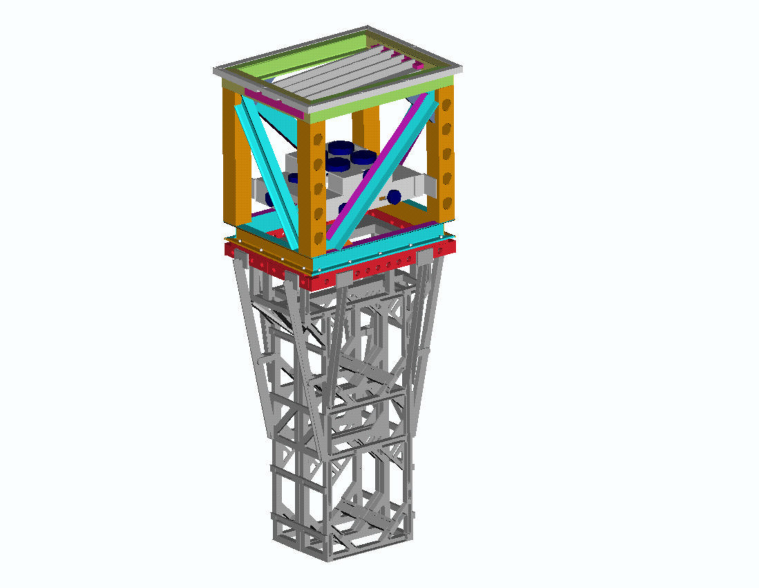

Fig 7. Complete structure with controls design of the implementation ring

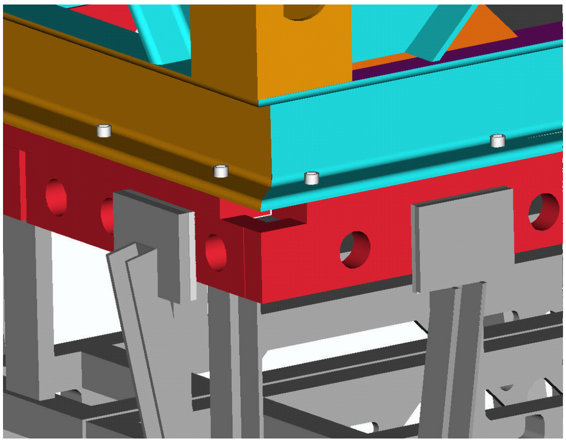

Fig 8. Cap head screws connecting upper structure to implementation ring spacer

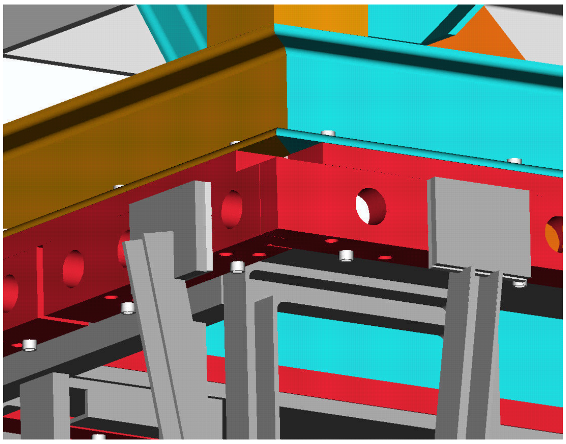

Fig 9. Cap head screws connecting implementation ring to lower structure top plate.

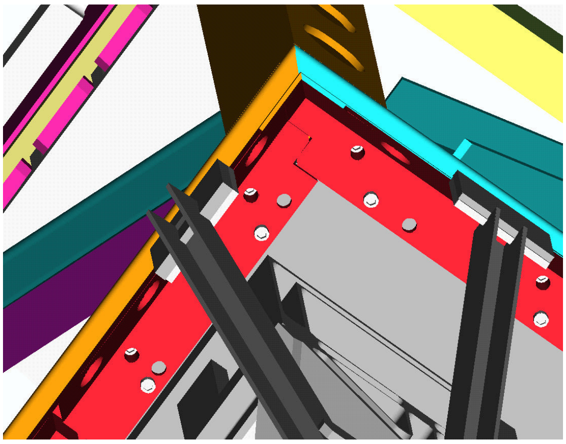

Fig 10. Cap head screws connecting L shaped piece of the implementation ring to the implementation ring spacer.

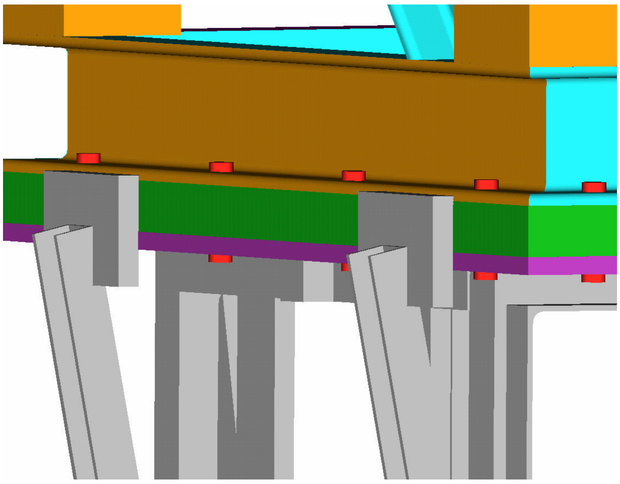

Fig 11. New design for the implementation ring and single bolted seam.

Section 2

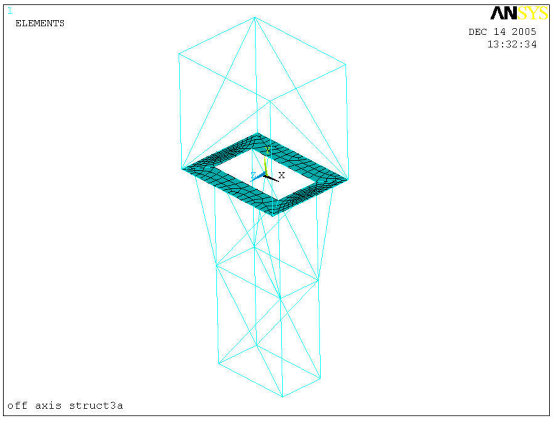

Fig 12. Combined beams and shell model of upper and lower structure.

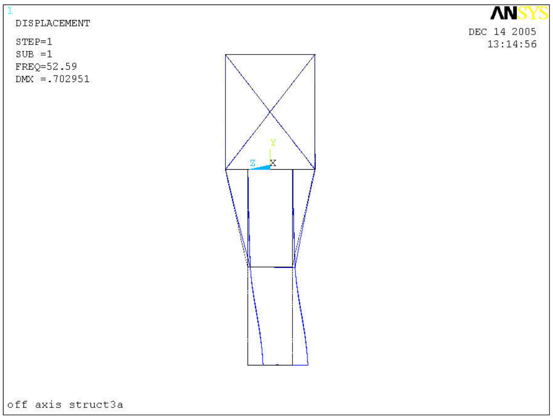

Fig 13. Combined beams and shell model of upper and lower structure. Outriggers symmetric about centre line, frequency 52.6Hz.

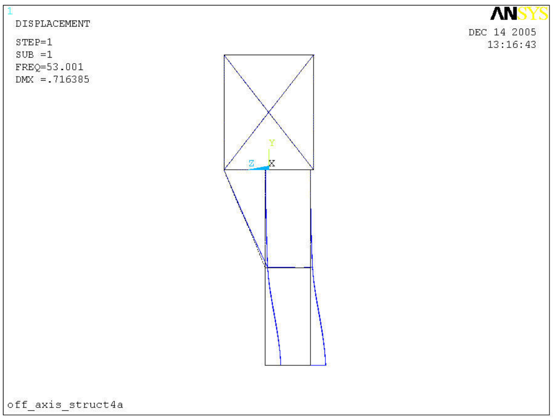

Fig 14. Combined beams and shell model of upper and lower structure. Outriggers on one side only, frequency 53Hz.

Conclusion

Moving the lower structure to one side to make the angle of the outrigger shallower does not improve the overall frequency. Increasing or decreasing the thickness of the plate does not effect the frequency as the ratio between stiffness and mass is maintained.

Section 3

This section takes the original combined structure and compares it to a structure that's design aims to reduce mass of the implementation ring and the number of bolted connections between the implementation ring, upper and lower structure. The second structure also offers more comprehensive cross bracing.

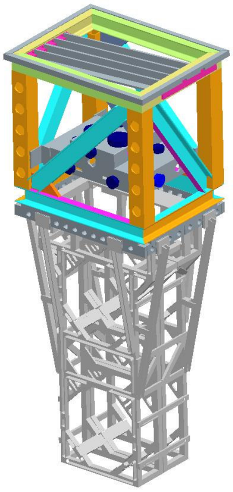

Fig 15. Original structure frequency results, 77,85 Hz

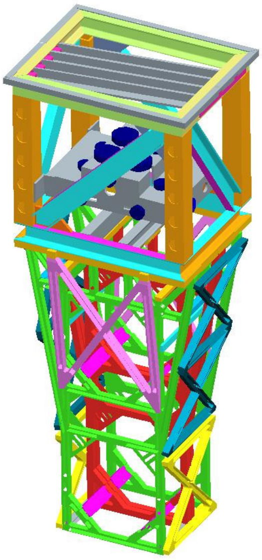

Fig 16. Second structure frequency results, 77,86 Hz

Conclusion

In reality the original structure in figure 15 has 3 seams of cap head screws to connect the upper to the lower structure by way of the implementation ring, the new design of implementation ring in figure 16 has one bolted seam. For this analysis the models connectivity is bonded, so the subtlety of the two designs for the implementation ring regards the use of bolts does not come through.

The reason the more comprehensive cross bracing has not improved the frequency is best described in section 6.

Section 4

The purpose of the following analysis is to see the effect on the lower structures frequency when using different clamping methods on the structures top plate and also the method of attaching the top plate of the structure to the face plates.

In reality the top plate is clamped around it's perimeter by the implementation ring, the face plates are then attached to the top plate some distance away from the ridged perimeter clamp, it has been considered that a diaphragm effect in the plate results from this offset. Cases have been run to qualify the significance of this effect.
Again this model has been run to analyse the effect of the bolted joints between the top plate and the lower structure, cases have been run that model the connection between the top plate and face plates as bonded, with screws and frictionless contact, with screws and no contact, with screws and a forced gap between top plate and the face plates.

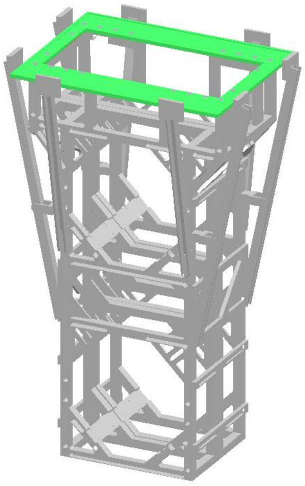

Fig 17. Lower structure including outriggers and top plate.

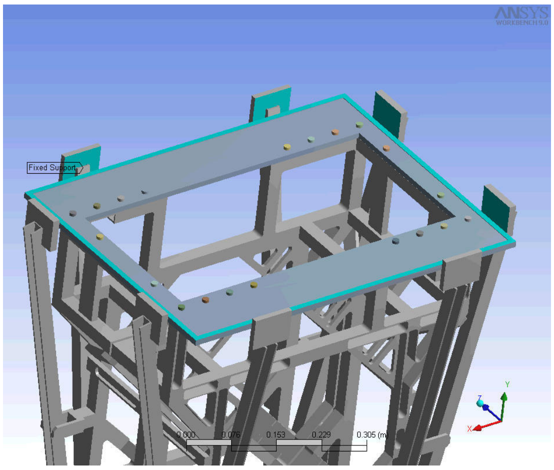

Fig 18. Lower structure with fixed supports representing case one. Fixed supports are maintained on the outriggers assembly pads to the implementation ring (implementation ring not included in model) and around the perimeter of the top plate.

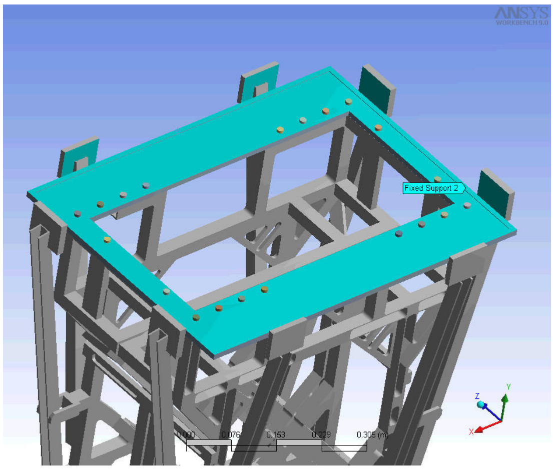

Fig 19. Lower structure with fixed supports representing case two. Fixed supports are maintained on the outriggers assembly pads to the implementation ring (implementation ring not included in the model) and on the entire surface of the top plate.

Table 3. Lower structure to top plate fixing

	Fixed supports case one, Top plate bonded to face plates.	Fixed supports case one, Top plate joined to face plates by screws and frictionless contact.	Fixed supports case one, Top plate joined to face plates by screws and no contact.	Fixed supports case two, Top plate joined to face plates by screws with frictionless contact.
Frequency Hz	111.6 114 138 218	110.5 113.5 137 216	107^{*} 112.7 137 213	113.5 114 139 221.5

	Fixed supports case one, Top plate joined to face plates by screws with 1mm gap between top plate and face plates.	Fixed supports case two, Top plate joined to face plates by screws with 1mm gap between top plate and face plates.
Frequency Hz	106.8^{*} 112.7 137.4 213	110.5 113.7 138 220

Conclusion

There is a very negligible gain between fixing the entire surface of the top plate and clamping around the perimeter, meaning that the diaphragm effect of the top plate is not a real concern. There is also a negligible effect between a bonded or a screwed top plate to face plate design when the screws have an infinite stiffness. The results also show that a screwed contact with no contact between the top plate and face plate is the same as a having a screwed contact and a gap between the top plate and face plate.

Section 5

Table 4 has the results from calum's clean room tests and the supporting FE results, the table shows how the frequency reduces as you remove parts of the structure, we regard these as data points. Table two looks at the percentage reduction as you go from one set of data points to another. The table suggests that the side plates have a twice the impact in the FE model as they do in reality. An explanation might be that in reality the bolted connections are moving.

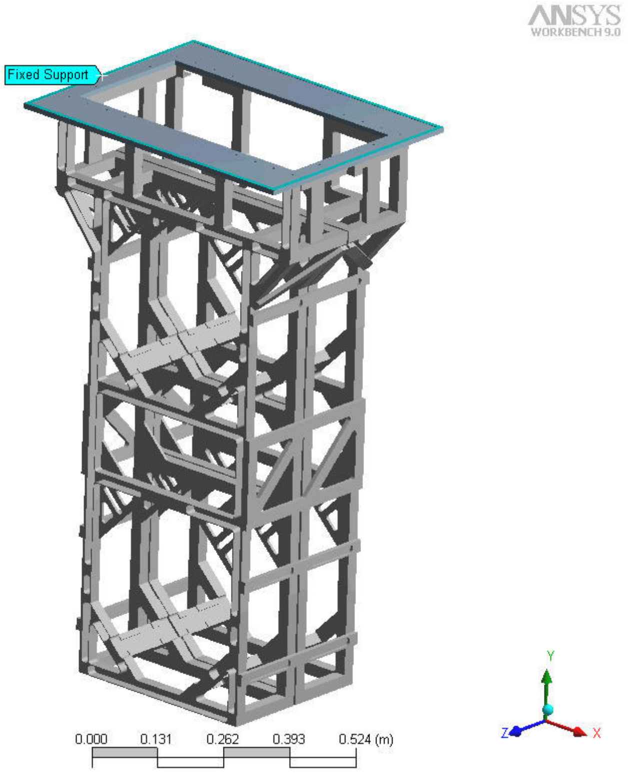

Fig 20. Top plate clamped around the perimeter, no outriggers

Table 4. Comparative results of Calum's clean room tests and the FEA results.

	Calum's clean room results Hz	FEA results Hz
Implementation ring, Top plate and outriggers.	56	114
Top plate no outriggers.	31	69
Top plate no outriggers and no plates on the side.	21	27
Top Plate and one half of the structure.	17	22

Table 5. Comparative results from table one with percentage decrease between data points.

Calum's results Range between data points.	Calum's results, range between data points percentage decrease.	FEA results, range between data points.	FEA results, range between data points percentage decrease.
56 – 31 Hz	45	114 – 69 Hz	40
31 – 21 Hz	33	69 – 27 Hz	61
21 – 17 Hz	19	27 – 22 Hz	19

Conclusion

Table 5 suggests that the side plates have a twice the impact in the FE model as they do in reality. An explanation might be that in reality the bolted connections are moving.

Section 6

The structure in this section tries to use the X bracing to maximum efficiency by connecting the hard points (stiff points) of the upper structure to the lower structure, the hard points of the upper structure being the four corners.

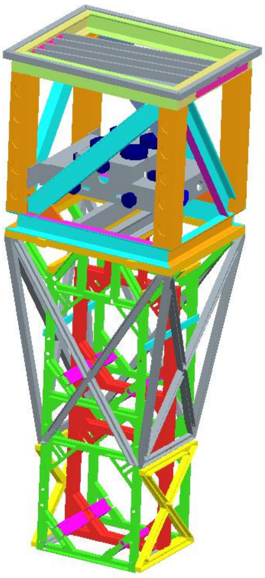

Fig 21. Hard point structure

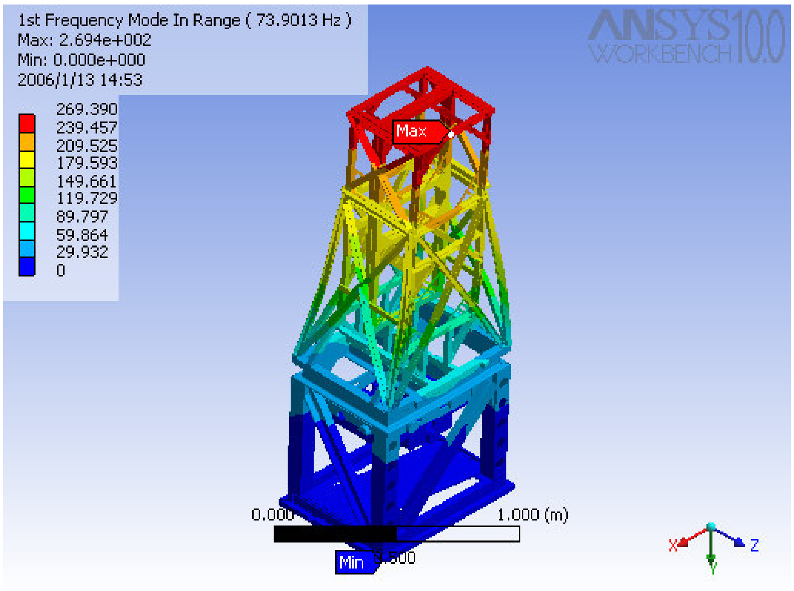

Fig 22. Hard point structure

Conclusion

Looking at results from previous models (section 3) the frequency in this study has decreased. The best explanation of this has been written by Dennis Coyne found at this link.

http://www.ligo.caltech.edu/~coyne/AL/SUS/quad/structure_theory_with_dc_comments.doc

The main body of the text is included below.

28 Jan 2006: Some comments from Dennis on the proposed x-bracing by Justin & Tim:

The existing quad controls prototype lower structure is reasonably stiff in cross-bracing, i.e. it acts as a single beam structure with strain continuity through the overall beam section. The existing quad controls prototype lower structure has a number of somewhat indirect load paths (red lines, both in plane and out-of-plane, or 3-dimensional) to the stiff corner points that the proposed adding bracing (green lines) also support. The truss formed from the four x-braced frames is certainly a more efficient structure for supporting these 4 stiff corner points.

However, the cross-sections of these four x-braced frames in the images below look to be comparable, or less than, the effective (combined) sections of the “monolithic’ 3D frame. So in effect you have 2 springs in parallel and one (the x-brace) is somewhat less stiff and adds mass, so the frequency decreases. If you could remove the 3D frame and use just the truss formed by the x-braces, I suspect you’d have much higher frequencies. Of course one can’t remove all of the elements of the existing 3D frame. However can one abandon much of the 3D frame and morph it (or join essential elements/features) into the truss formed by the x-braces?

Alternatively can one reduce the sections and mass of the 3D frame and add to the section/stiffness of the x-braces?

One should also ensure that the out-of-plane bending resonances of each “panel” formed by the cross-bracing is (well?) above the target lowest frequency as a means to ensure that they have adequate cross-section (bending stiffness) for their spans. This is comparable to looking at the panel frequencies in a skin-stiffened design (see section 4 and fig 11 of T030044-03)

Section 7

This section looks at the possibility of the structure being supported by a beam that goes between the lower structure and the seismic table. The model used for this exercise can be seen in section 3, it's traverse and longitudinal modes are 77 and 86Hz Table ? shows the results from an idealised beam having the modulus of aluminium but no mass. This idealised beam gives an indication of what is potentially possible for the structure when not considering the modes attributed to the actual beam itself. In the arrangement shown the beams do not effect the first traverse mode but improve the second mode by 50Hz. Table ?+1 shows the results of a beam with the mass and modulus of aluminium alloy, the first four modes are beam modes.

Conclusion

The results show that there is some mileage in supporting the lower structure to the seismic table. A beam with sufficient stiffness could be used to improve the frequency by 10 to 20Hz. However the beams would fall outside the SUS structure envelope, their location would have to be negotiated with other systems.

Table 6. Beam supports with the modulus of aluminium alloy but no mass.

mode	Frequency Hz
1st	85
2nd	129
3rd	169
4th	192
5th	197
6th	227

Table 7. Beam supports with the modulus and mass of aluminium alloy.

mode	Frequency Hz
1st	75
2nd	78
3rd	80
4th	80
5th	85
6th	129

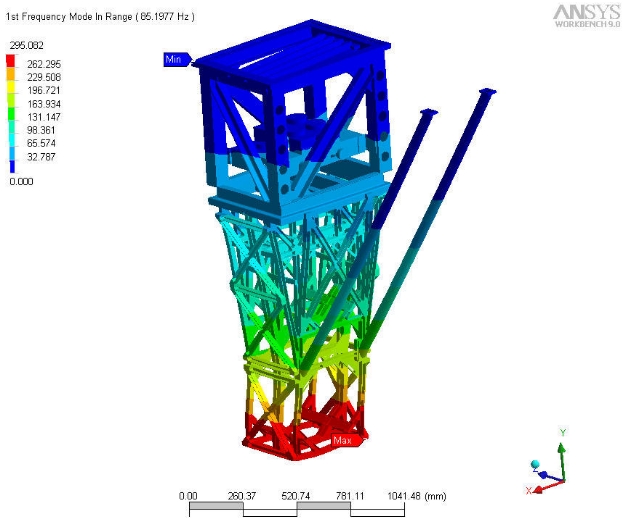

Fig 23. Beams to seismic table, First mode traverse direction 86Hz, beam has modulus of aluminium alloy but no mass.

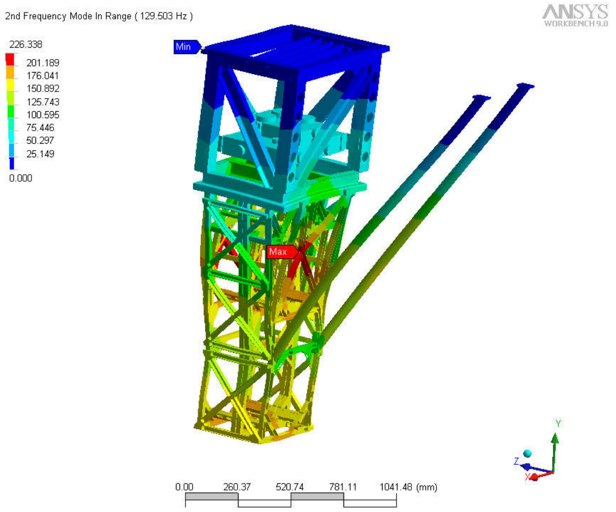

Fig 24. Beams to seismic table, Second mode 130Hz beam has modulus of aluminium alloy but no mass.

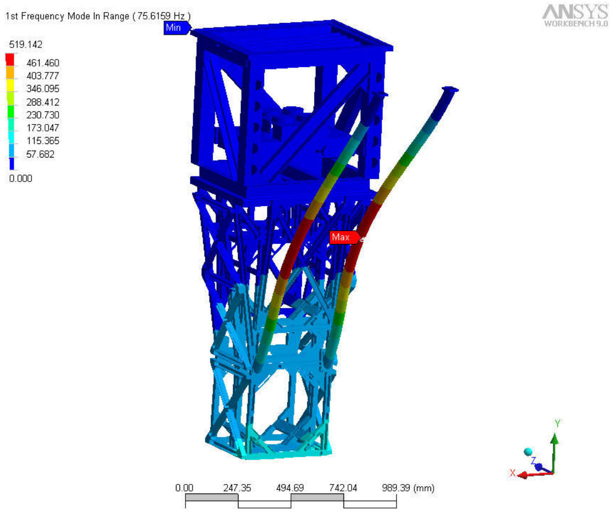

Fig 25. Beam to seismic table, beam has the mass and modulus of Aluminium alloy.

Section 8

The baseline design has the lower structure split into two, this allows the two chains, reaction and test chain, to be assembled and disassembled separately. This functionality is advantageous in a repair scenario.
The below lower structure does not have the ability to be split into two, the driver behind this type of structure is that only two face plates are required as opposed to four meaning less mass. Each face plate has a mass of 4kg meaning you loose 8kg in total. Some redesign of the remaining structure would need to be done to make sure the structure could manage the static load and that safety stops could manage any impact load. The assembly and repair scenario would need to be possible with this type of structure.
The structure in this section is a modified version of the structure shown in section 3, figure 16.

Conclusion

An initial lower structure design, with two face plates, gives a 10Hz improvement in the frequency.

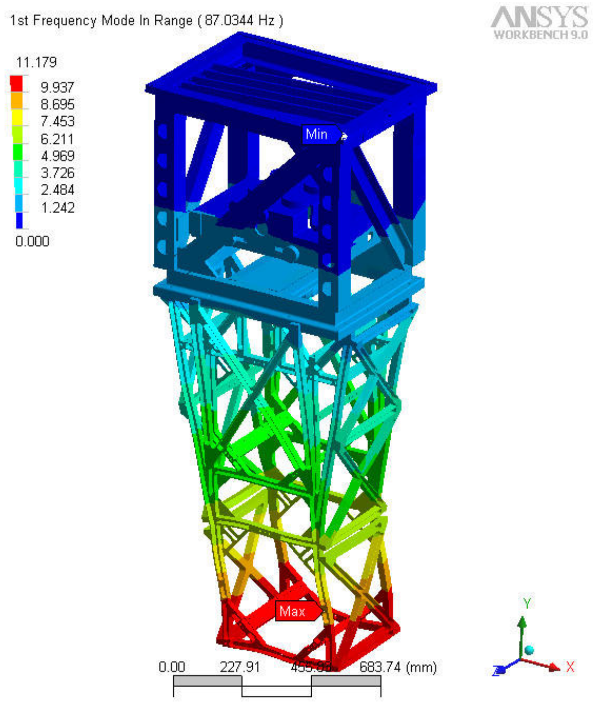

Fig 26. Non Split structure, first mode 87Hz.

Section 9

Modelling of bolted connections

Some finite element models of the lower structure have degradation similar to that seen in the actual frequency measurements but with no rational. The plan is to make a simple test structure to explore the behaviour of the bolted joints.
The proposed idea for the test structure has two simple face plates with triangulated side braces. With the triangulated side braces removed the frequency is independent of bolted connections apart from the attachment to the table. The frequency of the structure

will increase with the addition of the triangulated side braces, the new frequency is dependant on the quality of the bolted connections for the side braces.

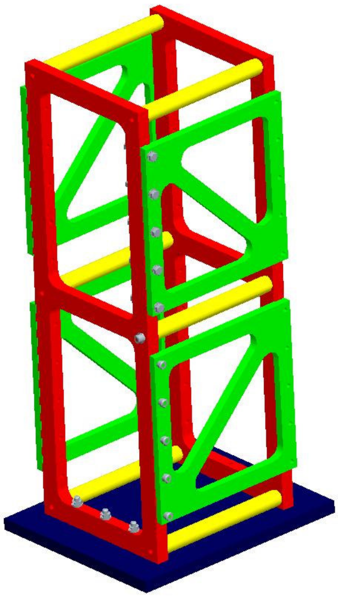

Fig 27. Bench test structure.

Possible tests on bolt variables

1. Measure modes with and without triangulated side plates.
2. Vary the number of bolts along the triangulated side plates, start with bolts just at the corners then go to the maximum.
3. Change the type of bolts from Aluminium to Steel, this changes the modulus of the bolts by more than a factor of two, if the bolt modulus is a factor in determining the frequency we should see a difference in the modal test. This will add weight to the discussion on how we model bolted connections in FE models.
4. Vary the Torque applied to the bolts.
5. Change the nature of the bolts in terms of their length, regards the side plates change screws to nuts and bolts.

Appendix

Definition Settings of contact regions in ANSYS

Type: The differences in the contact settings determine how the contacting bodies can move relative to one another. This is the most common setting and has the most impact on what other settings are available. Most of these types only apply to contact regions made up of faces only.

Bonded: This is the default configuration for contact regions. If contact regions are bonded, then no sliding or separation between faces or edges is allowed. Think of the region as *glued*. This type of contact allows for a linear solution since the contact length/area will not change during the application of the load. If contact is determined on the mathematical model, any gaps will be closed and any initial penetration will be ignored.

No Separation: This contact setting is similar to the bonded case. It only applies to regions of faces. Separation of faces in contact is not allowed, but small amounts of frictionless sliding can occur along contact faces.

Frictionless: This setting models standard unilateral contact; that is, normal pressure equals zero if separation occurs. It only applies to regions of faces. Thus gaps can form in the model between bodies depending on the loading. This solution is nonlinear because the area of contact may change as the load is applied. A zero coefficient of friction is assumed, thus allowing free sliding. The model should be well constrained when using this contact setting. Weak springs are added to the assembly to help stabilize the model in order to achieve a reasonable solution.

Rough: Similar to the frictionless setting, this setting models perfectly rough frictional contact where there is no sliding. It only applies to regions of faces. By default, no automatic closing of gaps is performed. This case corresponds to an infinite friction coefficient between the contacting bodies.

Frictional: In this setting, two contacting faces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to each other. It only applies to regions of faces. This state is known as “sticking.” The model defines an equivalent shear stress at which sliding on the face begins as a fraction of the contact pressure. Once the shear stress is exceeded, the two faces will slide relative to each other. The coefficient of friction can be any non-negative value