91 Burrendong Road
Coombabah 4216
Queensland, Australia
0408 681 932
carbon-works.com.au

From CarbonWorks...

Performance of domes using EMT tube Issue 6 21-02-2017

Hi – This is a very train of thought document given the circumstances.

MRU wishes the following answered:

1) compare a 40ft diameter L3 and L4 dome constructed of steel EMT tubing. The L3 uses 1” tube the L4 uses 3/4” tube
2) which dome performs better the L3 or the L4. To answer this now the L3 does much better mainly due to the use of 1” tube
3) Can't comment on hub strength with this model. But squashed tubes usually don't get to the same strength/stiffness as the tube in the direction required. It's convenient to squash a tube but its not a good engineering solution.

A beam model of both domes was provided by the forum and this dxf file was imported into Strand7. Linear, linear buckling and non linear static runs where run to establish the global behaviour of the structures.

Material non linearity (plastic failure) is not investigated and this would need to be done to determine the post first failure mode of the domes if the loading is greater than around 1000kgf. The NL material is included in the later models PS21-02-2017

Loadcase
The loadcase is a single hung load in the centre of the dome. This is the best place for it as the load is more or less perpendicular to the element direction. The load is trying to snap through the peak of the struts to the inside of the pentagon element. A unit load of 1kgf is applied to the node and then failure modes are determined as ratios of that load.

Restraints
Each node touching the ground is restrained in translation in 3 directions. This would be like using a tent peg or similar to hold it in place. The node is allowed to rotate as it likes.

Weight
The L3 dome weighs 563kg and the L4 weighs 593kg. Very similar. As the ultimate loads are a few tonnes the self weight is ignored at present.

Linear Static Buckling Results Pinned ends
ie the struts have no rotational resistance at their ends (ball joints)

Linear buckling is investigated first to determine what the ultimate load could be for the structure. The L4 buckles at a load of 1517kgf. The L3 buckles at a load of 2105kgf. However this buckle of the L4 does not mean the dome collapses. We have just identified its first elastic failure mode and approximate occurrence load. Interestingly the buckle is upward. This means the structure is settling down pushing the cell up. Now we know the structure can support a few tonnes we run the non linear solver to determine what happens as the structure loads up.

Non Linear Results - pinned ends
The NL solver applies a small load then solves the puzzle. It then resolves using the new geometry. Linear solutions assume the structure does not move compared to its original shape. At 500kgf the L4 has snapped though and starts descending. At 2500kgf the L3 has not yet snapped through and the metal is just starting to yield.

Stress analysis
L4 – at 500kgf the stresses are acceptable, if the EMT is mild steel of say 250MPa (36ksi) yield strength (later found EMT to be 370MPa strength). Around 139MPa max. At 1000kgf load we are over the 250MPa yield so its plastically deforming due to the dome having sunk 800mm at its centre. At 1500kgf we have lots of stress 800MPa so we are well into tearing territory.

L3 however at 500kgf is lightly stressed, at 1500kgf not much more then at 2500kgf we only at 10% of the yield stress so we have heaps to go. This says the L3 is the go.

Note on pinned end. It is not possible to have perfectly ball bearing ends in practice or in theory for this to be analysed. The solver presents a warning that it had to introduce a small amount of stiffness to the ends to be able to be solved. This is what happens in practice as well.

Linear Buckling Results - fixed ends
The L4 buckles at a load of 1721kgf which is not much different to the pinned end result of 1517kgf. This shows that the hubs do not contribute much here to the global stiffness.

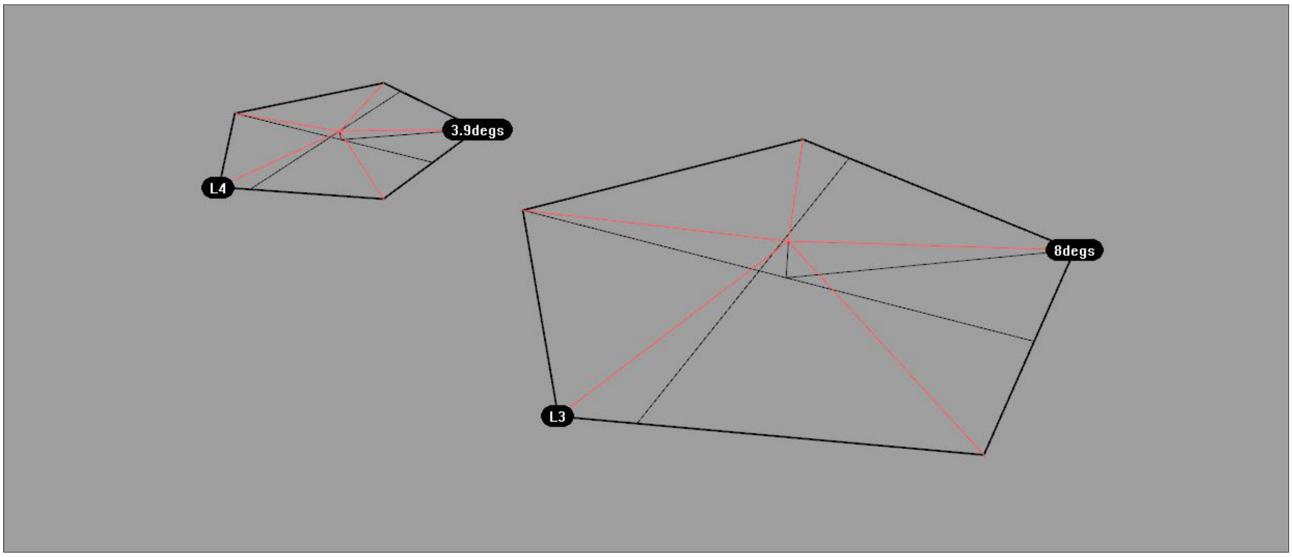
L3 buckles at 2105kgf compared to 2105kgf pinned so the end fixity does not matter. Its behaving as a continuum.

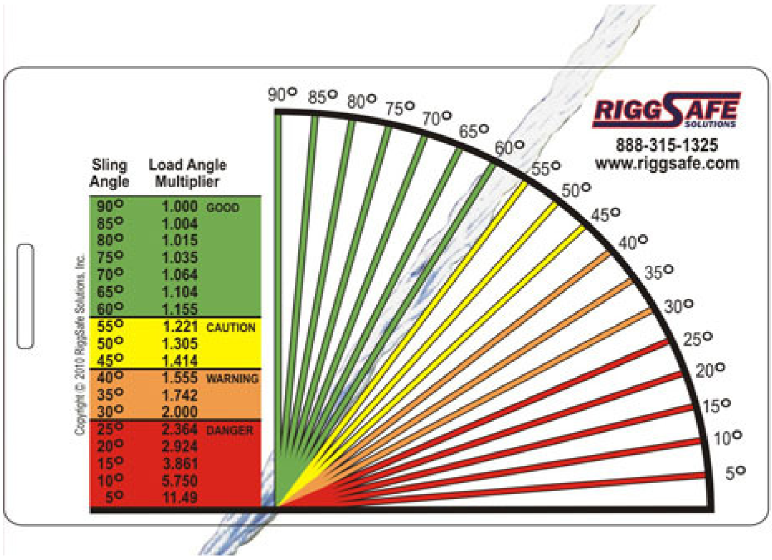
NL stress – fixed ends
I have only run the NL solver up to 2500kgf (2.5 tonne). The L4 is severely overstressed at 500kgf load with stresses way above its yield stress eg 500MPa. The L3 however is low stressed at 2000kgf with only a small area yielding.

Summary
L3 wins all round. The aim is to use tubes of very big diameter and thin walls to maximise their local inertia. Also the hubs need to be of the same bending stiffness as their tubes to maximise the membrane performance of the dome.

Addition 1
It has been commented on that the members may fail by Eulers and in this case they do not or maybe I figure this out later on. The top pentagon element in the L4 is very flat and its quite easy for the pentagon to “lozenge” and allow the peak to snap through to the inside of the dome, hence commencing its failure. I was going to run a small FE to show this but I'll put up some numbers instead.

In the diagram below I have snipped out the peaks of the two domes. The L4 strut length is 2.7657 inches. I have not scaled the dxf yet but the ratios will be the same. The L3 strut length is 5.5181 inches. The angle the strut makes to the plane of the pentagon in L3 is 3.9degs and in the L4 its 8degs. Anyone that has done a rigging course will know that these angles produce huge force multipliers in the associated members. In yachting in a classed boat we are not allowed to use a rigging angle under 8degs as they tend to be unstable. Looking at the L4 again the strut length is 2.7657” and the projected distance to the element centre is 2.759” this is a ratio of 100.24% which is very tiny. The L3 strut is 5.581” and its projected length is 5.4653” so its ratio is 102.1% so it takes a much bigger change to snap it through. The snap through is achieved by the pentagon “lozenging” this is where something changes shape in plane or it twists or it warps. A pentagon is not a self stable shape so as the dome squats (due to the downward load applied at the peak) the loads are distributed by the elements rotating and translating to accommodate the load. Remember that the pentagon is connected to a structure that can move. The distance from the peak to the pentagon plane in L3 is 0.19” and the L3 is 0.76”. All in all the L4 is very flat locally therefore closer to instability then L3. Coupled with the use of 3/4” tube to save weight it lacks enough local through thickness stiffness to support much load. If you made a small model of just these elements you would feel the difference in the ease that you can snap through the L4 vs the L3 even if it was cardboard I suspect. But that’s a plastic hinge not a lozenge but I'm sure you get the drift.





Rigging card. At 5deg the load ratio is 11.5x

Eulers Buckling

The L3-1” tube buckles at 1048kgf [474lbf) the 3/4” L4 buckles at 1464kgf or 662lbf. See below calculation. This is with pinned ends. A single bolt as proposed would need to be considered a pinned ended beam. If fixed these loads would be doubled.

PS 18/2/17

Eulers load

pin ended

$I_{3/4} = 5171\,mm^4$

$I\ 1'' = 14743\,mm^4$

$$F = \frac{\pi^2 E I}{L^2}$$

$$F_{cr}\ 3/4'' = \frac{\pi^2\, 200{,}000 \times 5171}{842.974^2} \left[\frac{N}{mm^2} \times \frac{mm^4}{mm^2}\right] = N$$

$F_{cr}\ 3/4'' = 14{,}364\ N$ (1464 kgf, 662 lbf)

$$F_{cr}\ 1'' = \frac{\pi^2\, 200{,}000 \times 14743}{1681.91^2}$$

$F_{cr}\ 1'' = 10{,}287\ N$ [1048 kgf] 474 lbf

fixed ends buckle @ 2x pinned load. but a one bolt fixture would be a pinned end I feel.

Looking at the non linear fixed end models at a hung load of 250kgf the strut load is L3 is -356kgf where the negative indicates compression. See below progression... this progression assumes no material failure it describes the structures elastic performance if the material does not plastically alter or fail. Once we establish this then we look at the stresses and decide does it elastically fail first or does something else happen?

	L3 (mm Z change)	L4(mm Z change)
125kgf	-178kgf (-1mm)	-306 (-4mm)
250kgf	-356 (-2mm)	-643 (-8mm)
500kgf	-720 (-5mm)	-1537 (-21mm)
562kgf	-812 (-5mm)	-2013 (-31mm) high load but no buckle
625kgf	-904 (-6mm)	-677 (-117mm) load redistribution
666kgf	-870 (-5.5mm)	-742 (-116mm)
688kgf	-997 (-6mm)	-512 (-120mm)
719kgf	-998 (-6mm)	-512 (-120mm)
734kgf	-1067 (-6.7mm)	-396 (-122mm)
742kgf	-1079 (-7mm)	-376 (-123mm)
750kgf	-1090 (-7mm)	-358 (-165mm)
875kgf	-1279 (-8mm)	-74 (-129mm)
940kgf	-1377 (-9mm)	**+64kgf** (-132mm)
1000kgf	-1469 (-9mm)	**+187** (-134mm) its snapped through and

become a tension member like a piece of rope.

1500kgf	-2252 (-14mm)	+1083 (-151mm)

This data is from the fixed end model so the buckling load should be twice the pinned load calculated.

The peak of the element in the L3 is 65mm away from the pentagon plane. The L4 peak is 232mm from the plane of snap through yet snaps through at half of that deflection and not at its Euler load.

So somewhere between 500kgf and 1000kgf the L4 has snapped through, so I put in a 750kgf and reran it, I kept putting in more loads to determine where the snap through is...

Determined that at about 900kgf the peak snaps through to the inside of the dome.

Looking at stress of the members, as the model has fixed ends the struts can support bending loads and stresses.

L4 model

125kgf	-90MPa stress OK
250kgf	-194MPa stress so OK
500kgf	-500MPa so it has yielded as above 370MPa stress
562kgf	+268 and -740MPa so has yielded badly

So the L4 dome cannot follow its elastic potential it fails the struts in bending at 500kgf

L3 Model

125kgf	-16MPa stress OK
250kgf	-33MPa stress so OK
500kgf	-67MPa so it has yielded

734kgf	-100MPa so OK
1000kgf	-138MPa so still OK
1500kgf	-214MPa
2000kgf	-294MPa
2500kgf	-380MPa so has yeilded (EMT 370MPa YS)

So the L3 can easily get to 1500kgf hung load and not buckle, whereas the L4 has buckled at 940kgf but yielded at 500kgf so has changed shape before buckling.

Linear buckling predicts the L4 to buckle at 1721kgf but the NL shows its lower.

The next step is to include material plasticity (yeilding deformation) to allow the material to stretch as well as the structure to deflect.

What I've learned

That to accurately model domes of this nature we have to use a very small increment in the NL solver. If the increment is too big you can miss bifurcation points in the elastic path of the structure. Linear stress and linear buckling do not predict the real deflections and stresses in the dome. Linear is OK to establish the round figure strength but then all work needs to be resolved in the NL domain. Commercial very stiff domes maybe very different but I expect optimised domes by weight will all have to be investigated via non linear methods.

Dig into the models I have sent they are quite interesting... Peter

Addition 2

MANUFACTURING PROCESS

Republic Conduit's EMT is manufactured from high-quality, flat-rolled steel that is uniquely formulated for its high malleability. After forming and welding, the tubes receive a satin-smooth, corrosion-resistant zinc coating courtesy of Republic Conduit's exclusive electrogalvanizing process. A final passivation layer added to the product further strengthens its corrosion-resistance properties.

SPECIFICATIONS

Architects and engineers desiring to specify Republic Conduit EMT should include the following description:

Electrical conductors shall be enclosed in Electrunite EMT in accordance with the National Electrical Code (NEC). Electrical metallic tubing shall be mild steel, electrically welded, galvanized and produced to the following specifications:

- UL standard for Electrical Metallic tubing - steel, UL797, file # E7465
- National Electric Code, Article 358
- American National Standards Institute C80.3
- cUL Listing for CSA C22.2 No. 83.1-07

EMT					
Trade Size Designator		Outside Diameter (OD)		Nominal Inside Diameter	
US	Metric	IN	mm	IN	mm
¾″	21	0.922	23.42	0.824	21.00
1″	27	1.163	29.54	1.049	26.60

AISI 1018 Mild/Low Carbon Steel

Physical Properties

Physical Properties	Metric	Imperial
Density	7.87 g/cc	0.284 lb/in^3

Mechanical Properties

Mechanical Properties	Metric	Imperial
Hardness, Brinell	126	126
Hardness, Knoop (Converted from Brinell hardness)	145	145
Hardness, Rockwell B (Converted from Brinell hardness)	71	71
Hardness, Vickers (Converted from Brinell hardness)	131	131
Tensile Strength, Ultimate	440 MPa	63800 psi
Tensile Strength, Yield	370 MPa	53700 psi
Elongation at Break (In 50 mm)	15.0 %	15.0 %
Reduction of Area	40.0 %	40.0 %
Modulus of Elasticity (Typical for steel)	205 GPa	29700 ksi
Bulk Modulus (Typical for steel)	140 GPa	20300 ksi
Poissons Ratio (Typical For Steel)	0.290	0.290
Machinability (Based on AISI 1212 steel. as 100% machinability)	70 %	70 %
Shear Modulus (Typical for steel)	80.0 GPa	11600 ksi

I looked at the EMT specs provided by MRU and it has a YS=370MPa & UTS=440MPa. So usually we assume YS tension equals YS compression for steel. It has 15% elongation to failure so I could set up a non linear materials spec for this. Prior I have assumed the steel to be 250MPa YS so I've updated the prior work to reflect the 370MPa YS.

Addition 3

Will include comments about the non linear material model. Here is the material table. I have run the pin ended model and will digest it before writing it up. Need to figure out a better way to present results.