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Eight Plane IPND Mechanical Testing

High Energy Physics Division

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1   Introduction

A mechanical test of an 8 plane IPND mechanical prototype, which was constructed using extrusions from the testing/tryout of the 16 cell prototype extrusion die in Argonne National laboratory, was conducted. There were 4 vertical and 4 horizontal planes in this 8 plane IPND prototype. Each vertical plane had four 16 cell extrusions, while each horizontal plane had six 16 cell extrusions. Each plane was glued together using the formulation of Devcon adhesive, Devcon 60. The vertical extrusions used in the vertical planes shares the same dimensions as the horizontal extrusions in the horizontal planes with the average web thickness of 2.1 mm and the average wall thickness of 3.1 mm. This mechanical prototype was constructed with end-seals on the both ends of the vertical extrusions. The gaps were filled with epoxy between extrusions and end-seals. The overall dimension of IPND is 154.8 by 103.1 by 21.7 inches with the weigh of approximately 1200 kg, as shown in Fig. 1.

Two similar mechanical tests of 3 layer and 11 layer prototypes have been done in order to evaluate the strength of the adhesive joint between extrusions in the NOvA detector. These mechanical prototypes were loaded by internal air pressure and successfully sustained up to 60 psi without any leaking of air and/or failure of the extrusions. During the testing, popping noises occurred when air pressure was about 36 psi. When air pressure was further increased, the popping noises with higher frequency and amplitude were heard again and again. It is believed that the popping noises were the results of the debonding of the adhesive joint due to swellings of the extrusions under the high pressure based on FEA analysis of these structures. More details of the three-layer prototype and the eleven-layer prototype can be found in NOvA-doc-1194 and NOvA-doc-2789, respectively.

The purpose of the IPND testing is the following:

- Mimic real loading conditions in a full height detector by using several loading steps so that the stress distribution of the adhesive is similar to that of FD.
- Verify the accuracy of FEA analysis
- Verify the safety factors for both buckling and stress analysis
- Find out the critical failure modes under combined loading conditions

Figure 1: Photo of the front and back side of the IPND prototype and the shield blocks

In the following sections, the IPND testing plan is detailed by describing several loading steps to simulation the stress and deformation of the full-height far detector. Then, the procedures are described in detail to implement the testing plan. After that, the experimental observations, strain and displacement readings are presented. Next, these experimental results are in comparison with the FEA model to check the accuracy of the FEA model. Finally, conclusions are drawn based on the experimental and FEA work and the future test plan is described for better understanding of the NOvA integral structure, as well as the FEA model.

2   The Test plan

2.1   The Loading Steps

Several load steps were applied to the IPND prototype to mimic the stress distribution of adhesive and find out failure modes, as listed in Table 1. First, the vertical modules were filled with water up to about 2 inch below the top end-seal. Water generated linear gradient pressure on the vertical walls and result in 5 psi pressure on the bottom. Then additional air pressure of about 14 psi was applied to achieve 19 psi at the bottom of the vertical extrusions. After that, four 6-ton concrete blocks were put on top of the IPND prototype one by one by a crane to simulate the weights of the full height vertical modules, the horizontal modules and scintillates in horizontal modules. Typically, loads are held for at least1 hour for each step. Based on the FEA analysis, the adhesive stress of the IPND prototype shows similar distributions of the Far Detector when

the air pressure reaches 19 psi and the four 6-ton blocks are applied. Unloading occurs in a reverse sequence.

Table 1: Loading steps of the IPND testing

Loading Step	Loading Process Description
1	Fill water into the vertical extrusions up to about 2 inch below the top end-seal
2	Apply 14 psi air pressure on the vertical extrusions
3	Place the first 6-ton weight block on top of the IPND prototype
4	Place the second 6-ton weight block on top of the IPND prototype
5	Place the third 6-ton weight block on top of the IPND prototype
6	Place the forth 6-ton weight block on top of the IPND prototype
7	Unloading four 6-ton weight blocks in the reverse order
8	Apply an incremental air pressure of 3 psi until the IPND prototype fails

2.2   Test Setup

2.2.1   Grout

The IPND prototype is required to stand on the floor independently without any support with the load evenly distributed across the bottom of the extrusions. This is of good similarity to the boundary condition of the final NOVA detected. In order to meet the requirement, the IPND prototype was grouted on the floor as shown in Fig. 2. First of all, a wood frame was constructed to contain the grout and protect the floor from the grout. The grout was mixed and put into a cell of the frame about 2 inches high. Then the IPND prototype was raised by a crane vertically and lowered down into the grout about 1 inch. The crane had hanged the IPND prototype for about a day to wait the grout dry. Complete dry of the grout took about 3 day.

Figure 2: Grout the IPND prototype

2.2.2   Extrusion End Seals

In order to fill water into the vertical extrusions and apply internal pressure, a 0.5 inch hole and a one 1.5 inch hole were drilled and tapped on the top end-seals. Since the end-seals were too thin to be tapped, plastic patches with the thickness of half inch were attached on the top end-seals

using Devon 60 adhesive, as shown in Fig. 4. The 1.5 inch hole was used to fill water, while the 0.5 inch was used for apply air pressure. Water was filled first into the 1.5 inch hole with the other hole wide open. While filling water into the extrusion, technicians also setup the fittings of the air hoses on the 0.5 inch hole and cap of the water hole. The hoses were connected to a manifold. Each vertical extrusion was also equipped with a pressure gage to measure the air pressure. The manifold had a hose connected to a pressured vessel, which supplied pressured nitrogen to each extrusion. In this configuration, the internal pressure of each vertical extrusion can be controlled independently and facilitate the detection of air leakage.

During loading of the blocks, it is crucial that the blocks seat on top of vertical extrusions horizontally and their center of gravity should be aligned with the center of the IPND prototype precisely. Wooden support blocks were designed and constructed for this purpose. Two wooden support blocks with the height of 5 inches were placed on either side of the patch. On top of those, a larger wooden block with the height of 0.5 inch was setup to transfer weights of the concrete blocks through the support blocks and the end-seals to the vertical extrusions, as shown in Fig. 4. The wooden support blocks were leveled to create a top surface to facilitate evenly loading on the vertical extrusion from the weight blocks. This ensures the weights blocks sit evenly and there was only vertical load without moment applied to the IPND prototype.
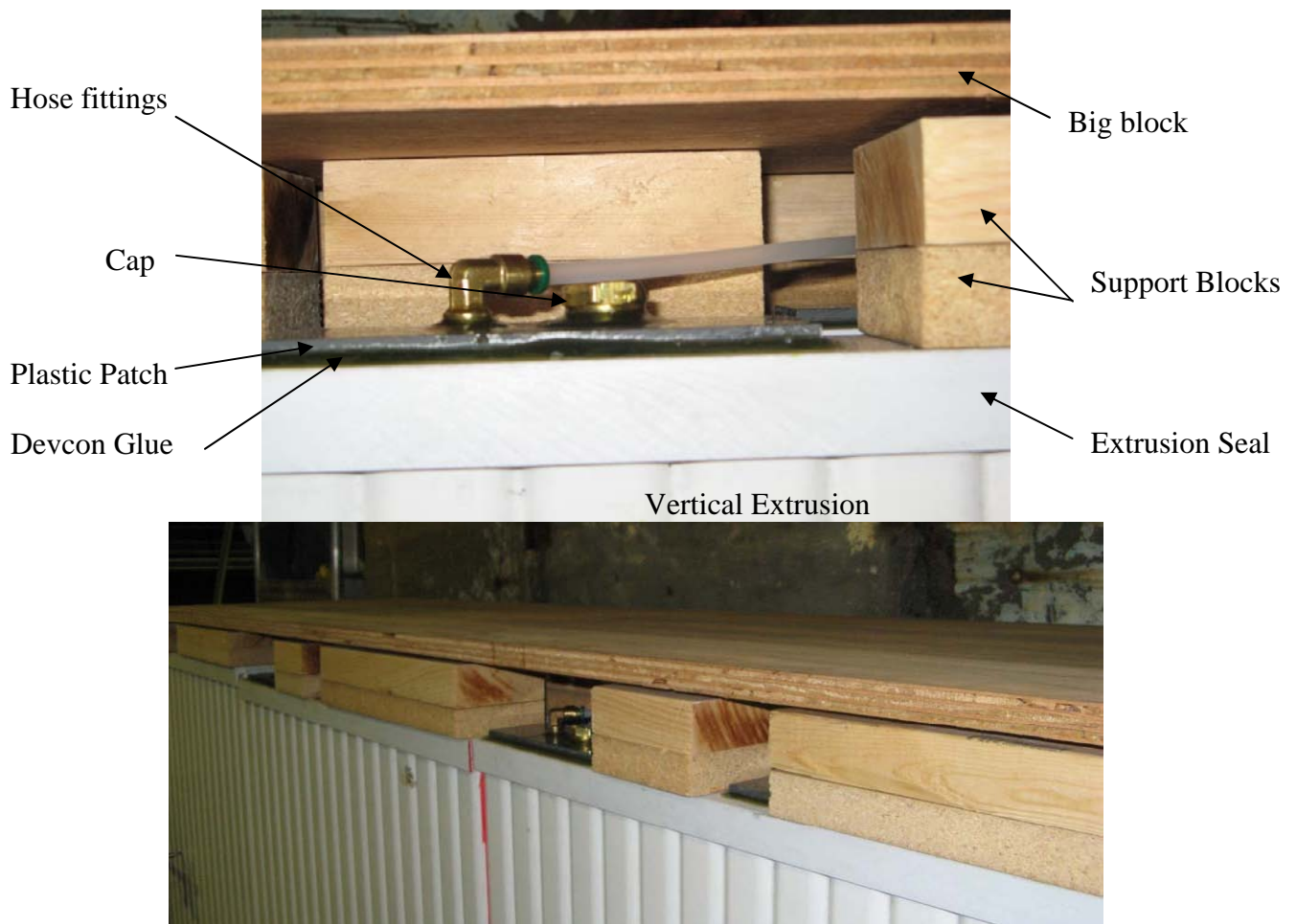

Figure 3: the top end-seal assembly of the vertical extrusion

2.2.3   Shield Blocks

The greatest hazard of the testing was that the concrete blocks would fall down to the floor from the top of IPND. In order to mitigate this hazard, the IPND prototype was placed in a shield made by big concrete blocks for protection in the event of catastrophic failure of the extrusion/end-seal while being pressurized and loaded, as shown in Figure 1. Three sides of the IPND prototype were enclosed by the concrete blocks. Two side blocks, consisting of one B and C blocks, sit on the sides of the IPND prototype. A front block consisting of eight B blocks stood in the front of the IPND prototype. On top of theses blocks, a C block was placed onto the base front blocks. The front blocks were used to shield the water outburst as well as to provide additional support to the top weight blocks in the case of catastrophic failure. These side blocks were slightly lower than the support shims about 2 inches. It should be pointed out that the gap between the weight blocks and the top of the side blocks was controlled to be approximately half inch using additional wooden shims. After the first six-ton weight was placed on top of the IPND prototype, the gap between the weight blocks and the top of the side blocks was measured. Since this gap was larger than half inch, wood shims were place on top of the side blocks to make the gap approximately half inch. In case of catastrophic failure of the IPND prototype or end-seals, the bottom concrete blocks would fall on to the two side blocks and sit on top of them, while the top weight block would be hanged by the crane using the cables. With only half inch falling displacement, the maximum tapered angle could reach 1.6 degree according to the calculations. Therefore, the unstable flipping and falling out of the side blocks of the weight blocks would not be possible.

2.3   Instrumentation

Strain gages and dial indicators were mounted to the edges and outside surfaces of the vertical extrusions of the IPND prototype to measure strains and displacements at the points of interest. It is convenient to describe location and orientations of the instrumentations with a defined coordinate system and a layer and extrusion numbering system. The coordinate was so defined that the positive Z direction was aligned with the upward direction of the vertical extrusions. The positive Y direction was parallel to the surface and the positive X direction was the direction of the inward depth, as shown in Fig. 5. The most outside layer of the vertical extrusion was designated as Layer #1, with second most outside layer labeled as Layer #2, so on and so forth. The most left extrusion in each layer was named as Extrusion # 1 and the most right extrusion was called as Extrusion #4. In each extrusion, the most left cell was entitled as Cell #1 with the most right cell Cell #16.

A group of three strain gages, a rosette, can measure the strains in the direction of their axis. After conversion, the strains in any direction can then be found. Since the edges of the vertical extrusions sustains most severe stresses, as predicated by FEA, two strain gages, denoting S1 and S2, were mounted at heights of 28 inches on Cell #1 of Extrusion #1 of Layer #1 and 2, respectively. There were also four strain gages mounted on the center of the outside surfaces of the vertical extrusions at two heights as well, as shown in Fig. 5. The strains from the rosettes were converted to strains in the X,Y and Z direction for comparison to the FEA model.

In addition, six indicators were placed at the outside surface to measure the displacements. The layout of dial indicators on the IPND prototype is shown in Fig. 5. There were two indicators on the edges to measure side movements and swelling of the IPND prototype at sides.

There were 4 indicators sitting on outside surfaces at different heights to measure deformation or buckling of the IPND prototype. Again, the displacements would be compared to FEM analysis.
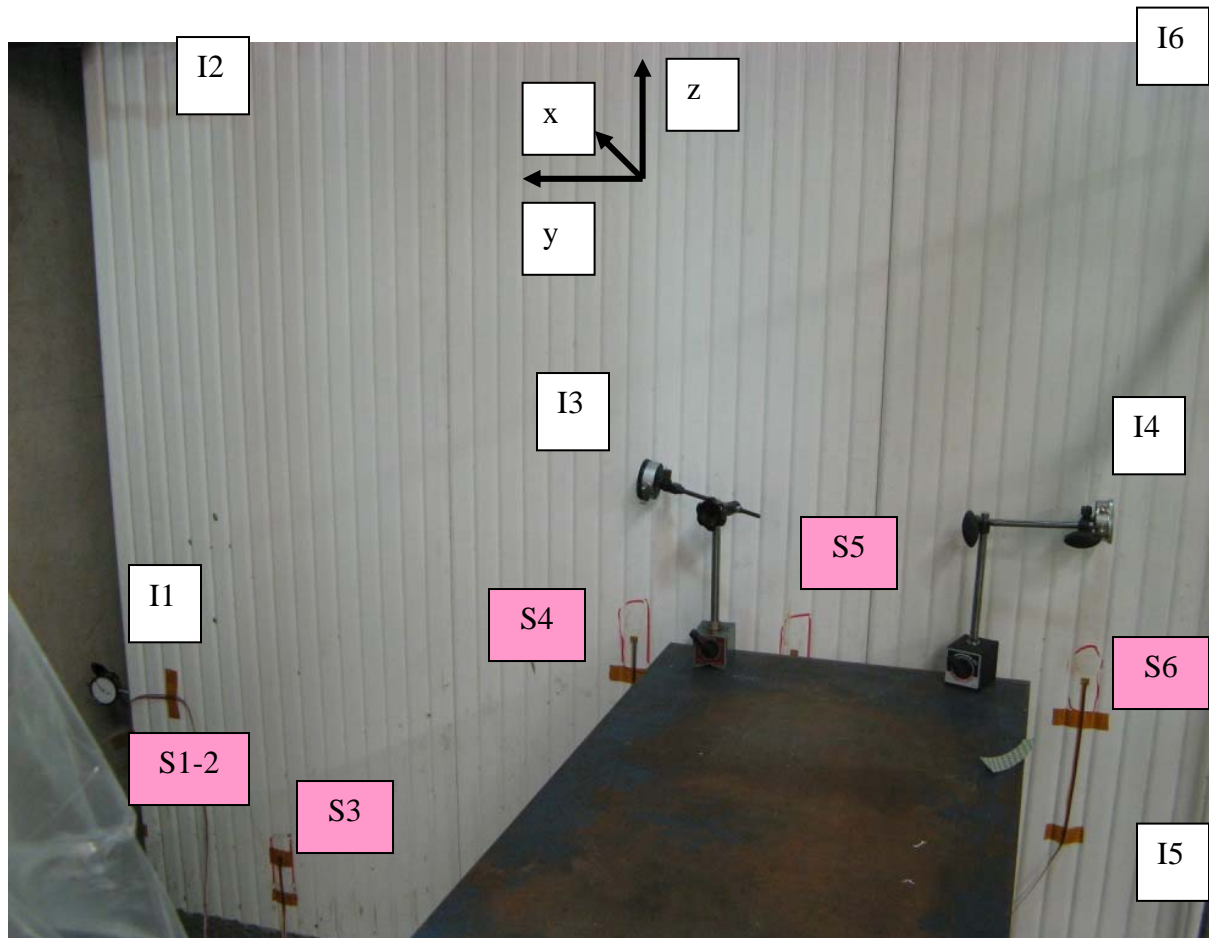

Figure 4: Layout of strain gages and dial indicators on the IPND Prototype

3   Experimental Results

3.1   Water Filled and 14 psi Pressure Applied

Once all the preparations and instrumentation were complete, The IPND prototype was ready for application of the loading as described in Table 1. Step 1 was to fill water into the IPND prototype. In order to do that, each extrusion of the IPND prototype was filled by water one after the other. It took approximately 15 minutes to fill water into an extrusion and about 5 hours to fill waters for all extrusions. There was no leakage of water observed during the filling process. 14 psi pressure was applied after the filling. There was a valve and pressure indicator installed for each extrusion to easy control and detection of the leakage. Initially, there was leakage associated to one extrusion, and was solved immediately. There is no obvious observation except the reading from the dial indicators and strain gages.

3.2   Load Weight Blocks

Loading weight blocks on the top of the IPND prototype was the most difficult and time consuming task. Before the loading process, each block was examined for structural integrity and weighted using a scale, as shown in Fig. 6 Each 12X12 feet block weights about 5 ton.

Figure 5: Weight the block using a scale

Weight blocks had to be loaded in a controlled way to a precise location in order to provide only vertical loads with no moment applied to the IPND prototype. In addition, there should be no impact on the IPND prototype when the block touches the IPND prototype. The bottom of the block had to be oriented horizontally. On Nov. 13 morning, the first 5 ton weight block was loaded successfully on top of the IPND prototype, as shown in Fig. 7. There were some gaps between the shim and supporting blocks, indicating uneven loading on the top. The gap between the weight blocks and the top of the side blocks was controlled to be approximately half inch by putting additional wood shims on top of the side blocks, as shown in Fig. 7. On Nov. 13 afternoon, other 5 ton and 2 ton weight blocks were loaded on top of the IPND prototype successfully with total weight equal to 12 ton, as shown in Fig. 8. On Nov. 14 afternoon, two 5 ton blocks were added up on the other weight block, which brought the total 22 ton weight setting on top of the IPND prototype. ***This 22 ton weight was equivelent to weight of 15 m high PVC structure plus the scintillator (both V+H).***

Figure 6: Put the first 5 ton weight block on top of the IPND prototype

Figure 7: Put the 12 ton weight blocks on top of the IPND prototype

Figure 8: Put the 22 ton weight blocks on top of the IPND prototype

3.3   Dynamics

After 10 ton of weight was loaded on the top of the IPND prototype, Victor Guarino pushed the IPND on the top end. On the top end, both the IPND prototype and weigh swung up to about ¼ inches back and forth. The dial indicator #2, which was located in middle left, oscillated as well. There were some apparent variations of the strain gage reading during loading and unloading of the weight blocks, as shown in Fig. 9. After the weight blocks were removed, an impulse excitation was applied to the top of IPND by quick push about half inches and release. The responses of strain gages were recorded and shown in Fig. 10. And these dynamic behaviors caused by external excitation damped out slowly with natural frequency of about 2 HZ.
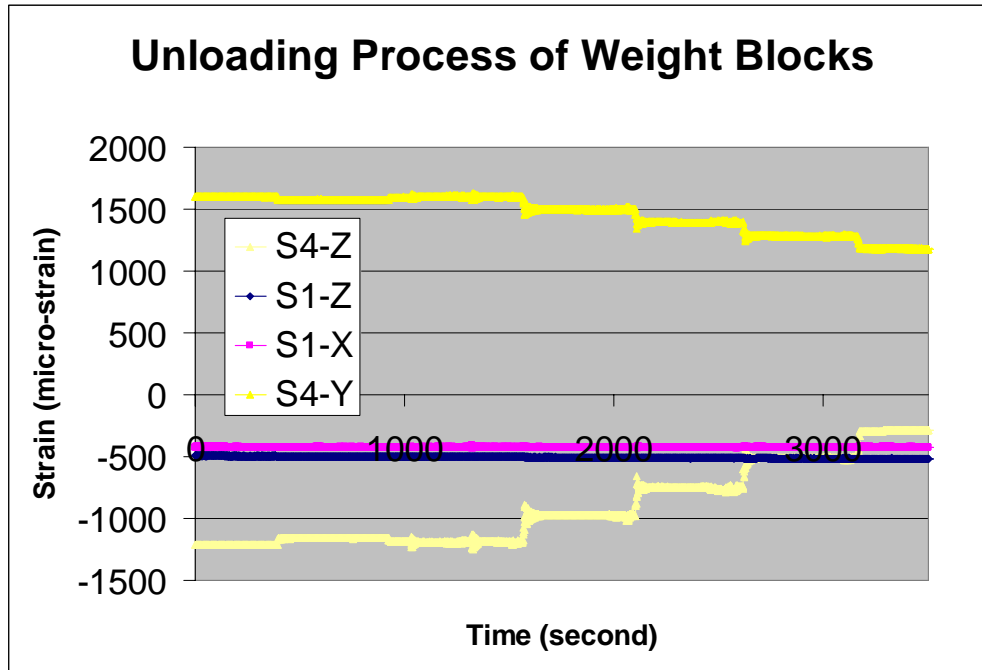
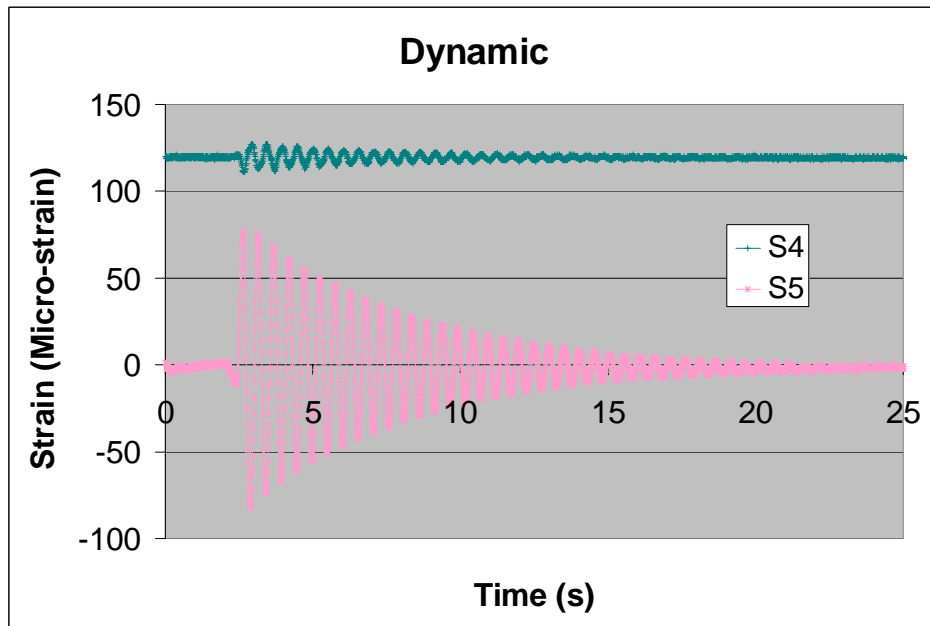Figure 9: Dynamics during unloading process of weight blocks

Figure 10: Free vibration without weight blocks

3.4   Internal Pressure Test

After the weight blocks were removed, the pressure test is carried out to find out the failure mode of the IPND extrusions and adhesive bonds under the internal pressure. Three new strain gage rosettes were attached to IPND to replace problematic rosettes. The test conducted on the IPND prototype was a progressive pressurization of all the 4 vertical layers from 0 psi all the way to 55 psi in additional to pressure generated by water. All cells were pressurized at the same pressure

together. Before the pressure reached 20 psi, there was no apparent noise or other abnormal phenomena observed. When the pressure was increased to 20psi, few popping noises were heard from the prototype. It is believed that the popping noise that was heard was from failure of the adhesive bonds. As the pressure was kept increasing to 26psi, there were more noises. As the pressure was increased to 50 psi slowly, the popping noise shows up again and again.

When the pressure was increased to about 53psi, a loud bomb sound was heard and a piece, as shown in Fig. 11, was blasted upwards from the top of cell #1 in layer #1 due to the internal pressure. The extrusion where fracture happened is shown in Fig. 12. It is clear that the PVC is elastic since the shape of the piece almost exactly matches the piece which is missing in the extrusion. The fracture piece was blow upward, indicating that the crack was initiated from the bottom. This is also confirmed by the serrated shape of the edge at the bottom. The sharp edge on the both sides is the result of fast propagation of the crack up to the top.

Figure 11: PVC piece from the extrusion

Figure 12: Fracture on the extrusion

Visual inspection was then conducted to investigate what is the root cause of this fracture. It was found that two knitting on the webs occurs at center of the fracture piece, as shown in Fig. 12. It should be noted that the crack place of the webs is smoothly. Later during the destruction of IPND, it was found that the knitting lines were all the way down to the bottom of the extrusion as shown in Fig. 13. This knitting can also be confirmed from the reading of strain gages rosette #3 shown in Fig. 13. This will be explained more detail in the following section.
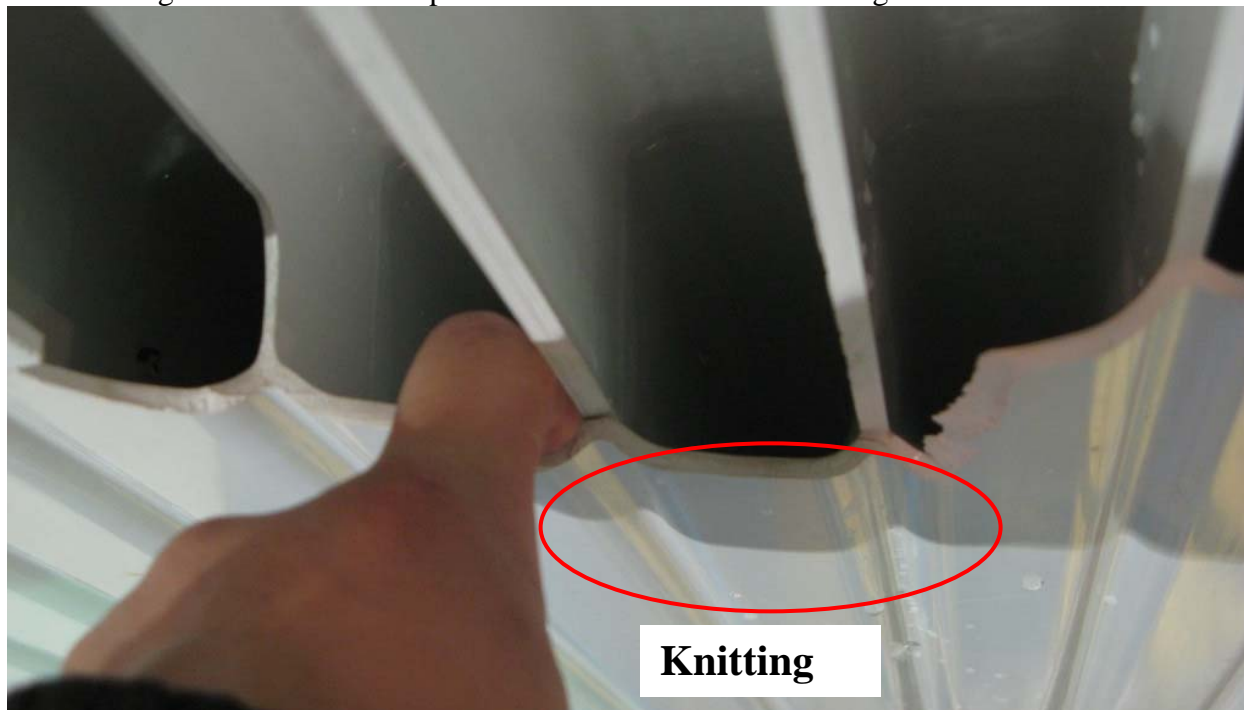

Knitting
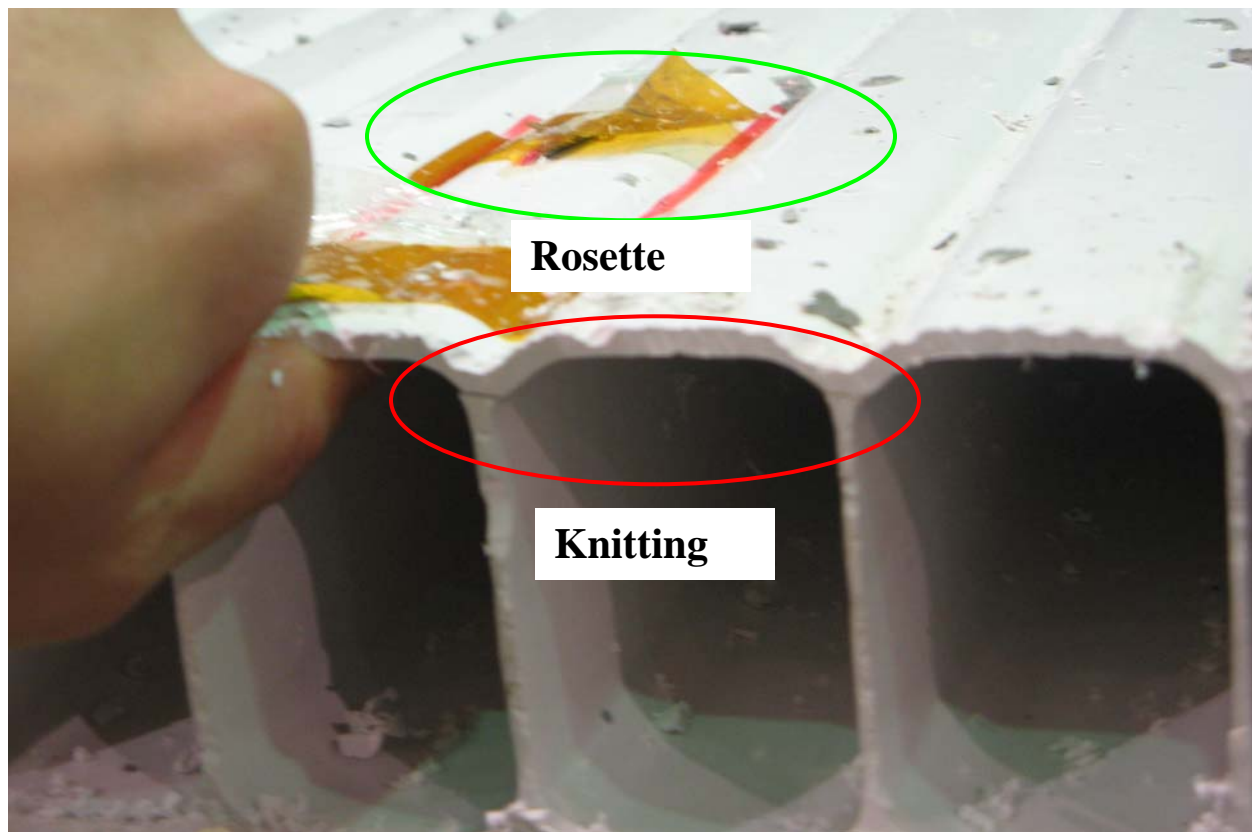
Figure 13: Knitting on webs on the top

Figure 14: Knitting on webs at the bottom

3.5   Destruction of IPND

After the completion of the internal pressure test, the IPND prototype was ready for destruction in order to investigate the failure causes of extrusions and the adhesive conditions including the coverage and strength.

After water had been drained, the IPND prototype was laid on the floor. A crowbar was used to peel the extrusion, as shown in Fig. 15. Significant force was needed to peel off one layer of extrusion. Crack sound indicating the peel off of the adhesive pad was heard in this destruction process from time to time. It was observed that the peeling of adhesive pads did not propagate due to discontinuity of the adhesive pad as a result of the scallop between cells of the extrusion. Fig. 15 shows an extrusion which was broken in middle when a fork lift was used to peel at the top end.

The adhesive bonds between these two extrusions were exposed and could be examined. It was clear that most of adhesive was attached to the vertical extrusion, as shown in Fig. 16(b), with only some trace could be found on the horizontal extrusion. It should be noted that the adhesive were laid onto the verticals using a hand hold glue gun during constructing IPND. It took about 10 minutes to lay adhesive on one extrusion. Then the vertical extrusion was placed onto the horizontal extrusion and then was compressed using a 75 lb roller. A close-up view of the adhesive pads is shown in Fig. 17. The largest pad was about 60% of the total coverage, while the smallest pad covered only about 25% of area. However, the bonds seemed to not have any

problem during the test, indicating even portion of adhesive was needed for the structure to perform its function.
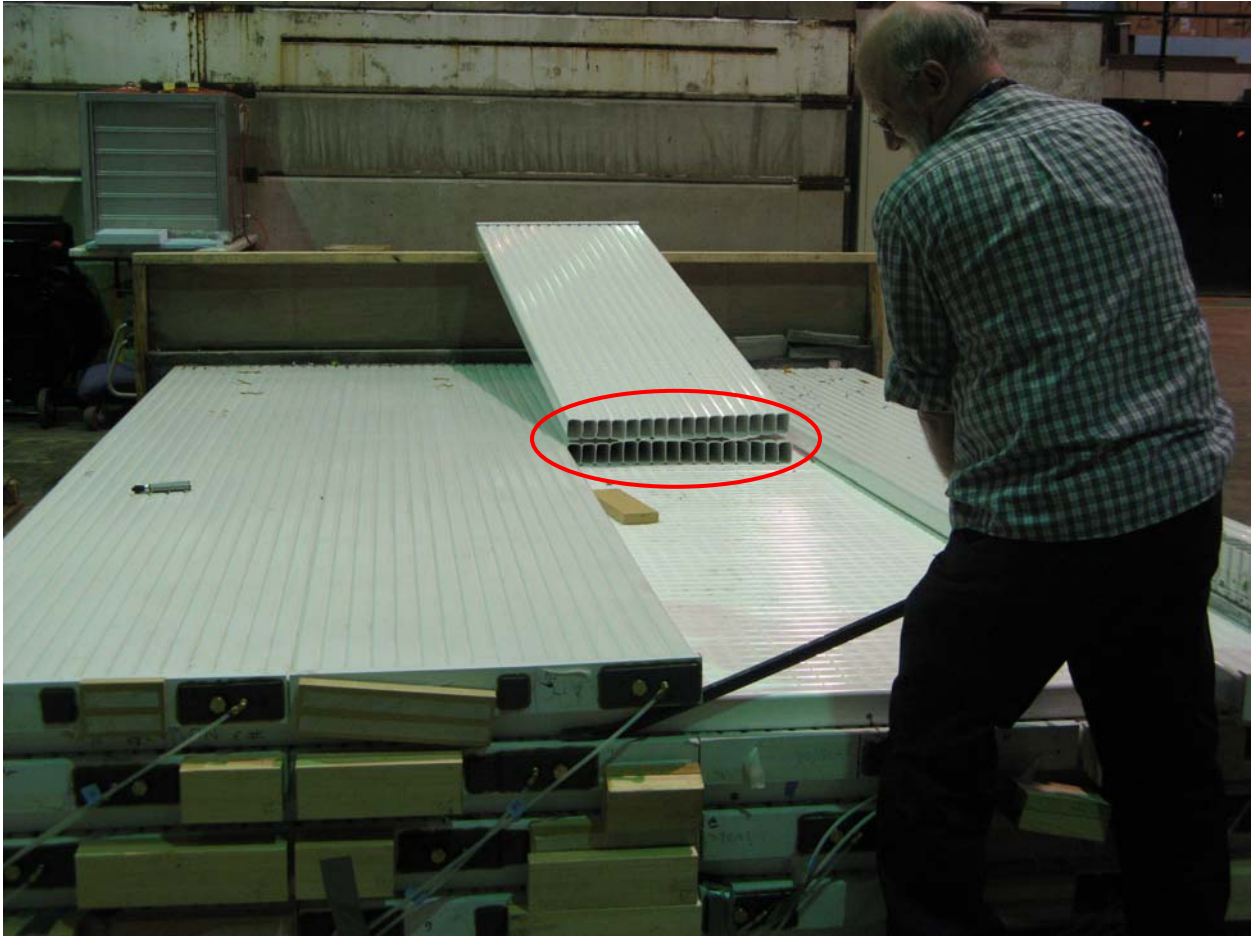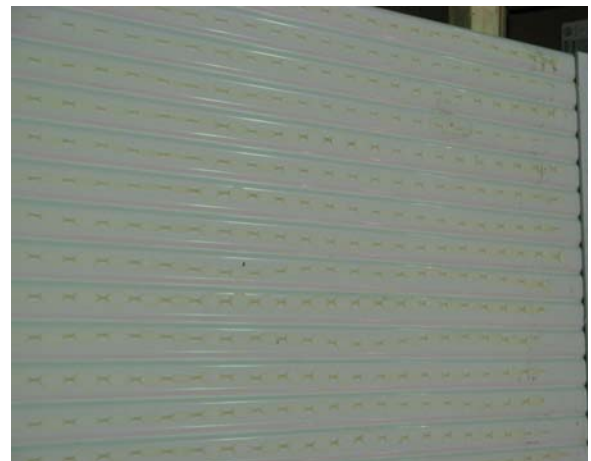

Figure 15: Destruction process of IPND

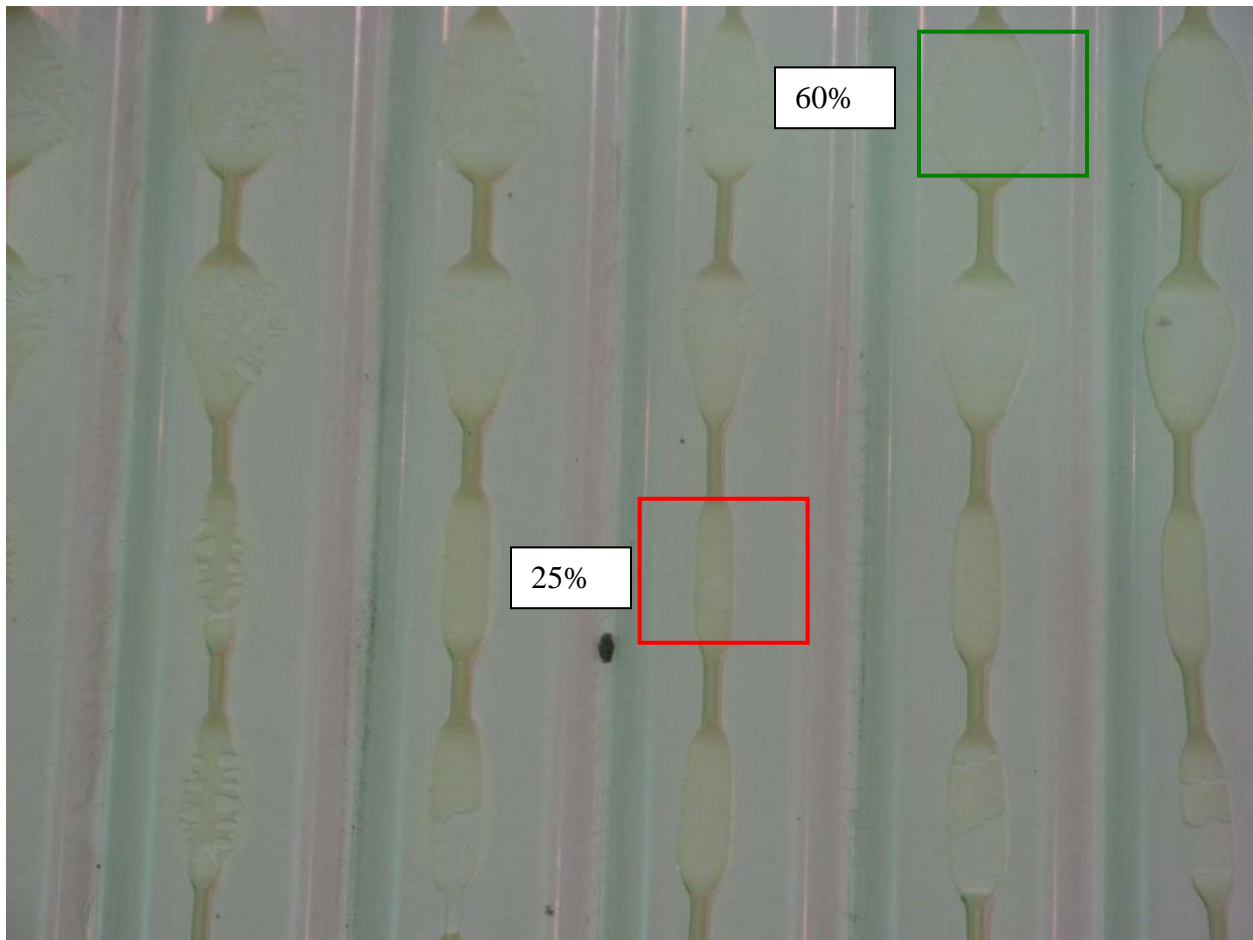| (a) | (b) |

Figure 16: Adhesive bonding condition

Figure 17: Close-up view of the adhesive pads

4 Comparison with the FEA Model

This was the first time we had chance to conduct a large scale prototype study. To validate some of earlier FEA modeling work, we've developed both a full 3D model and a half slice model which has been used extensively in the previous stress and stability study for a full height detector. The half cell _ "slice model" is shown in Fig. 18a with its height being 6 extrusions and width being 8 layers. The model was loaded with water+ air pressure to form a 19 psi at its bottom as test did. The shielding block was simulated with a dummy block which had a vertical weight=5, 10, 15, 20 and 22 ton. The wall thickness was assumed to be 3 mm for the side wall and 2 mm for the web for both vertical and horizontal. The PVC modulus was assumed to be 0.36 mpsi for this unknown garage door type extrusion. Both the vertical (Z) and bending strains (Y) at the location of 38 " from the ground were extracted and compared with the strain gage reading from #s4, #s5 and #s6 at the same height as well as a similar interior location. Fig 18b was a full size 3D model.

4.1 Strains
a) Result from a half cell model:

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The results are shown in Fig 19 for the vertical strain (Z) and in Fig 20 for the bending strain (Y). The FEA result seems very compatible with the measurement. It falls right within three strain gage reading band as expected. In theory, the strain gage reading of s1, s2 and s3 should be the identical or very close due to the similar location (Y and Z). The deviation within these strain gages could be contributed to the wall thickness variation from an un-tuned die as well as the test apparatus/stain gage set-up errors. By plotting the result against three of them, an "average" sense or bandwidth can be established.

The buckling calculation was also done to predict how much weight it could carry for this test structure with 3mm/2mm wall thickness. The FEA predicts that the structure should be able safely to withstand a top weight of 22 ton with 19 psi pressure at its bottom as shown in Fig 4.4. It has been successfully load tested up to 22 ton without any scratches and even any noticeable bowing, as expected. ***Total weight of PVC (H+V) plus the scintillator in the horizontal for a full height (15.5 m) detector equals about ~14 ton and ~22 ton for the PVC and scintillator including both vertical and horizontal extrusion***.

As an extra note is that the extrusion, used in the test, is a under-sized extrusion with a wall thickness being less than 3 /2mm for both vertical and horizontal. In the reality, the vertical extrusion will be 50% thicker than the one used in the test.
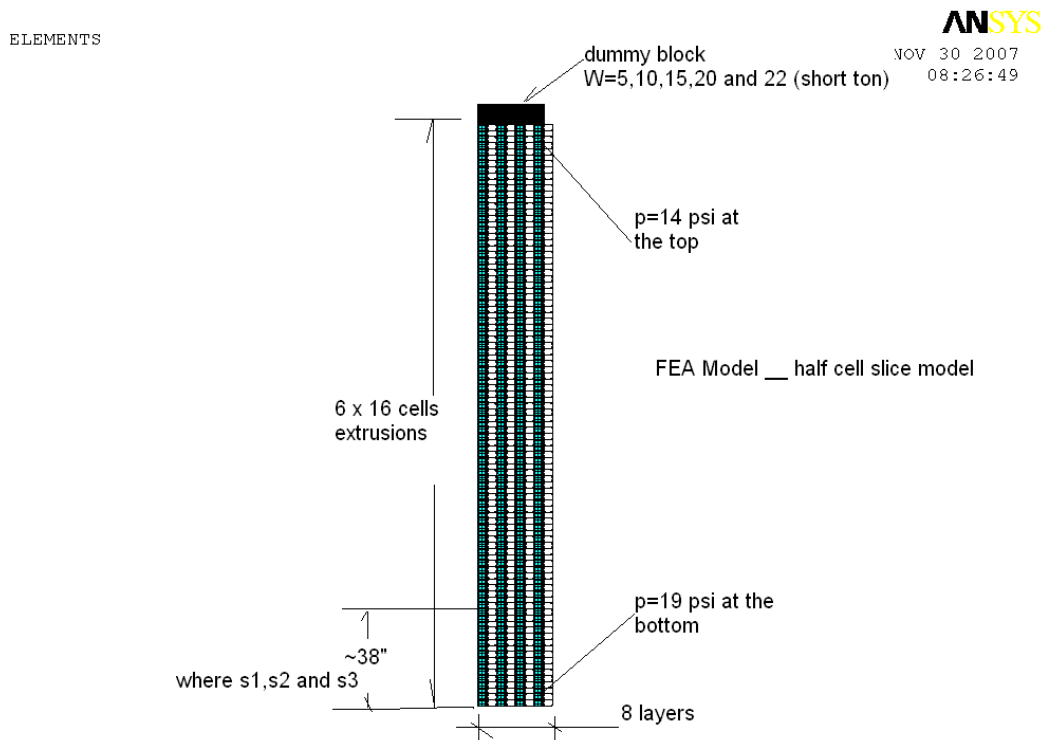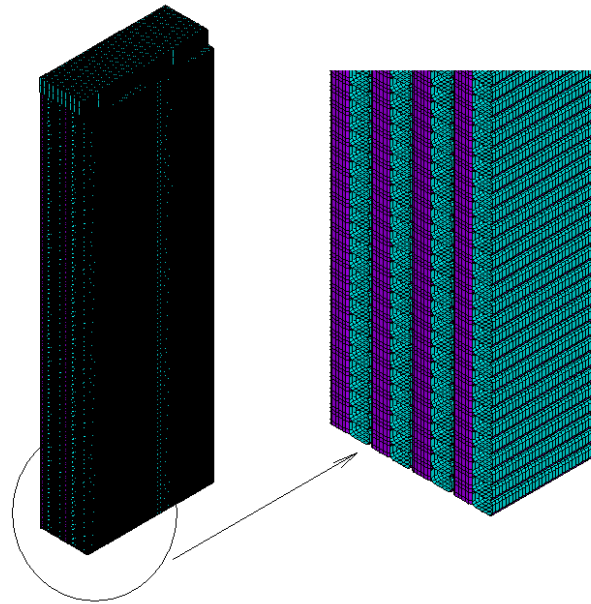
Figure 18a: The FEA slice model for the test structure

FEA full size 3D model
For 8 layes IPND

side/web=3/2 mm,cell e=0.36E6 MPSI, P (air)+5.414 (due the water)=19 psi bottom+

Figure 18b: A 3D Full size Model

Vertical strain Z vs top weight (with water+air=19 psi)

FEA prediction based on
E=0.36 mpsi; t=3 mm/2mm

14 ton ~15 m full heght mass including pvc
(V+H) and oil weight (H only)+19 psi

22 ton ~15 m full heigh mass
including pvc (V+H) and oil
weight (H+V)+19 psi

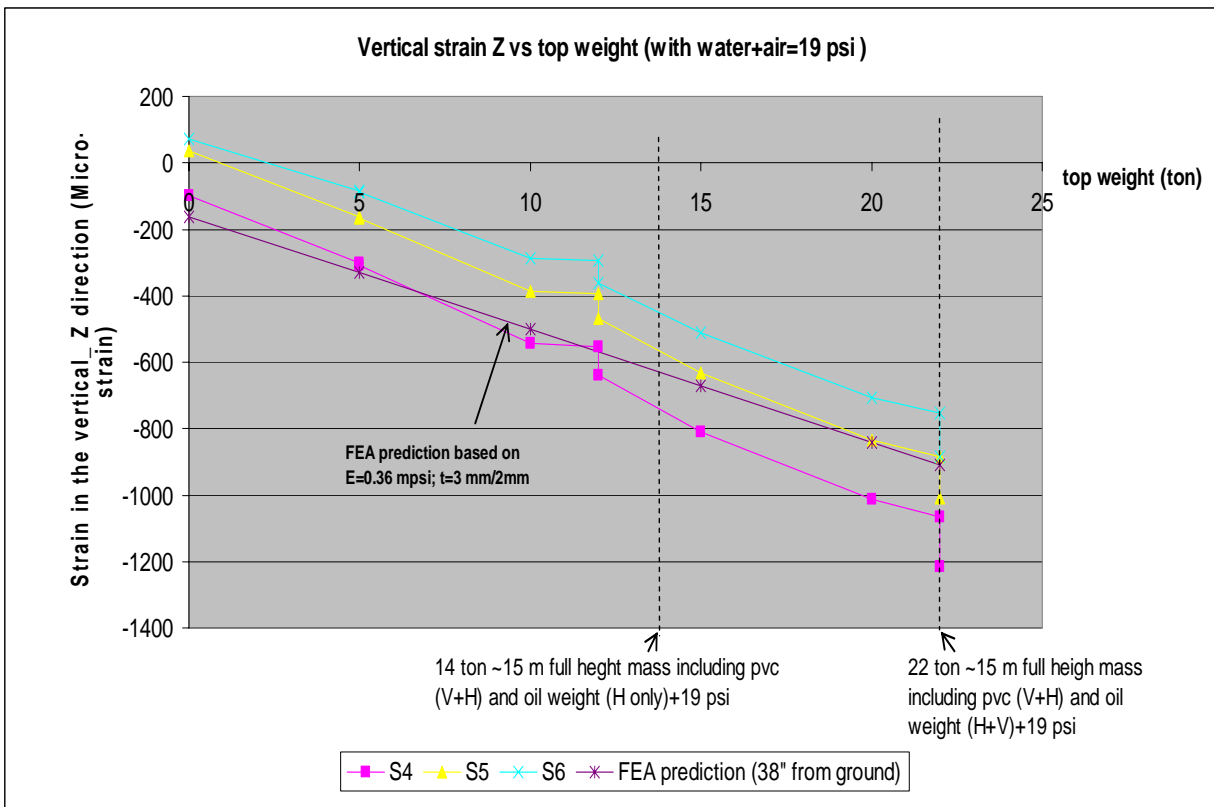S4   S5   S6   FEA prediction (38" from ground)

Figure 19: Comparison of FEA and strain gage measurement
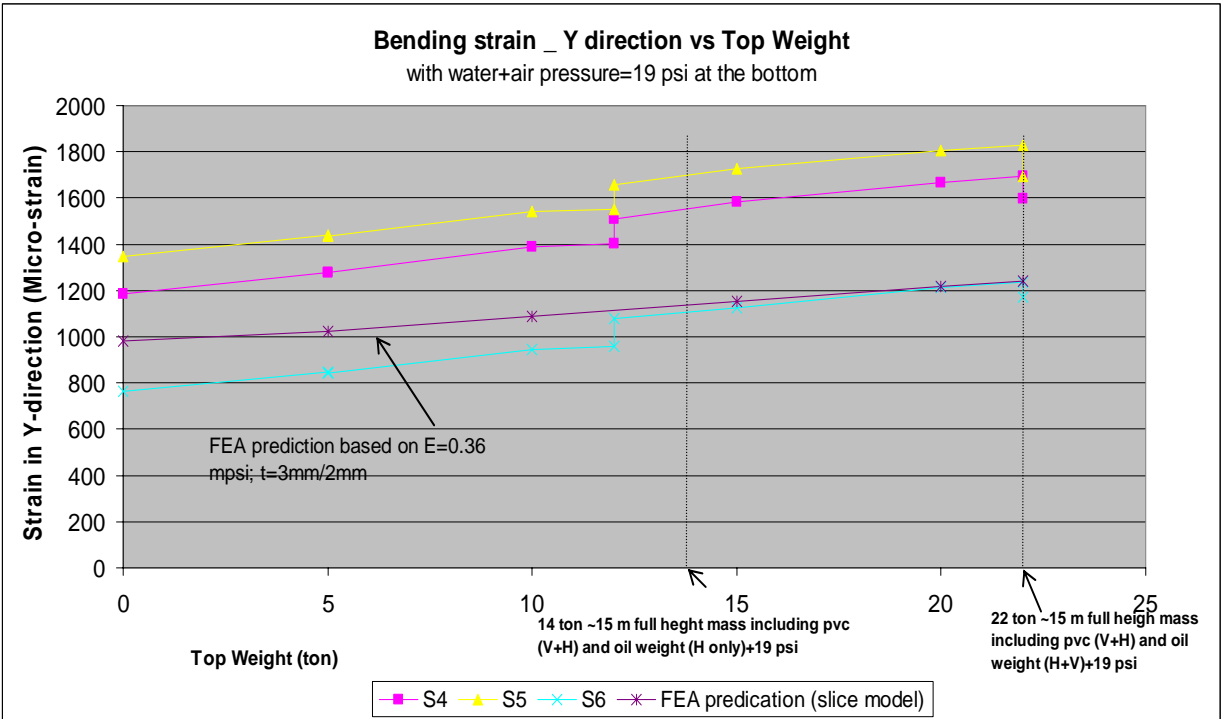in the vertical direction from a "half cell" model

Figure 20: Comparison of FEA prediction and strain gage measurement
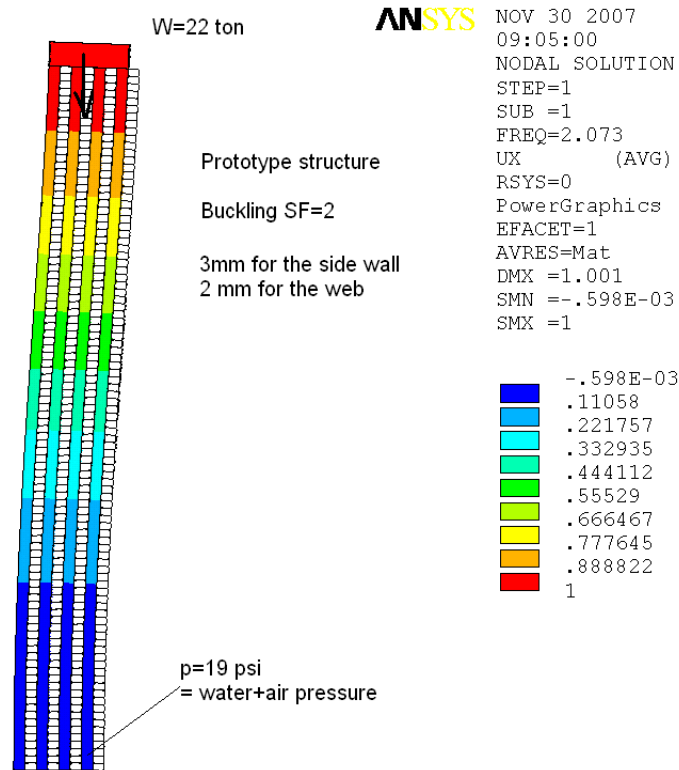in the bending direction from a half cell model

Figure 21: The Buckling SF for the test structure under 22 ton

b) Result from a 3D full size model

A 3D FEA model will provide a complete strain gage comparison from s1 through s6. Fig 22 shows a vertical strain as a function of the top weight. FEA results indicate that the vertical strain is linearly proportional to the top weight. The test result indicates the similar trend for the reading of s4, s5, and s6. However, the readings from the s1, s2 and s3 show a flat pattern, regardless the top weight. One of the reasons could be the strains gage itself. Second reason is that the bottom of the concrete block is not <u>perfect flat</u> such that a slight curvature will result from an uneven vertical loading. It is mostly loaded on the center portion. The end cell, where the s1 and s2 located, is relatively untouched such that a flat curve for the s1, s2 and s3 and a slightly overloaded case for the rest of sensor are observed as shown in Fig 22. The hand calculation, given by Zhao, for 22 ton case matches reasonably well with the FEA result, as well as the test data from s3, s4, and s6 if above factors are considered . But, a "positive" sign of the vertical compress strain for s1 reading is still remaining a mystery to us. It could be the gage itself since the bending strain reading from s1 gives a "negative" sign as well.

Therefore, we've compared the result for the bending strain without considering s1 data as shown in Fig 22. Both FEA and strain gage indicates a relative flat curve for the bend strain as expected. The difference for the s2 reading (top curve and data) is bonded by ~20%, which is most like due to the thickness variation of the extrusion. The wall thickness of 3/2 mm, used in the calculation, is a rough average number from the untuned die. A slight variation of the wall thickness is more than sufficient to cover the 20% deviation in the bending strain reading since the thickness is very sensitive for the bending stain. Therefore, a parametric study is carried out by varying the wall thickness up to -25% as shown in Fig 23. It seems that the FEA result matches very well for the s2 bending data by just varying -10% of the wall thickness and covers most data range with 25% variation of the wall thickness. The actual wall thickness measurement indicates the variation can go up to more than 50% in some places. By considering the "garage type" extrusion with so many un controlled factor, the FEA predication and test data fits more than reasonably well.
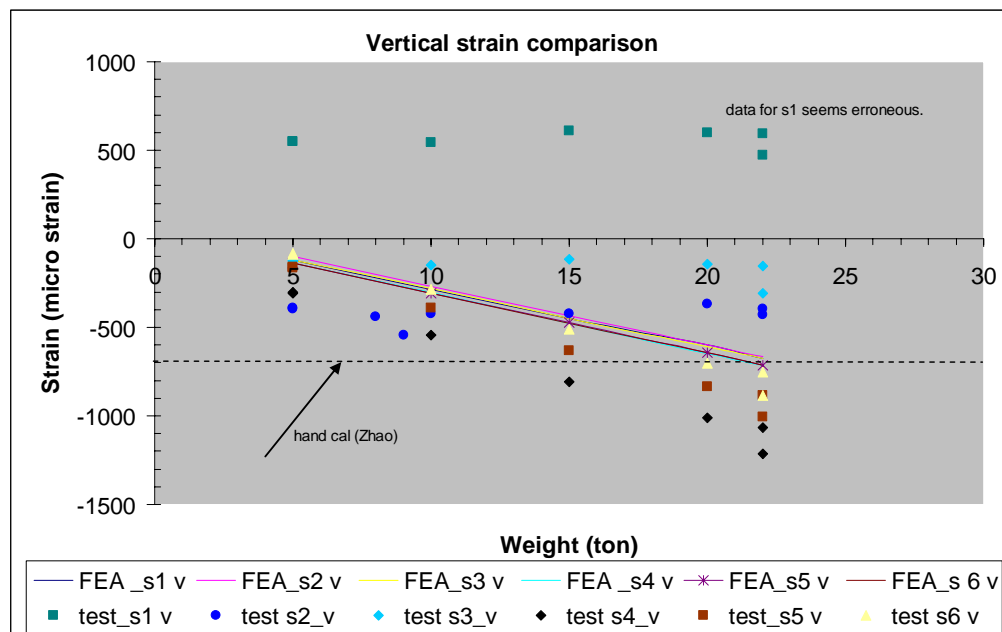

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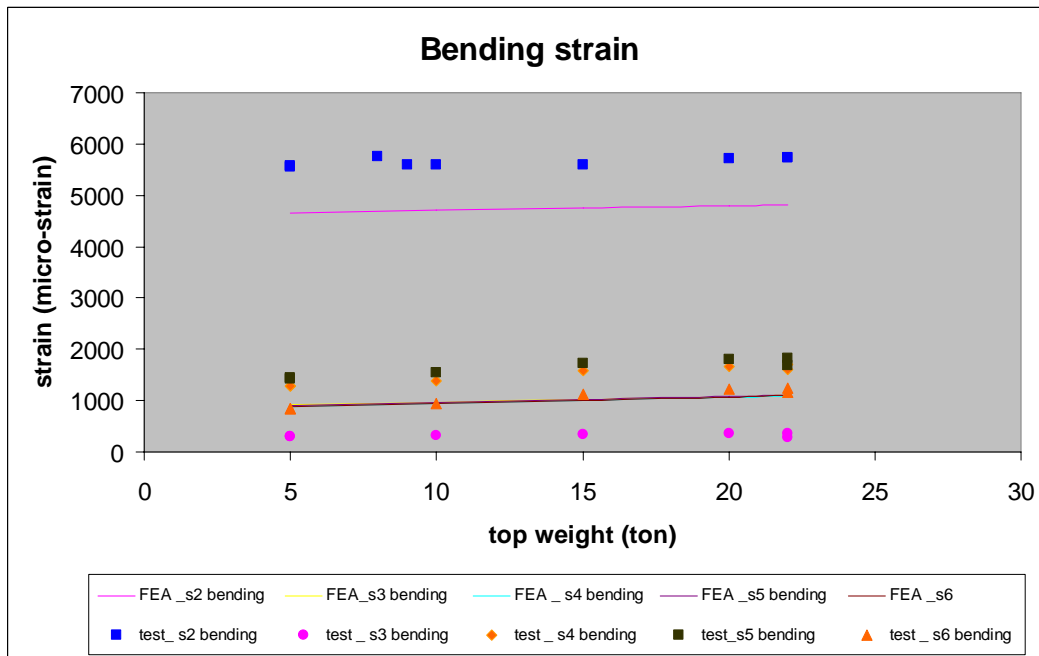Figure 22: Comparison for the vertical stain based on the 3D model

Bending strain

Figure 23: Comparison for the bending stain based on the 3D model

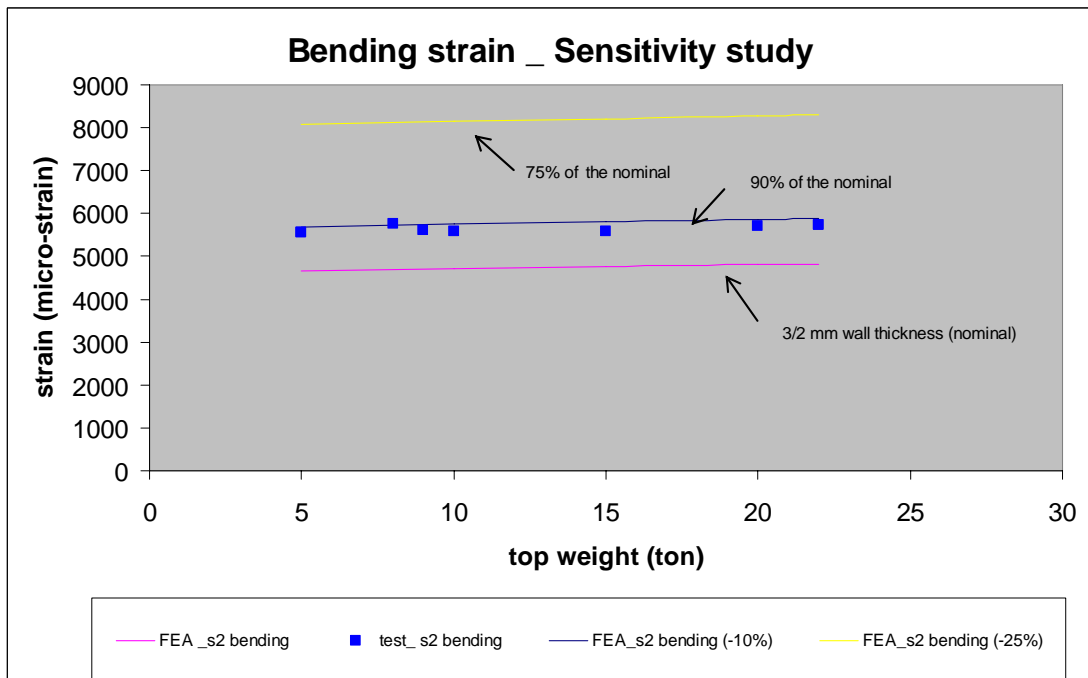**Bending strain _ Sensitivity study**

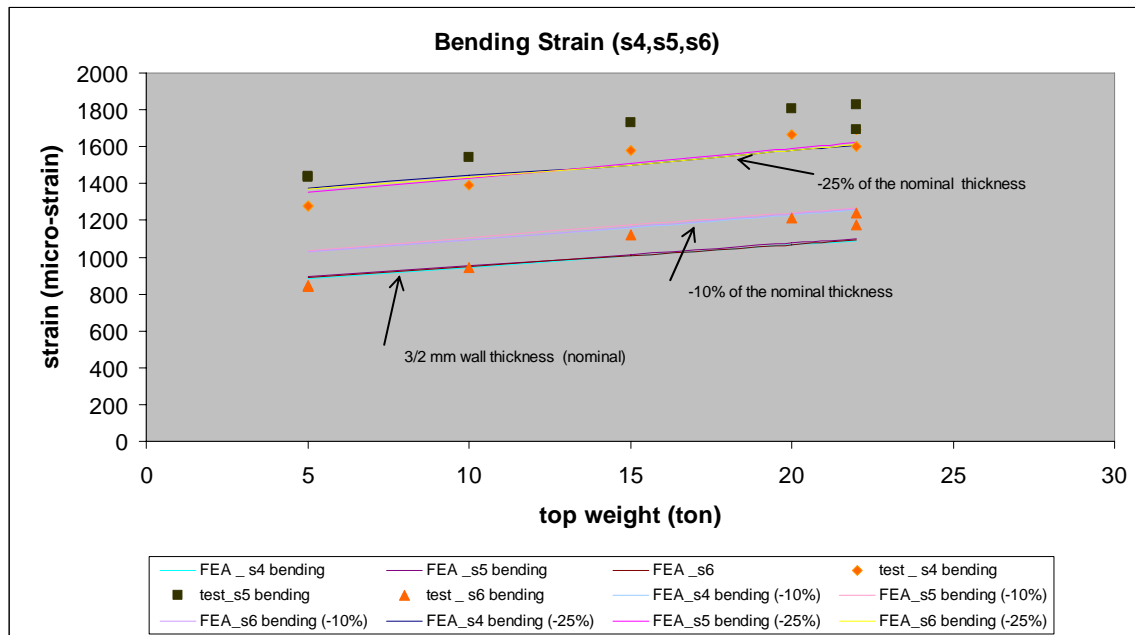Figure 24: The wall thickness effect for S2 bending strain

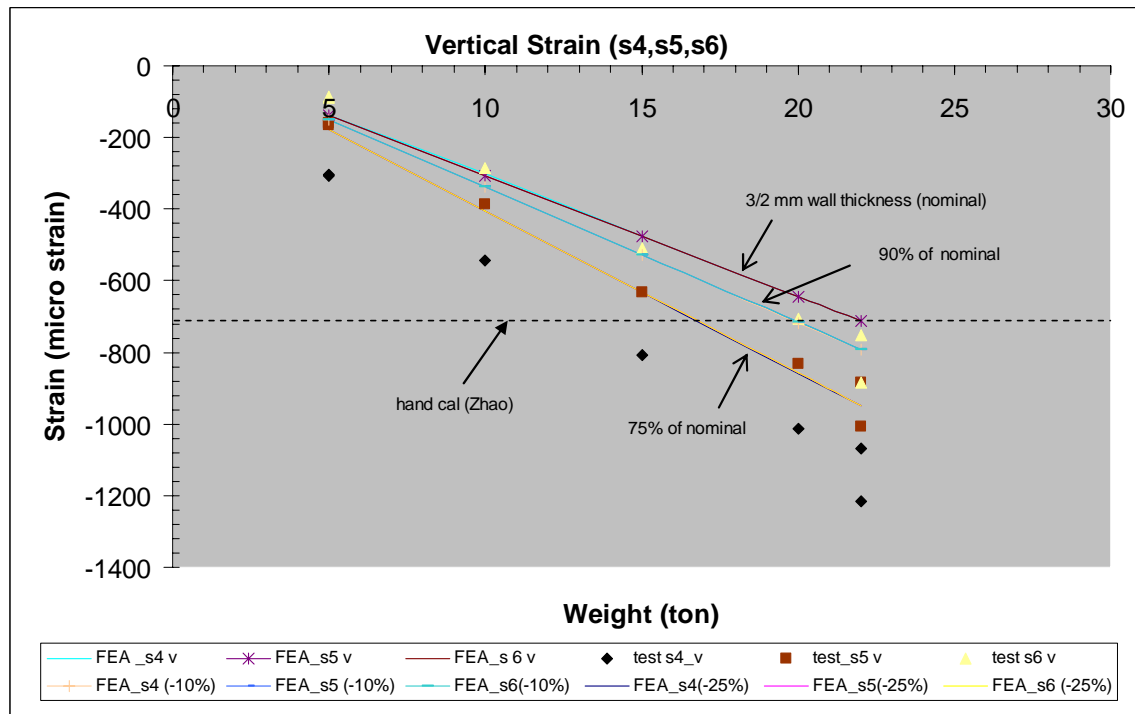Figure 25: The Wall thickness effect for s4, s5 and s6 bending strain

Figure 26: The Wall thickness effect for s4, s5 and s6 vertical strain

4.2 Displacements

The displacements of dial indicators at various locations are plot against the weight on the top of IPND, as shown in Fig. 16. The displacements are linearly proportional to the weight at most

locations with different sensitivities. The drop at weight of 22 ton is a consequence of continuous loading for 16 hours. We believe creep has play critical role in this.

The dial indicator reading has not been compared for this test due to the lack of the assessment from the back side of the structure. A rigid body motion can not be eliminated without an indicator on the other side of the structure at the same location.To obtain the swelling reading, two dial indicators, located on the same locations (identical Y and Z) and opposite side (-x, +x), are required. Also, it is very difficult to access the initial shape of the structure, including both vertical in Z and width in Y direction, which has an "amplify" factor once the top weight is loaded. For example, the reading from indicator 1 and 6 should be ~ same in theory since they are located at ~ same height on the first and last cell. However, the actual reading for I1 and I6 is quite different. Therefore, we've provided table 1 and 2 here just for the reason of the completeness. The experiment data and result from FEA are attached in Appendix.
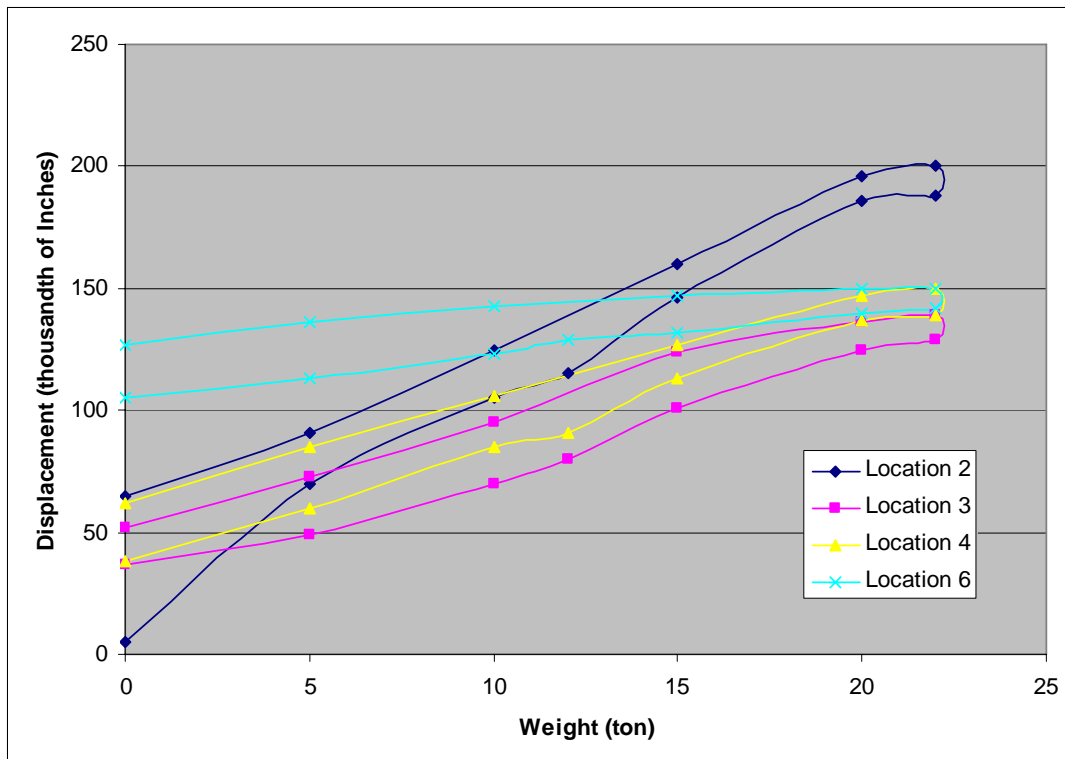
Figure 27: Displacement vs. Weight load

4.3 FEA comparison for the 55 psi load

This prototype structure was subjected to a destructive internal pressure test without the top weight. The structure is able to sustain up to ~55 psi until it has been exploded as shown in Fig 12. To understand it better, we've created the several FEA models to simulate this destructive test. The first model is a 3-D model with the end seal included as shown in Fig 28. The result shows that the "end effect" is minimal as shown in Fig 29 & 30. Therefore, a 2-D model was also created due to its efficiency as shown in Fig 31 & 32. The comparison chart of Fig 33 shows that the 2D model is sufficient.

a) Linear analysis

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Both 2D and 3D model indicates that the maximum bending stress is about ~5800 psi for P~ 30 psi if one of the web experiences the knitting issue. This is where we would expect the extrusion to fail if the test material is similar to PEB (see nova PEB tensile test from Nova-docdb-98-v1). However, the actual test shows the structure can sustain the pressure up to ~ 55 psi. The linear analysis (by assuming E=0.36 mpsi) DOES yield a conservative result.
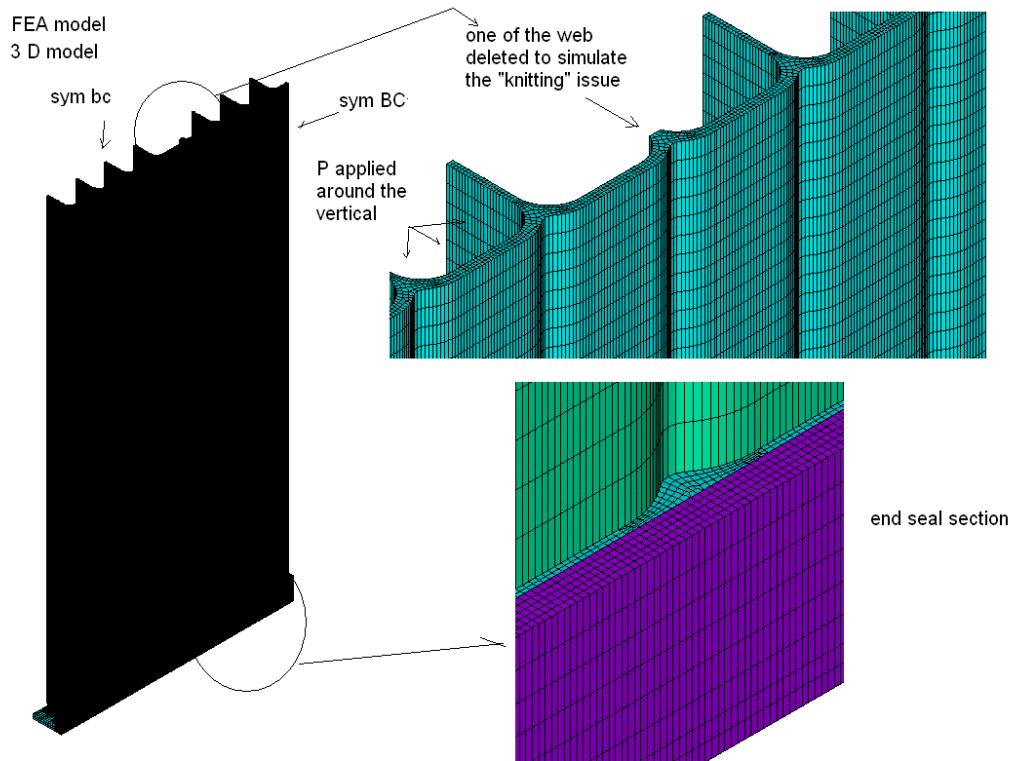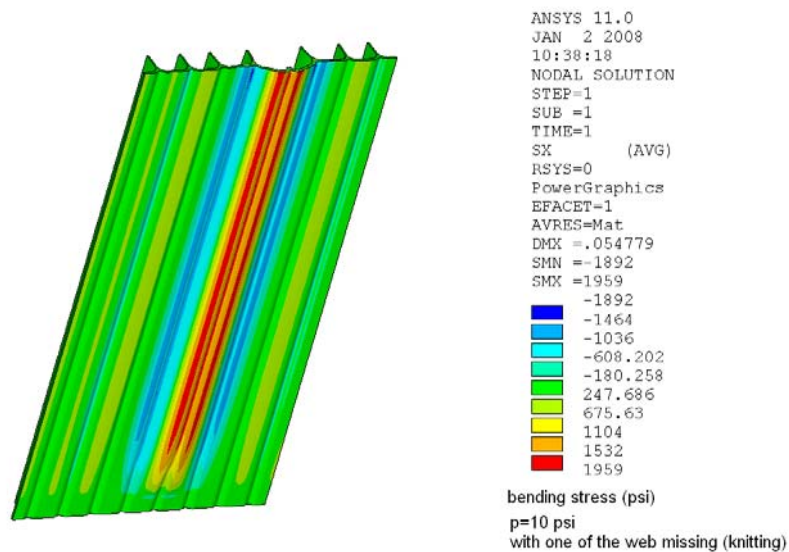

Figure 28: The 3D-FEA model

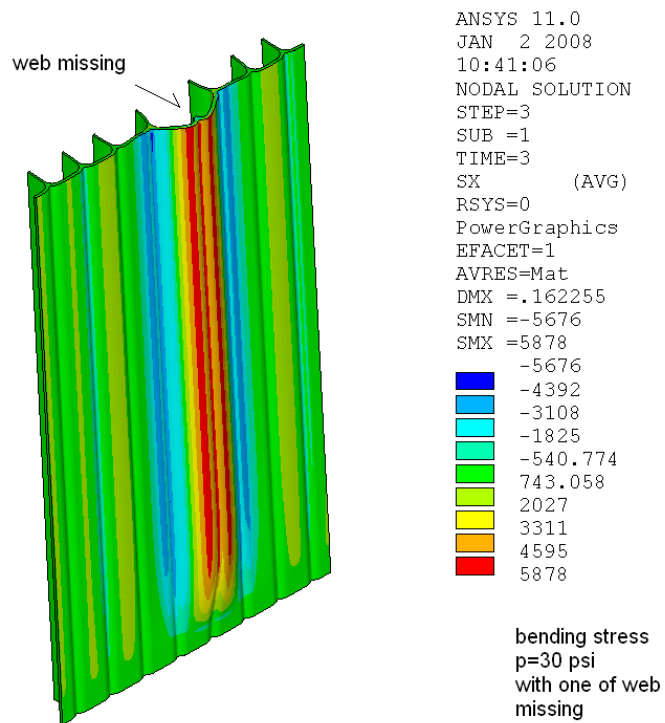Figure 29: The bending stress for p=10 psi with one of the web missing

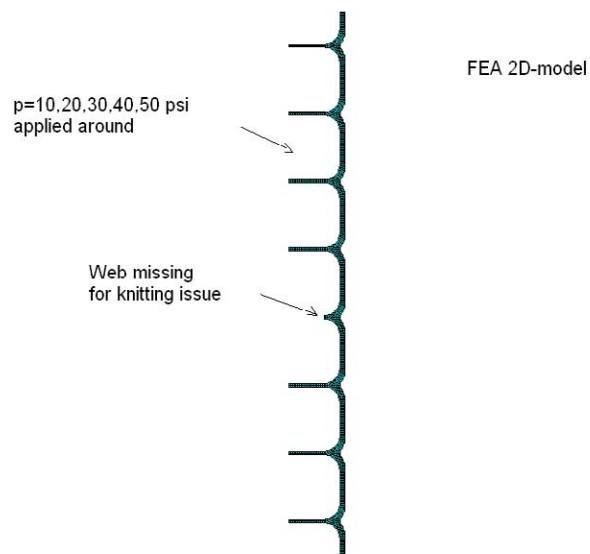Figure 30: The bending stress for p=30 psi with one of the web missing
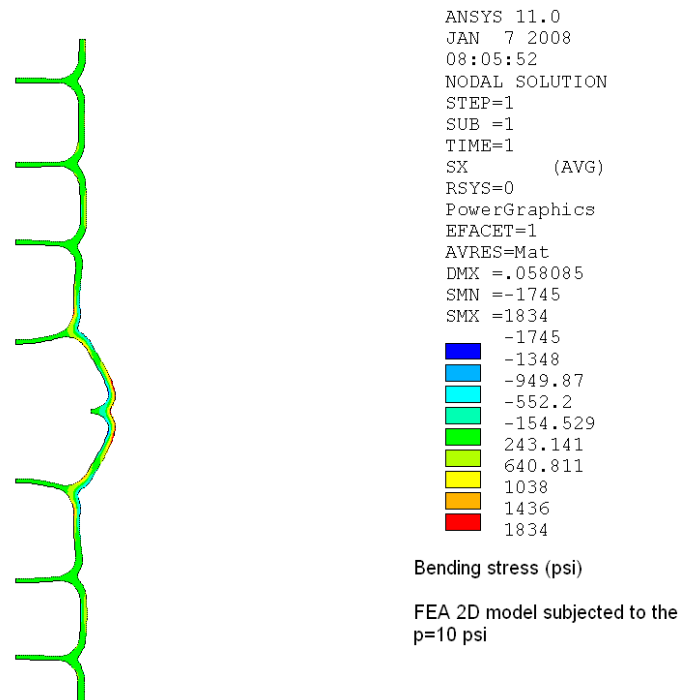

Figure 31: FEA 2-D model

ANSYS 11.0
JAN 7 2008
08:05:52
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SX   (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.058085
SMN =-1745
SMX =1834
     -1745
     -1348
     -949.87
     -552.2
     -154.529
     243.141
     640.811
     1038
     1436
     1834

Bending stress (psi)

FEA 2D model subjected to the
p=10 psi

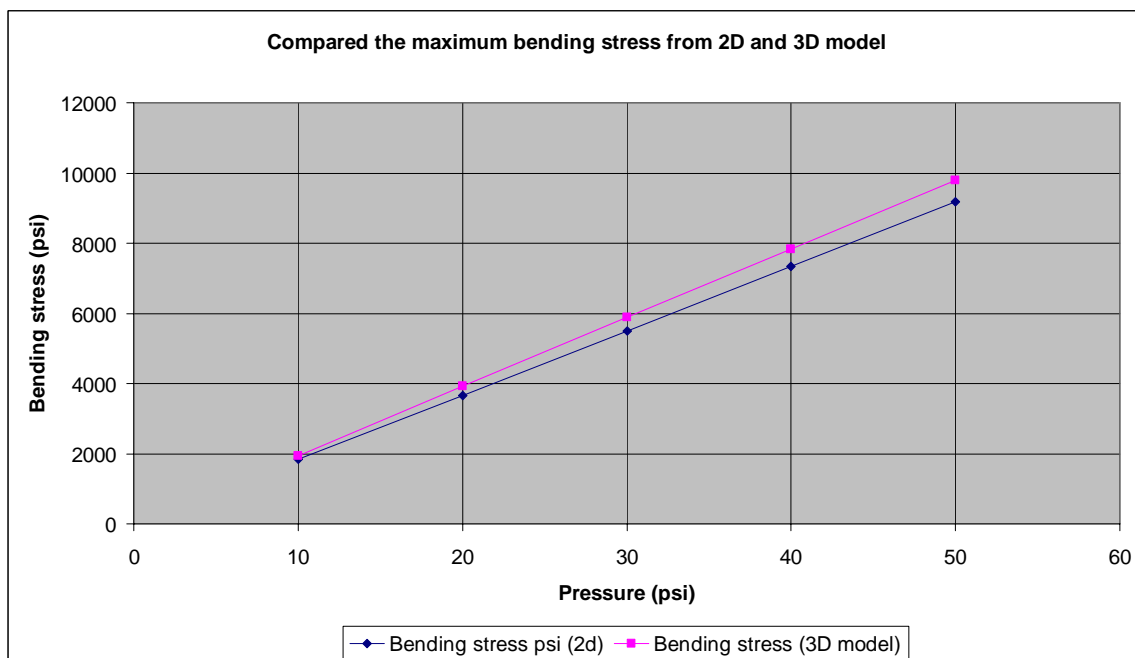Figure 32: The bending stress for p=10 psi (2D model)

Figure 33: The bending stress from 2D and 3D model

b) Non linear analysis by using PEB stress-strain curve

Since this is a destructive test, it will be very interesting to simulate it with a nonlinear stress - strain curve. A PET B stress-strain curve is currently available to us. We've assumed that the material in the test is a similar material. A 2-D model is used for this non-linear plasticity analysis as shown in Fig 34. It includes all the "birth defects" observed (2 web root knitting and one very thin web next to it). By pressurizing it to p=55 psi, the stress result indicates that both

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bending stress in the side wall and the tensile stress in the thin web (t=1 mm) reaches above 5,000 psi which is considered to be a break point as shown in Fig 35 & 36. It seems to us that the structure could be broken anywhere from either the side wall or thin web as soon as the pressure hits 55 psi. The tensile is more dangerous than the bending due to a possible "plastic hinge" effect. We think that the thin web (1 mm) was most likely broken first since its stress is in tensile nature (uniformly cross the section) and the side wall might follow after that due to an excessive span length.
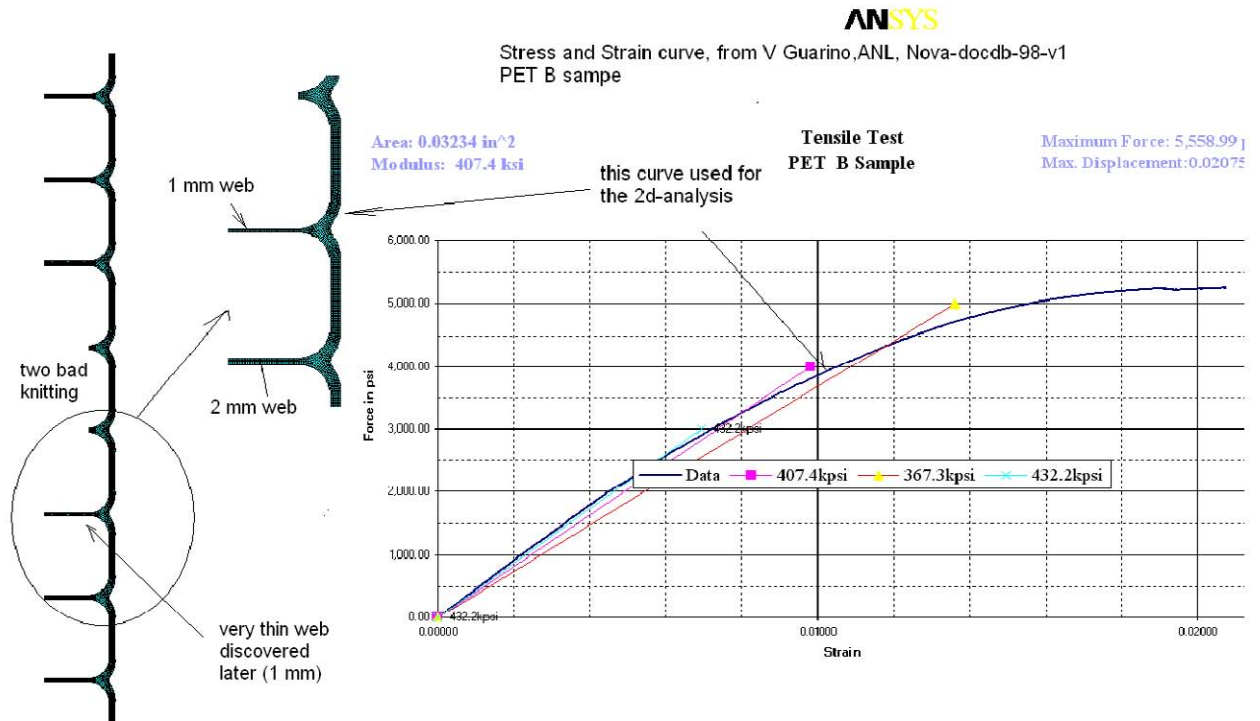

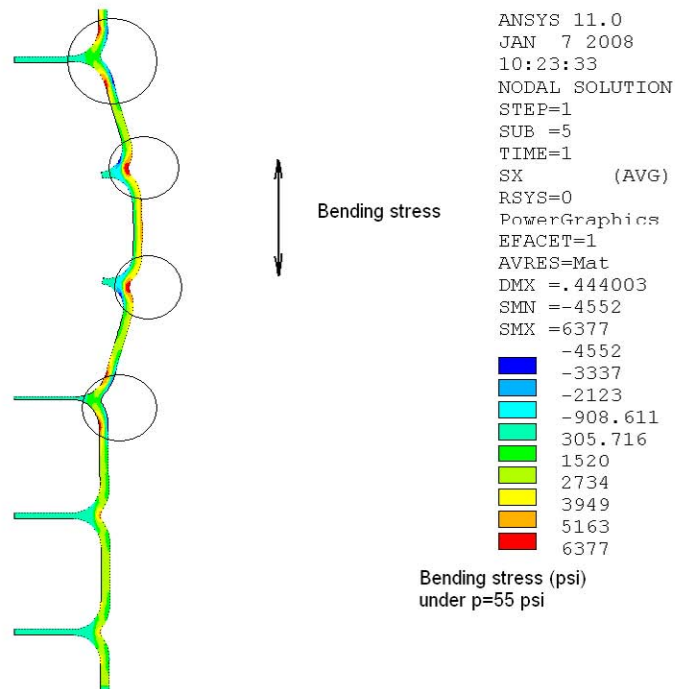Figure 34: 2-D Non linear plasticity model

Figure 35: 2-D bending stress based on the non linear plasticity model for the side wall
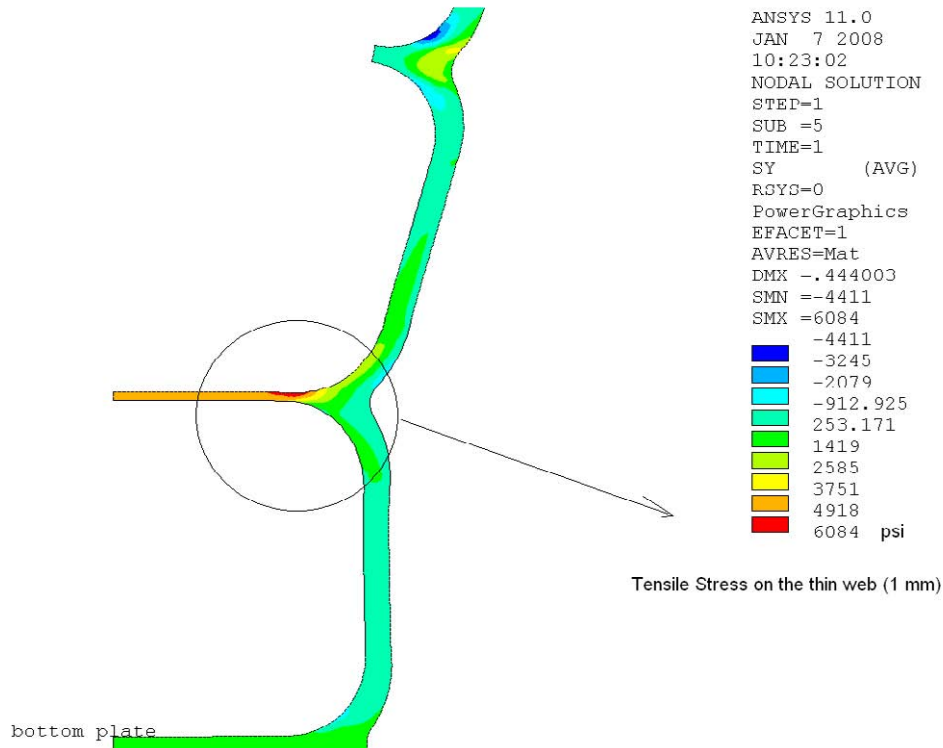

Figure 36: 2-D tensile stress based on the non linear plasticity model for the web

5   Conclusion and Future Work

A large NOvA IPND prototype mechanical testing was successfully conducted to verify the structural strength as well as the related safety factors. The test showed that the IPND prototype was able to sustain under the loading of weight of itself and scintillator. Two FEA models were built to verify the measurement data from the test. The prediction from FEA slice model seems correlated reasonably well to the test result, even under a "rough" estimated condition for the wall thickness (from an untuned die) and an unknown property of "garage type" extrusion. A full size of FEA 3-D model also agrees very well with the test data from strain gage readings.

It is worthy to point out that the stress distribution of the structure is predominantly determined by the internal pressure, while the buckling stability relies more on the loading weight from the extrusions themselves and scintillate. Results of conducted internal pressure tests, including 3-cell, 11-cell and the IPND prototypes, have been correlated to the FEA analysis very well. We believe we have quite good understanding of response of the NOvA structures subjected to the internal pressure, while the understanding of buckling stability is far behind. Therefore, more effect should be laid to improve the buckling considering that the FEA analysis usually is not able accurately modeling the stability as good as the stress analysis.

The IPND structure was mostly built using "scrape" piece extrusions (whatever available in shop). Therefore, a future test should be more focus on by using a actual real extrusions, for example like Nova -27 (if a final choice is made) and extrusion from a tuned die (very important). We should/will repeat 11 layers test with an ACTUAL thicker piece for the vertical to verify the adhesive joint and similar large scale prototype with a symmetry case, either 9 or 11 layers with the dial indicator on the both side.

Appendix

Table 1 Test result for dial indicator

Test Steps	Time (Minutes)	Locations 1	2	3	4	5	6
Fill water	0	8.5	24	16.5	15.5	53	-10
	90	8.2	21.2	16.5	17.9	44	-11.2
	2800	-4.1	18.8	31.5	29.5	46	0
14 psi Pressure	0	7.5	10	33.1	34	155	47
	1000	26.5	5	36.5	38	140	105
5 ton Weight	0	25.5	70	49	60	195	113
10 ton Weight	0	25	105	70	85	303	123
12 ton Weight	0	25	115	80	91	298	129
15 ton Weight	0	25	146	101	113	340	132
20 ton Weight	0	26	186	125	137	NONE	140
22 ton Weight	0	26	188	129	139	0	142
	960	26.5	200	139	150	39	150
20 ton Weight	0	26	196	136	147	45	150
15 ton Weight	0	25	160	124	127	102	147
10 ton Weight	0	25	125	95	106	297	143
5 ton Weight	0	25	91	73	85	385	136
0 ton weight	0	27	65	52	62	303	127

Table 2 FEA result for the dial indicator location

	#1	#2	#3	#4	#5	#6
5 ton	13.94	0.97	-7.97	-8.12	-0.28	13.45
10 ton	13.49	-1.22	-9.31	-9.47	-11.79	13
15 ton	13.05	-3.4	-10.66	-10.83	-23.3	12.54
20 ton	12.6	-5.59	-12.01	-12.19	-34.8	12.08
22 ton	12.43	-6.46	-12.55	-12.73	-39.4	11.9