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Summary of Calculations Performed to Evaluate the Structural Integrity of the 6-Pack Container Pallet

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Summary of Calculations Performed to Evaluate the Structural Integrity of the 6-Pack Container Pallet

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1 October 1999

Abstract

The 6-Pack Container Pallet is a space-frame structure, designed by Mason & Hanger Corp. to hold six AL-R8 containers together in a convenient bundle. The AL-R8 containers hold nuclear weapon components that require special care and consideration. The primary purpose of the 6-pack assembly is storage, but there is some manipulation as the 6-pack is loaded, moved and stacked.

Recently, there has been an upgrade to a new AL-R8-SI container that is heavier than its predecessor was. The analysis discussed herein was conducted to ensure that the increased stresses due to the heavier containers are within design safety limits.

At this time, however, there is disagreement as to what the strength requirements for the 6-pack pallet are. Depending on which classification applies to the structure, a factor of safety (yield stress over design stress) of 3.0 or more may need to be satisfied.

This report documents strength analyses of loaded 6-packs performed at Lawrence Livermore National Laboratory (LLNL). The entire 6-pack assembly was discretized into a mesh with a total of 38682 first-order finite elements. The stresses were found for four characteristic load cases using the implicit code NIKE3D. This was a static strength analysis only. Dynamic loading was not considered. Stability, also, was not addressed.

There are two 6-pack pallet designs under consideration: one that uses 1/2” diameter bolts and one with 3/8” bolts. In both cases, the maximum torque applied to the bolts is 55 in-lbf. This analysis finds the minimum factor of safety based on yield to be less than 3.0 in the main load path of both the 1/2” and 3/8” diameter bolt designs. In general, the peak stresses found in the 1/2” bolt design are less than those of the 3/8” bolt design.

At the welded ends of the main tube section that spans the length of the pallet, the minimum safety factor is 2.14 when 1/2” bolts are used and 1.77 when 3/8” bolts are used. Minimum safety factors of 1.91 and 1.78 were found around the bolt holes in the lateral supports in the 1/2” bolt and 3/8” bolt designs, respectively.

Introduction

The 6-Pack Container Pallet is a structure used to bundle six AL-R8 containers so that they can be moved, stacked and stored conveniently. The cylindrical drum-shaped AL-R8 containers are typically used to store nuclear weapon components. Though the container itself provides adequate protection against contamination, a sudden impact may still render the contents unusable. Therefore, it is important to ensure that the containers are not subject to unnecessary hazardous conditions. At the time of writing, the specific strength requirements for the 6-pack are still in debate.

Usually, the strength criteria for acceptance of a design include meeting or exceeding a mechanical factor of safety. When in doubt, a conservative yet common guideline is a factor of safety of at least 3.0 based on yield (see *LLNL Mechanical Engineering Design Safety Standards Manual*, Section E.5). This is to say that the yield strength of the material at any particular location in the structure must be at least a factor of 3.0 times the greatest mechanical stress found at that location for any encountered loading condition. The purpose of the safety factor criterion is to provide a cushion against weaknesses in the actual materials and fabrication methods that go into making the structure, *not* weaknesses or limitations in the analysis that predicts the stresses encountered. Therefore, refinement in analysis and predicting stresses more accurately is not a justification for relaxing safety factor requirements.

A safety factor requirement is usually based on yield strength because material behavior beyond the yield point can be variable and sometimes unreliable. Furthermore, frequent cycling close to or beyond yield can begin to aggravate fatigue mechanisms of failure. Because of these considerations, it is advisable that until less stringent guidelines are approved, a factor of safety of 3.0 based on yield should be satisfied at all locations along the main load path of the structure. Specifically excluded from this requirement are members that are designed to yield to accommodate varying container dimensions. For instance, the cover is expected to exhibit some yielding when barrels of differing heights are inserted and the bolts are torqued down. The cover therefore will be considered exempt from the safety factor of 3.0 requirement for the purposes of this study. The proper authorities, however, should formally approve this exemption.

Mason & Hanger Corp. originally designed the 6-pack pallet, illustrated in Figure 1, for lighter containers and different bolts. The largest part of the pallet is its base, an assemblage of structural steel plates, angles and tube sections, all welded together. The cover is made of plates and angles, welded also. The six containers are placed onto the base, with the cover above them. Six grade-5 carriage bolts are threaded up through the base, then through the cover, then torqued down. This is the basic “assembled” configuration of the pallet, later known as load case #1. Though a drawing of an empty 6-pack is shown in Figure 1, diagrams and pictures of 6-packs with all containers in place and bolted together are shown in Figures 2 through 7.

This study is motivated by concern over increased demands placed on the pallet, particularly from a 78% increase in the container weight. This increase is due to a transition from the old AL-R8 containers to AL-R8-SI containers with an improved “sealed insert” design. The decision for acceptance of continued use of the current design may depend largely upon whether or not

this pallet is designated a “lifting fixture”. If so, its safety factor on yield would definitely need to be 3.0 or greater. The purpose of this report and the analysis it details is not to accept or reject the current design of the 6-pack pallet for use with sealed insert containers, but to provide an accurate assessment of stress levels during its use. The decision to accept, reject or modify the current design for this use is up to those who establish acceptable risk levels for the handling of AL-R8-SI containers and their contents.

The 6-pack pallet is a complex space-frame structure. Load paths through the structure are not intuitive. This can make simple hand calculations either too conservative or unreliable. Because of this complexity, detailed finite element calculations of the entire structure were deemed necessary for the best possible understanding of the structure. This report details assumptions made during the finite element model’s development, the methods used to perform its analysis, and the results found and their implications.

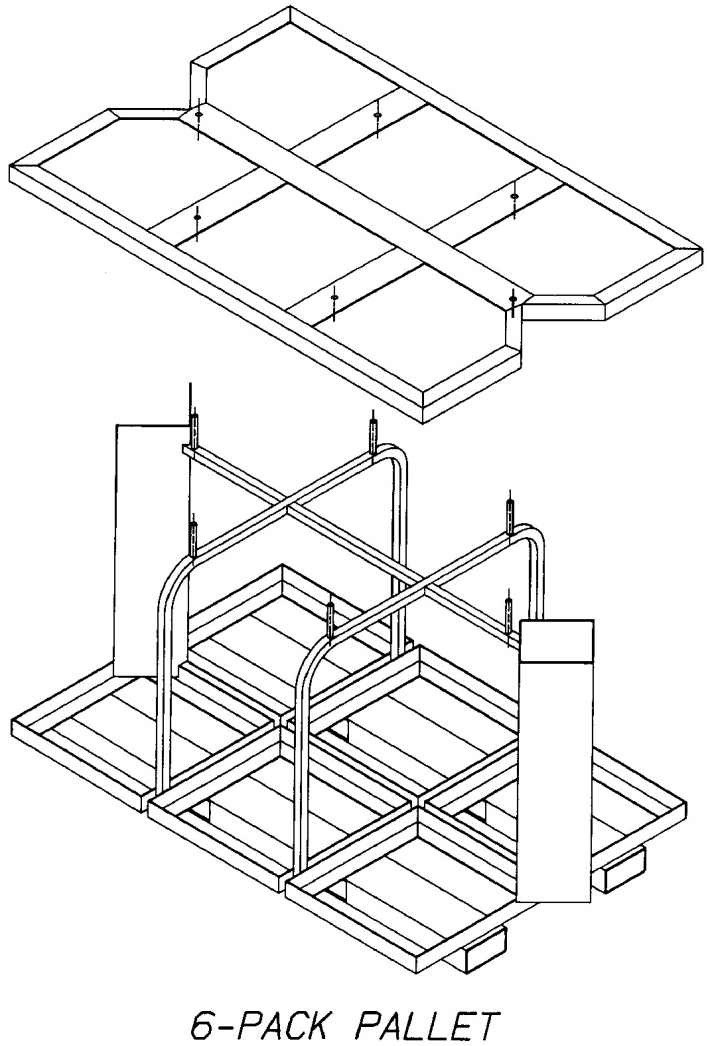


FIGURE 1: A drawing of the 6-pack cover (above) and base (below). Once the six containers are in place, the assembly is held together by the six bolts. Drawing is from Mason & Hanger Co., Inc.

Assumptions

There are several assumptions made during the analysis and limitations to its results that are worth noting. Firstly, this analysis addresses only strength concerns, not stability. The 6-pack pallet with sealed insert containers is reported by Mason & Hanger to have passed any necessary stability criteria. Secondly, this analysis does not consider any kind of dynamic loading (such as drop, impact, vibration or seismic loading). Severe dynamic loading could potentially increase stresses by a factor of two. However, assuming smooth, slow and gradual loading, static analysis is appropriate.

Two current 6-pack designs exist: one with 1/2” nominal diameter bolts and one with 3/8” bolts. *Mechanical Engineering Design* by Shigley and Mischke and many other references contain a design equation relating the tightening torque (T) on a bolt (of nominal diameter D) with the axial preload in the bolt (P) by means of a lubricity or nut factor (K). The relationship between these quantities is T = K D P. Knowing that the bolts used in the 6-pack assembly are zinc-plated, analyses by Mason & Hanger and this analysis assume K to be 0.25, although for most generic applications K is usually assumed to be about 0.2. In this situation, use of K = 0.25 results in a significantly smaller preload, and is ultimately less conservative. The maximum torque to which the bolts are subjected is reported to be 55 in-lbf. For the two bolt sizes of interest, the corresponding axial bolt preloads are calculated as follows:

For 1/2” bolts: $P = T / (K D) = 55 \text{ in-lbf} / (0.25 \times 0.5 \text{ in}) = 440 \text{ lbf}$

For 3/8” bolts: $P = T / (K D) = 55 \text{ in-lbf} / (0.25 \times 0.375 \text{ in}) = 587 \text{ lbf}$

Note that because the amount of torque applied is the same, the 3/8” bolt design requires more severe bolt preloading. Washers and boltheads, modeled as bonded to their bolts, are assumed to have a diameter twice the nominal diameter of the bolts. It is assumed that forces can only be transmitted from the cover to the base through the six bolts and through the containers themselves; there is no direct contact between the base and the cover.

It is assumed that all AL-R8-SI containers are identical, having a weight of 213.6 lbf, a height of 30 in and a diameter of 18.4 in. The coefficient of friction (μ) for steel-on-steel is assumed to be 0.3. All steel is assumed to have a modulus of elasticity of 2.9×10^7 psi, a Poisson’s ratio of 0.29, and a density of 0.283 lbm/in^3. A-36 steel plate and angles are assumed to yield at 36000 psi, while the A500-68 tubing has a yield stress of 46000 psi. Once yielded, steel parts are assumed to have a hardening modulus of 1.1×10^5 psi. The grade-5 carriage bolts are assumed to have a yield strength of 92000 psi.

Four static load cases are considered. In “Assembled” load case #1 (shown in Figure 2), the 6-pack base is placed flat on the floor with containers standing centered in their bays with the cover on top. Gravity is applied first, then the bolts are tightened to their appropriate axial preloads.

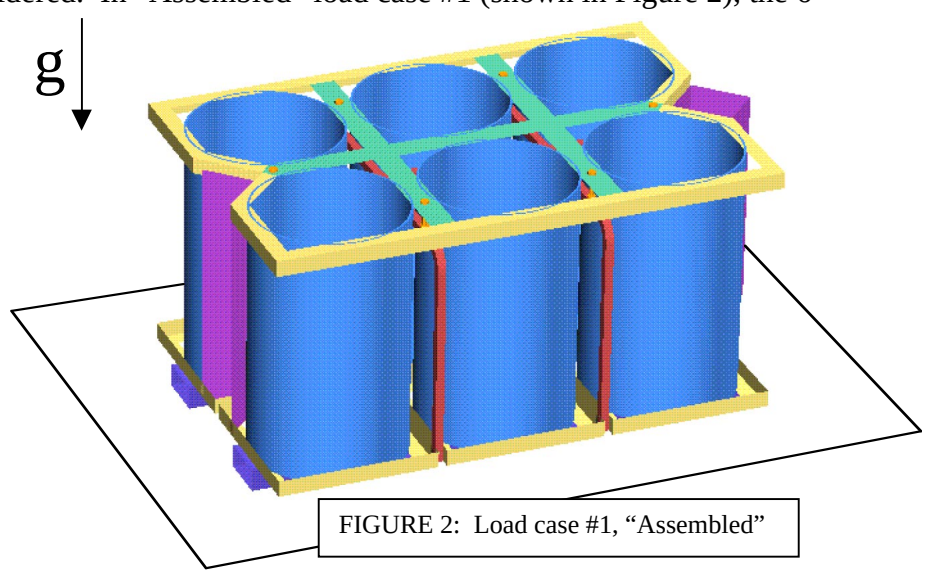
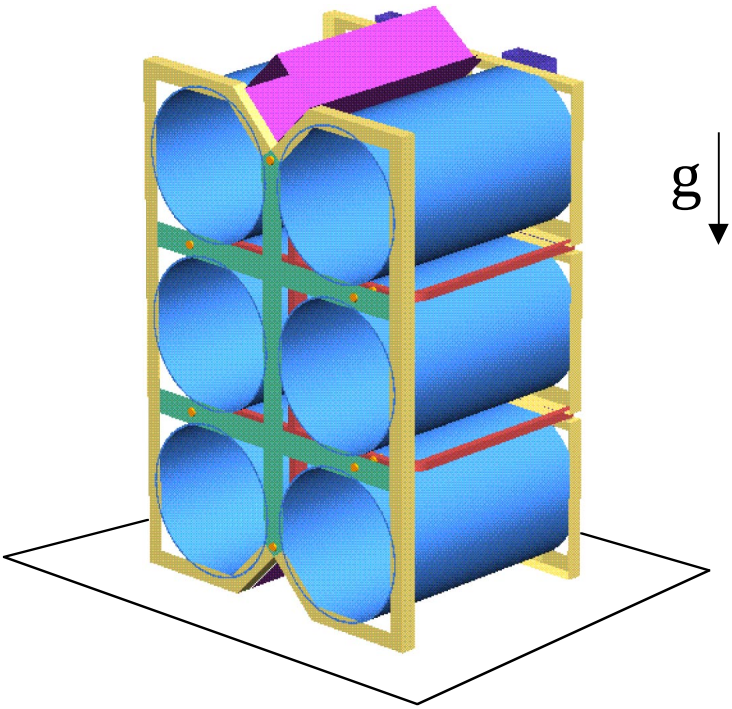


FIGURE 2: Load case #1, “Assembled”



In “Upright” load case #2 (shown in Figure 3), the assembled 6-pack from load case #1 is assumed to have been turned 90° statically (so slowly that dynamic forces can be neglected) so that the gravity vector now points from the full diamond support toward the half diamond support. The 6-pack rests on the floor only on the ends of the forklift tubes and the cover flanges on the half-diamond end of the assembly. The stresses in the bolts change considerably because of this new orientation. For a few parts of the assembly, this tends to be the most severe load case.

FIGURE 3: Load case #2, “Upright”

In “Stacked” load case #3 (shown in Figure 4), the upright 6-pack from load case #2 has the equivalent weight of another identical 6-pack assembly applied on the full-diamond end, distributed only on the upward pointing cover flanges and forklift tube ends. The magnitudes and locations of the applied loads are based on a 6-pack’s total weight and center of gravity. Precise alignment is assumed between the contacting surfaces of the two 6-packs. Misalignment would probably cause some stress concentrations without altering the main load path significantly.

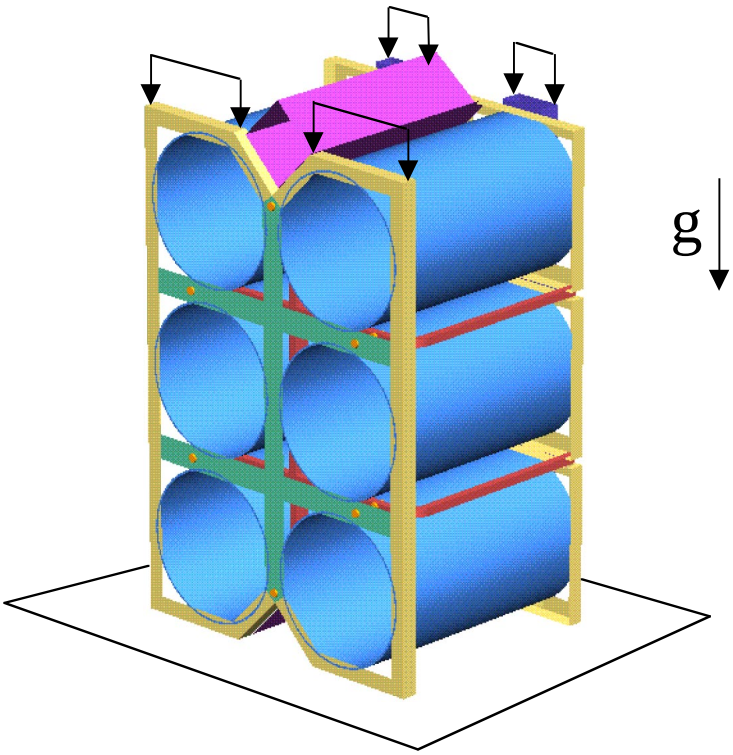
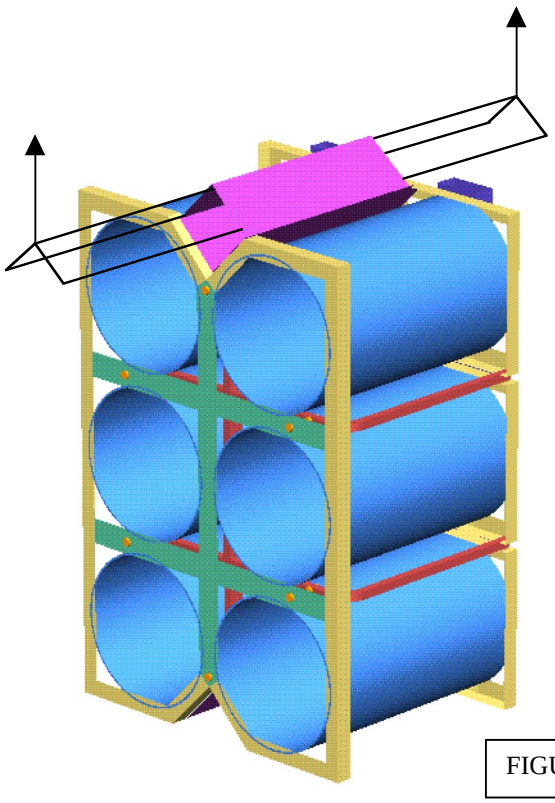


FIGURE 4: Load case #3, “Stacked”



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In “Hanging” load case #4 (shown in Figure 5), a single 6-pack is hanging from the arm of a loader by its full-diamond end. The loader bar is assumed to be rigid, diamond-shaped and only slightly smaller than the diamond tube. There is no contact with the floor. For most parts of the assembly, this is the most severe load case. For all load cases, floors and loading bars are assumed to be perfectly rigid, frictionless and aligned normal to the gravity vector.

Figure 6 shows multiple 6-packs “in the field.” Note that load cases #2, 3 and 4 are typical during the assembly’s use.

FIGURE 5: Load case #4, “Hanging”

FIGURE 6: 6-packs under conditions of load case #4 (left), load case #3 (middle-bottom), and load case #2 (middle-top & right)

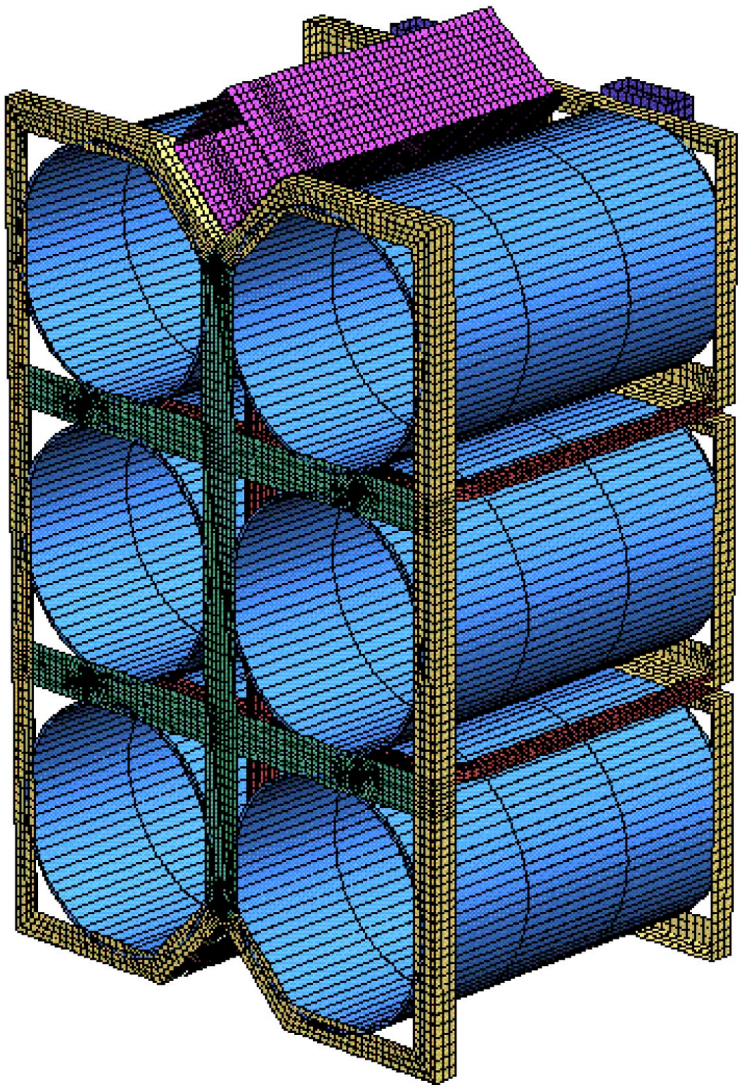


FIGURE 7: (above) The mesh used in analyzing the 6-pack assembly is relatively coarse in most places, finer near critical connections. All structural steel parts are modeled using shells.

Methods

The structural system was analyzed using a finite element method model. The program TrueGrid was used to generate the finite element mesh of the system (see Figure 7). The mesh contains 23658 first-order quadrilateral shell elements with elastic-plastic material models to model the structural steel parts. In addition, 12864 hexahedral brick elements with simple elastic material models were used to model the bolts. Finally, 2160 rigid shell elements were used to model the containers. Each container was modeled as a rigid body with only six degrees of freedom. Welds were simulated by merging coincident mesh nodes together, leaving a continuous mesh through each weld with no special boundary conditions. Finer meshes were used in regions known to exhibit larger stresses and stress gradients, particularly near highly stressed bolted and welded connections. In total, the model has 49109 nodes and 190449 active degrees of freedom. The weight calculated by TrueGrid for the 6-pack structure (without containers) is almost exactly 300 lbf, the figure reported by Mason & Hanger. Slide surfaces (with friction) exist between (1) the containers and the base, (2) the containers and the cover, (3) the bolts and the base, and (4) the bolts and the cover. Figure 8 shows the mesh of hexahedral solid elements used to model each of the bolts.

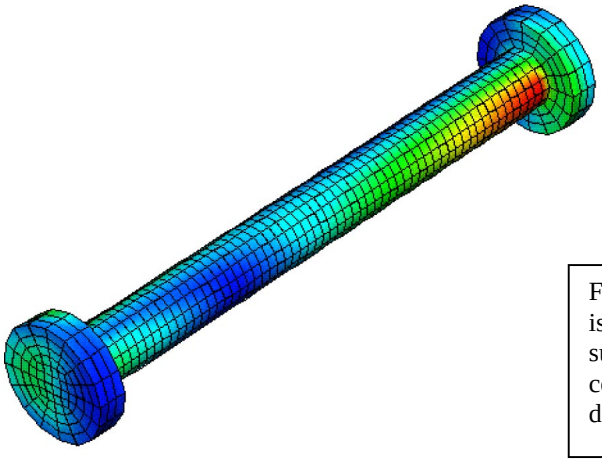


FIGURE 8: (left) The mesh used to model the bolts is composed of hexahedral (brick) elements. Slide surfaces apply forces to boltheads. The color contours show a typical effective stress distribution due to mostly axial load with some bending.

NIKE3D, an LLNL-developed non-linear implicit three-dimensional finite element analysis code for solid and structural mechanics, was used to analyze the 6-pack pallet finite element model. GRIZ, also an LLNL code, was used to post-process the NIKE3D output data and generate element stresses. The elastic-plastic material model incorporates the decreased stress of plastically deforming sections in calculating moments and deflections in shell elements. Bolt preloads are applied by shrinking the bolt shaft materials axially. A computationally intensive iteration scheme makes the bolt preloads accurate to 3% of their desired quantities. The whole analysis process requires 3 to 4 days of computations on a DEC to complete preloading and all 4 load cases for a particular set of input parameters.

Results

Since this is a strength analysis, the generic "stress" reported here is the "effective" or "Von Mises" stress invariant, a scalar quantity that can be used to quantify safety margins. NIKE3D uses effective stress to determine whether the elastic limit has been reached or not. The stresses reported are either at an arbitrary location within a brick element (in bolts) or at a shell's mid-plane (in structural steel parts).

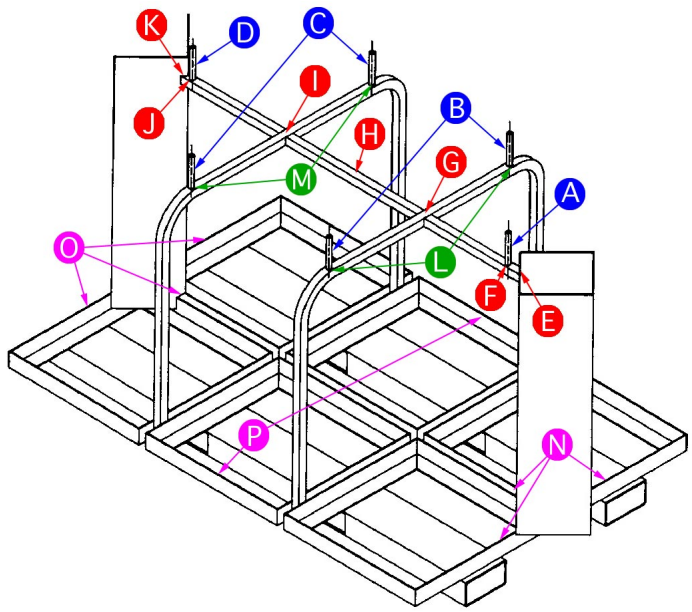


FIGURE 9: Locations on the 6-pack base referenced by Table 1

Various critical locations in the 6-pack base with possible local stress peaks are pointed out in Figure 9. Peak stresses in these locations for each of the 4 static load cases are tabulated in Table 1 for both a 6-pack pallet with 1/2" bolts and with 3/8" bolts. Load cases #2 (upright) and #4 (hanging) tend to be the most critical for all the locations. Also tabulated for each critical location is the factor of safety based on the yield stress and the highest stress encountered at that location for any of the load cases.

As shown in Table 1, multiple locations within the 6-pack would not satisfy a 3.0 factor of safety on yield criterion. High stress locations that may be of concern include tube cross-sections near the bolts (locations F, J, L & M of Figure 9), the welds at either end of the main support (locations E & K) and the angles at the base of the full-diamond support (location N). The simulations predict that the grade-5 bolts have adequate safety factors. Analysis also predicts some yielding in the cover, especially near the bolt holes. There would be significantly more yielding if not all the containers were the same height. However, it is assumed here that the cover is not a critical load path member – that yielding in the cover is indeed permissible. Specific values of stresses and safety factors in the cover are therefore not reported.

SUMMARY OF 6-PACK ANALYSES EFFECTIVE (Von Mises) STRESS VALUES (in psi)			1/2" BOLTS					3/8" BOLTS				
	LOCATION OF STRESS PEAK	YIELD STRESS	LOAD CASE #1	LOAD CASE #2	LOAD CASE #3	LOAD CASE #4	WORST CASE F.S.	LOAD CASE #1	LOAD CASE #2	LOAD CASE #3	LOAD CASE #4	WORST CASE F.S.
A	Bolt #1	92000	5160	8360	7400	16100	5.71	9980	16400	15500	27800	3.31
B	Bolts #2 & 3	92000	6410	11400	11000	13100	7.02	12700	22400	21800	27800	3.31
C	Bolts #4 & 5	92000	6410	11000	10600	12900	7.13	12700	21900	21400	26300	3.50
D	Bolt #6	92000	5130	9910	9410	15900	5.79	9920	17000	16300	21000	4.38
E	Main Support Weld near Bolt #1	46000	8470	15900	15300	12000	2.89	11700	20500	19900	16300	2.24
F	Main Support at Bolt #1	46000	6690	13000	12200	8200	3.54	8180	14700	14100	11100	3.13
G	Main/Lateral Support Junction near Bolt #1	46000	2610	4930	4830	9810	4.69	3510	6240	6150	11800	3.90
H	Main Support at Mid-span	46000	2590	4920	4770	5320	8.65	3560	6310	6190	6710	6.86
I	Main/Lateral Support Junction near Bolt #6	46000	2640	5090	4930	8760	5.25	3560	6550	6400	10400	4.42
J	Main Support at Bolt #6	46000	6360	11600	11400	19200	2.40	7790	13200	13000	20600	2.23
K	Main Support Weld near Bolt #6	46000	8280	15000	14600	21500	2.14	11400	19300	19000	26000	1.77
L	Lateral Supports at Bolts #2 & 3	46000	13000	23900	23000	22500	1.92	14600	25200	24700	24200	1.83
M	Lateral Supports at Bolts #4 & 5	46000	13000	23700	23100	24100	1.91	14600	25100	24600	25900	1.78
N	Angles at Base of Full-Diamond	36000	3020	4830	3890	12600	2.86	4080	5660	4860	13500	2.67
O	Angles at Base of Half-Diamond	36000	3100	4850	3920	4730	7.42	4160	5670	4910	5310	6.35
P	Outer Base Angles at Middle Bay	36000	3890	8340	8580	8730	4.12	5190	10800	11000	11100	3.24

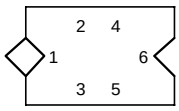
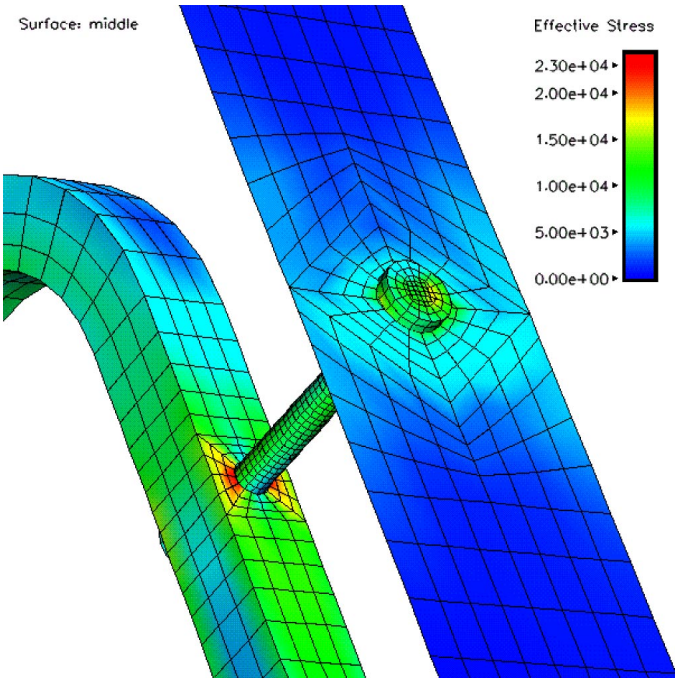


TABLE 1: Peak effective stress and overall safety factors at various 6-pack base locations of interest (shown in Figure 9). The results from 2 analyses are shown: for 1/2" bolts and for 3/8" bolts. The maximum stress over all 4 load cases encountered at each particular location is printed in blue. The factor of safety (defined as yield stress over maximum effective stress encountered) is printed in green if at least 3 and in red if less than 3.

The associated input and output files for the analyses discussed in this report are currently located on LLNL's Compass Cluster file system within the directory "~/dino/6pack/Final". Within this directory are two more directories named "D=0.375" and "D=0.5", depending upon which bolt size is used. Each of these directories contains three complete analyses, entitled "LC1", "LC2-3" and "LC4" (load cases 2 and 3 are combined into one analysis). These directories contain "trugrdi", a TrueGrid input file; "trugrdo", the corresponding TrueGrid output file and NIKE3D input file; and assorted NIKE3D output files beginning with "n3". Usually "n3plot" and its continuation files are all that is necessary for running GRIZ and reviewing results.

Discussion

The worst factors of safety predicted are for the hanging load case (#4) near bolts #4 & 5, shown in Figure 10. The problem here is that much of the 1x1 tube cross-section far from the neutral axis, the part most responsible for resisting the bending induced by the axial load in the bolt, is taken away by the bolt hole. This causes a stress concentration around the edges of the hole, particularly where the cross-section is a minimum (and right where the load is applied). If there was a flaw in the material near these bolt holes, it could cause significant yielding and too much deformation at these bolts. If the cover becomes too loose, a container could fall from its normal

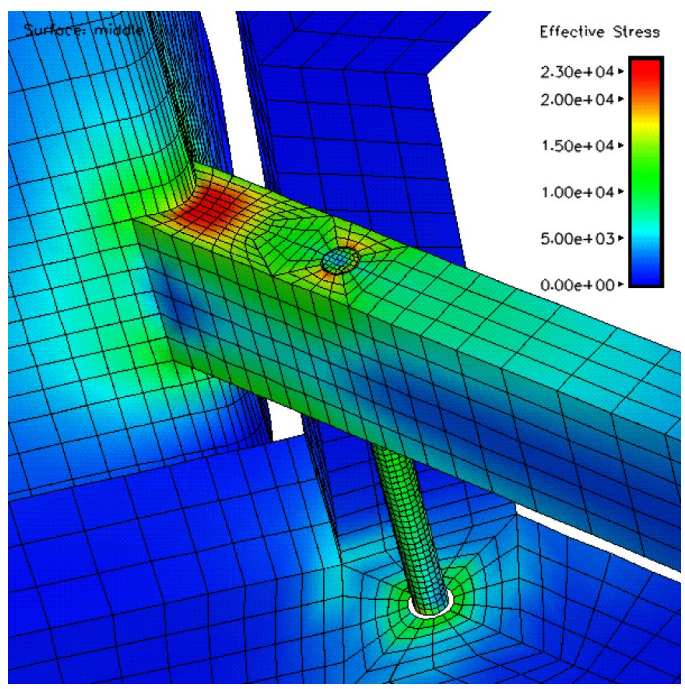


position in the 6-pack. Increasing the safety factor decreases the likelihood of such an event. Reinforcing these 1x1 tubular sections at the lateral bolts may overcome this problem.

FIGURE 10: Effective stress at location M (lateral supports near bolts #4 & 5) during load case #4 (hanging) for the 6-pack with 3/8" bolts. A stress concentration occurs because of the hole where the bending moment is highest. Blue and green areas have a factor of safety of 3 or better. Yellow and orange regions have a factor of safety between 3 and 2. Bright red areas have a factor of safety less than 2. Similar effective stress magnitudes exist on the opposite side of the 1x1 tube section.

Another area of concern is at the junctions between the main support beam and the full-diamond and half-diamond supports on either end of the 6-pack, shown in Figure 11. The stress peak here is located right on the 6-pack's plane of symmetry, at the tip of the curved plate that makes up the support, a reasonable location for a stress concentration. Similar to the above case, there are also large stresses around the nearby bolts (#1 & 6). Large upward concentrated forces along the beam contribute to a large bending moment near these very stiff supports, and therefore very large bending stresses. The situation is slightly worse at the half-diamond end near bolt #6. If a crack was present due to a welding error, or if the joint was structurally weak for some other

FIGURE 11: Effective stress at locations J & K (main support at bolt #6 and weld) during load case #4 (hanging) for the 6-pack with 3/8" bolts (viewed from below with boltheads removed for increased visibility). A stress concentration occurs at the welded junction with the half-diamond support's corner. Blue and green areas have a factor of safety of 3 or better. Yellow and orange regions have a factor of safety between 3 and 2. Bright red areas have a factor of safety less than 2. Slightly lesser effective stress magnitudes exist on the opposite side of the 2x1 tube section. The peak stress does occur right at the welded seam between parts, though the post-processor reports nodal stresses that are averages of stresses from adjoining elements.



reason, this could cause the joint to yield significantly. Too much deformation could result in a failure that would drop all the barrels. Adding more material along the sides of the main support where it joins the diamond supports could also reinforce this region.

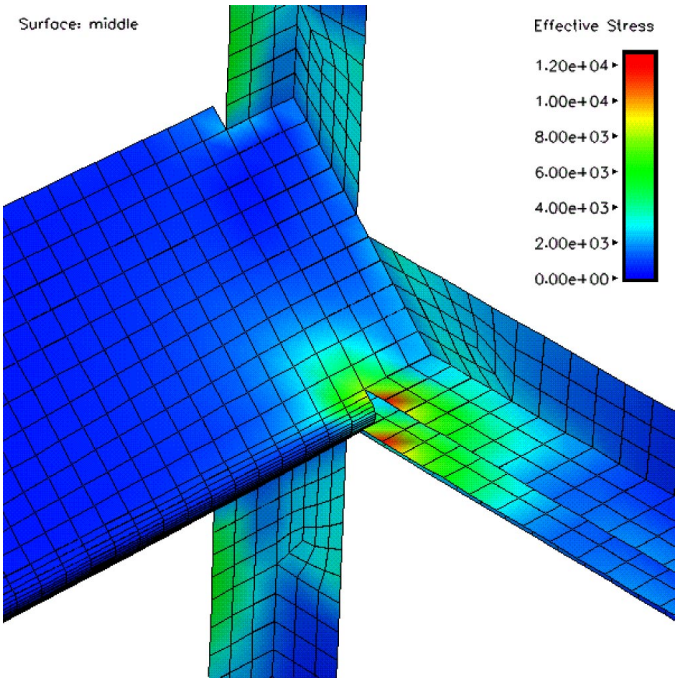


FIGURE 12: Effective stress at location N (angles at base of full-diamond support) during load case #4 (hanging) for the 6-pack with 3/8" bolts. A stress concentration occurs because of the large moment transmitted around this corner. Only the bright red areas have a factor of safety less than 3.

A final location of high stress exists at the bottom of the large diamond support where it is welded to the base angle bays supporting it, shown in Figure 12. When hanging (load case #4), the weight of most of the base and any reactions through the base angles are transmitted through this 90° connection. This condition, though probably not as conducive to a quick fix, is not as severe as some of the previously mentioned ones are.

It is interesting to note that load case #3 (stacked) tends to be less severe than load case #2 (upright). This does make intuitive sense. Assembly tends to make the central portion of the 2x1 main support bow outward. The increased weight from above tends to rectify this bowing, providing more confinement. This stacked state exhibits less deformation in general and therefore smaller stresses at its weaker points.

To gain more insight into the load path through the 6-pack pallet, stresses were integrated across bolt cross-sections to determine the amounts of axial and shear load passing through them. These findings are summarized in Table 2. Note that as long as the 6-pack is sitting on the floor some way (load cases #1, 2 & 3) there is relatively little shear in the bolts. For the hanging case (load case #4), more load is transmitted up through the bottom of the base than through the bolts. This happens mostly because the forklift tubes make the bottom of the base much stiffer than the bolted top (therefore making the bottom pick up more load), but also because moments exist around each container to prevent it from tipping out of its bin.

SUMMARY OF 6-PACK ANALYSES BOLT FORCE VALUES (in lbf)		$^1/_2$" BOLTS				$^3/_8$" BOLTS			
	LOCATION	LOAD CASE #1	LOAD CASE #2	LOAD CASE #3	LOAD CASE #4	LOAD CASE #1	LOAD CASE #2	LOAD CASE #3	LOAD CASE #4
Fx: Longitudinal Shear	Bolt #1	-13	-11	-7	-73	-8	-7	-5	-54
	Bolt #2	-3	4	4	-32	-3	3	3	-35
	Bolt #3	-3	4	4	-32	-3	3	3	-35
	Bolt #4	2	9	9	-28	3	11	12	-27
	Bolt #5	2	9	9	-28	3	11	12	-27
	Bolt #6	13	31	29	-62	8	17	15	-30
	All Bolts	-1	45	49	-254	-1	38	40	-209
Fy: Lateral Shear	Bolt #1	0	0	0	0	0	0	0	0
	Bolt #2	27	39	37	37	22	32	31	33
	Bolt #3	-27	-39	-37	-37	-22	-32	-31	-33
	Bolt #4	27	39	37	34	22	32	31	33
	Bolt #5	-27	-39	-37	-34	-22	-32	-31	-33
	Bolt #6	0	0	0	0	0	0	0	0
	All Bolts	0	0	0	0	0	0	0	0
Fz: Axial	Bolt #1	429	741	742	568	571	934	926	862
	Bolt #2	429	765	736	736	572	960	921	984
	Bolt #3	429	765	737	737	571	958	920	982
	Bolt #4	429	763	737	731	571	957	921	998
	Bolt #5	429	763	737	732	570	956	919	997
	Bolt #6	429	779	738	887	571	972	919	1096
	All Bolts	2572	4577	4427	4391	3428	5736	5525	5919

TABLE 2: Axial and shear force magnitudes in bolts for both bolt size assemblies and all load cases.

Conclusion

Static finite-element structural analyses were performed to assess the strength of the 6-Pack Container Pallet used by Mason & Hanger Co., Inc. The analysis predicts that the 6-pack pallet, when used with AL-R8-SI containers and manipulated as usual, would not meet a safety factor of at least 3.0 on yield at all locations in the main load-bearing sections of the assembly. Also, small amounts of localized yielding were found in the cover near the bolted connections. The decision whether or not to proceed with use of the current design and procedure depends upon what guidelines are established as acceptable design criteria for fixtures used with AL-R8-SI containers and their contents.