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Some Comments on the Shiva Spaceframe Earthquake Damage

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On January 24, 1980, at 11:00 a.m., an earthquake, measuring 5.5 on the Richter scale, shook the Livermore Valley. There were three very pronounced shocks, the first at 5.5 followed by two, one at 5.2 and the other at 4.8, on the Richter scale. The Shiva spaceframe was shaken out of alignment. Shiva consists of two frames, a laser frame and a target frame. Components on each frame stayed within alignment with respect to each other, but the target frame moved with respect to the laser frame. Shearing of the seismic anchor bolts on the target frame was responsible for this misalignment. The operations staff was kept out of the laser bays until the unanchored frame was made safe. The reason for the seismic anchor failing lies in the unique design of the frame as an optical bench, not as a building or as a normal load bearing structure. This was the third in a series of earthquakes for Shiva, the first occurring on June 20, 1977 at a magnitude of 4.7 on the Richter scale and an epicenter 2 miles away. The second quake was on August 6, 1979, with a magnitude of 5.9 and the epicenter 60 miles away. There was no damage or misalignment due to these first two earthquakes. The third however, severely tested the Shiva system and will be the subject of this report. Accelerometers were not in operation on the system so we do not know what the acceleration forces were. Our subsequent investigation however, gives us some indication of these forces.

The frames are fixed at a single point, Figure 1, and all other support points are on rollers and allowed to expand in all directions

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from this point. This is to prevent distortions of the structure due to thermal gradients. The fixed point is a seismic anchor, which has the primary function of resisting a horizontal earthquake acceleration, in any direction, equal to 25% of the acceleration of gravity. This design standard was established to make the system safe against loss of life or severe injury, and in preventing the facility from being seriously damaged by spaceframe motion or being structurally damaged beyond reasonable cost and schedule boundaries of recovery. All components on the frame itself, are mounted with very stiff supports for optical stability. All interfaces between these component supports and the spaceframe are designed with bolts approximately twice as strong as the floor bolts. None of these interface bolts failed. A major problem can occur if the frame is tied too firmly to the floor; large earthquake forces can be transmitted through the frame with subsequent structural damage, component damage, and possibly falling components.

Misalignment:

In the January 24 quake, the bolts that held the target chamber frame to the floor failed and some of its expansion roller bearings were damaged with indication of vertical bouncing or tipping. The frame was displaced to a position 0.4" west and rotated counter clockwise approximately 0.75" measured at its outer perimeter. This was determined by a survey made as soon as the area was made safe for people to work. This survey determined the location of both frames with respect to bench marks outside Building 391 which were used several months before to transfer the Shiva centerline to the new Nova construction site. The bench marks were checked and had not moved. The survey also showed that the laser frame was within 1/16" of where it had been previously. Its primary seismic anchor was intact. The bolts did not break, however they moved slightly and some of the concrete grout around them was damaged. Bolts were sheared that hold bearings which resist turning about the seismic anchor. Bearings were not damaged.

Replacement anchors were designed to allow safe realignment. The laser frame did not have to be moved. The target frame weighing 495,000 lbs. was jacked up approximately .25 inch with 15 hydraulic jacks, all bearings were removed, inspected, repaired and reinstalled. The frame was lowered onto these bearings, moved to its original position and securely anchored. Throughout this maneuver the frame was under complete safe control in case of another quake.

The new anchors were installed to meet the new laboratory requirement of 0.5 g horizontal acceleration. We feel that this is not too stiff to compromise the decoupling criteria, but future systems will be thoroughly analyzed to insure this.

Investigation indicates that all the bolts did not resist the load simultaneously; that there was some bending (see Figure 2) on the bolts, and that they failed in a zipper fashion in tension and shear. The new design requirement of 0.5 g will help avoid the zipper effect in subsequent earthquakes. However, future designs should have controlled breakaway anchors.

Bolt failure:

The overturning moment on the target frame was resisted by the center hub which is tied to the surrounding frame by spokes (Figure 3). These spokes are fairly rigid and transmitted the tipping forces to the bolts anchoring the hub to the concrete floor. This is the vertical force that put the bolts in tension. Each spoke ties to one of the five towers of the spaceframe. These towers are tied together, and could not have acted independently to put a moment on the center hub. Calculations indicate there would be structural damage to these spokes if there was large relative vertical motion between towers. With the spokes acting together to resist the over turning moment due to a 25% horizontal acceleration, a bending stress of 32,000 psi would occur in each spoke (Figure 4). The yield stress for each spoke is 46,000 psi. There was no indication of yielded metal on the spoke structure, which indicates loads were not

above the yield stress on any of the five spokes. This resulted in a rather evenly applied vertical force to the hub and the floor bolts.

From this, a reasonable assumption is that the floor bolts saw both tension and shear. Combining these stresses by the square root of the sum of the stresses squared, yields the maximum shear stress or the resultant bolt stress. One of the reasons for understanding how the floor bolts failed is to have data for future designs, such as Nova. Knowing the "g" forces applied to the frame would be very useful data.

There were very few (if any) bolts that showed the classic cup-cone fracture usually found in pure tensile failure. All the remaining bolts, thirteen out of twenty (7 were taken as souvenirs), show 45° shear face and 90° shear face fractures, indicating tensile and shearing stresses. All bolts indicate some bending due to the failure of the concrete grout. (See figure 2) The bolt holes have a clearance hole for assembly convenience which is 1/4" over the 3/4" bolt diameter. Because of this clearance hole, and because the bolts were not concentric with the holes, some of the bolts were under shear stress before others, and that at some time during the loading all bolts were in some phase of elastic stress-strain simultaneously, but did not reach their ultimate stress simultaneously. What can be derived from this information is a range of horizontal acceleration estimates, by assuming the bolts shared the load sequentially in groups. For example, if groups of five bolts are used, the "g" loading would be as follows:

No of bolts failing simultaneously	Combined stress tens - shear "g"	Shear stress only "g"
20	.88	.67
15	.66	.51
10	.44	.34
5	.22	.17

The figures under "shear stress only" are included to show the range under the more conservative assumption of using shear stress and ignoring tensile loading. Fracture stress values in the bolts are (Ref. 1).

Max shear stress $S_s = 55,300$ psi
Max tensile stress $S_t = 93,300$ psi

Combining the tensile and shearing stress to find the maximum resultant shearing stress:

$$S_s \text{ max} = (S_s^2 + \frac{S_t^2}{4})^{1/2}$$

$$S_s \text{ max} = 72,349 \text{ psi}$$

Force required to break 20 bolts:

$$P = 6.04 \text{ sq"} \times 72,349 \text{ psi} \\ = 436,988 \text{ lbs.}$$

The "g" loading from this:

$$g = \frac{\text{force}}{\text{weight}} = \frac{463,988 \text{ lbs}}{495,000 \text{ lbs}} = .88$$

These figures show the horizontal acceleration loading could have ranged from .17 g to .88 g. This is a wide range of uncertainty and indicates the importance of designing a system with positive control, such as shear pins or plates when ductile breakaway design is required. Included in mounts that are controlled to fail at specified loads should be recovery snubbers so the load is always under control and does not move too far out of alignment. These features are being designed into the Nova seismic anchors.

Conclusion:

The design of the seismic anchors for the Shiva laser frame and target frame met their basic design criteria, no injuries, and no equipment damage. The laser frame bolts did not break. The target frame bolts did break. This evaluation indicates the over turning moment was the difference between the target frame and the laser frame performance. No damage occurred on the laser frame which was not released from ground motion, thus indicating stronger bolts are justified. Making the target frame anchor bolts stronger to equal that of the laser frame would allow better protection against misalignment, yet not be too stiff to cause structural damage.

In estimating horizontal acceleration it seems apparent to me that the force was above .25 g. The bolts on the laser frame could not be tested because they did not fail and could not be removed. However, using the shear value of the tested bolts (assuming they have the same properties) and not considering an overturning moment (because it is small compared to the target frame), one gets a horizontal acceleration of .75 g.

Not knowing the sequence of bolt failure for the target frame, one can only assume some failure mode within the bracketed values of 0.17 g and 0.88 g. The factor of safety of this higher number is 3.5. The lower value is below our design criteria and too low to believe. Reason points toward an acceleration of something less than 0.88g and probably between 0.4 g to 0.6 g.

Though the outcome was favorable, the lesson learned is to design to avoid sequential failure of floor anchors. For Nova the anchor will be dynamically analyzed using the response spectra approach. Design consideration will be given to the inclusion of shock recovery mounts with heavy lift jacks at each support point for repositioning.

References:

1. Test report 77⁰ - 6543 and 6542 LLL material testing lab of Materials Test Engineering Division; and UCIR-1358 internal report.

fig. 1

fig. 2