Axial Testing of Makeshift Buckling Restrained Braces

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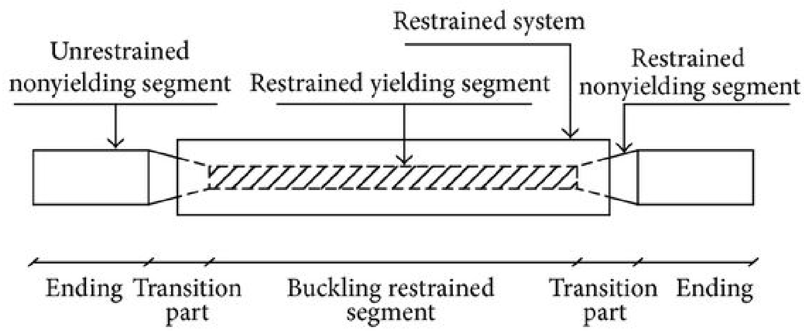
Environmental and Social Impact:

The testing and research in significant lateral force resisting systems is important to furthering the resilience, adaptability, and economy of structural systems. Lateral force resisting systems is still a fairly young concept to many structural practices. The new potential methods of manufacturing a buckling restrained brace (BRB) frame is open for pursuing recycling practices such as the reuse of non-disposable materials. Also, these new methods of formulating BRB systems will open doors for structural engineers to pursue a lateral system that better fits their specific project with significant financial savings.

Introduction:

The buckling restrained brace frame is a lateral system that has been used for over 30 years. Designed for minimal usage in the 1980's, the system allows for a building mechanism that both dissipates energy from lateral motion, as well as resists significant lateral forces. Buckling restrained braces (BRB) are proprietary members, therefore their usage in construction often factor in as a fairly significant cost for buildings. Generally, bids for building projects work toward an effort to decrease the overall cost of the building while also meeting code requirements. This project works toward observing the performance of BRBs when utilizing different core encasements to see how they perform relative to each other. BRBs are relatively thin steel members that are encased with grout as to provide bi-axial compressive strength and prevent failure by buckling. The restraint on the steel member allows for an overall increased compressive capacity, as well as match that with the tensile capacity to maximize the energy dissipation in the system. Allowing the member to withstand similar tensile and compressive forces is critical in the process of repetitive, cyclic forces during seismic situations. Furthermore,

it is important to understand that the non-encased portion of the member is to be able to withstand much more significant forces than the interior portion. This allows for the control of the location of failure within the member during significant seismic activity and the possibility for the owner to potentially replace the potentially damaged member in the BRBF system.



Typical BRB Composition

One of the customizable portions to these systems is the filler material that encases the steel. Our research dwells on the concept of making comparisons between the usual grout material and the use of other, more commonly available materials.

Initial Hypothesis:

The use of a viscous fluid to encase the steel member of a buckling restrained brace may provide a significant improvement to the structural compressive capabilities of the system. If so, the system will also provide damping capacity to the overall structure thereby improving the seismic performance.

Testing Materials:

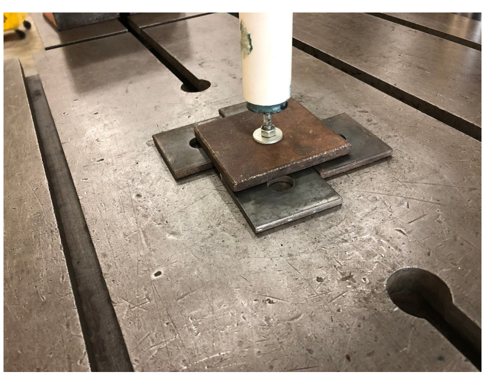
- 6 tubes consisting of the following encasement material: 2 grout, 2 tar, and 2 flubber
- 2' long, 1" Ø PVC pipe, typ.
- ¼" Ø zinc threaded rod, typ.
- Rubber Stoppers to friction-fit the size of the PVC pipe.
- Epoxy
- Generous amount of grease

Testing Setup:

We used the Riehle Machine in the High-Bay Lab at California Polytechnic State University, San Luis Obispo because it was all that was available to provide us a force with a correlating displacement to the nearest thousandth of an inch. The machine is capable of reading forces on a dial to a precision of 5 pounds. The machine is incapable of providing tension and compression loading in a cyclic fashion, so we decided to take the liberty of cycling the members through a series of compressive loading, followed by a tension test. That being said, our test specimen underwent a series of slow, static loading. Dynamic testing was not a means of experiment we could undergo due to time constraints and a lack of sufficient resources.

The Riehle Machine
Architectural Engineering Department of California Polytechnic State University, San Luis Obispo

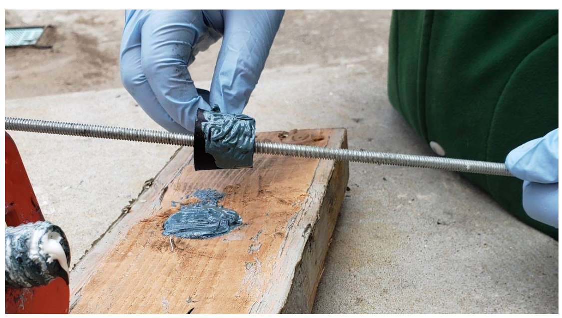
For the compression tests, we crafted two significantly thick steel plates to pin the ends of the rods into place. They were crafted to friction-fit the machine we had and allow no rotational freedom to the ends of the system. This allowed for the member to be forced into solely axial stresses and provide as little initial P-Delta effects to the ends as possible.



Base Restraint

Top Restraint

Construction of the test specimen consists of cutting the rods and PVC pipes to their designated, equal lengths. The ends of the zinc rods are grinded down in order to be able to screw the respective nuts into place. ¼” holes are drilled into the centers of the rubber stoppers and slid into place on the zinc rod. Heavy amounts of grease is applied to the zinc rods prior to being put into the encasement PVC. This is to ensure that there is no bonding between the rod and the filler materials. The initial stopper is coated with epoxy prior to being jammed into the end of the PVC. Once the stoppers are sealed into place, the designated material is poured into the tubes. Constant vibration and motion is applied to the materials in order to minimize any air pockets from existing. Once full, the second rubber stopper is applied to the open end of the PVC and epoxied into place. The epoxy is left to cure for a minimum of 24 hours to ensure its full strength. The samples with grout material is given a minimum of 7 days to cure in order to ensure significant compressive capacities.



The Thorough Application of Epoxy

The Test Specimens

The grout is constructed with a ratio of 3 parts sand to 1 part cement, as well as gradual addition of water until a mashed-potato-like consistency is achieved. The solution is a process learned in the constructing of grout to provide an approximate f'c capacity of 2500 psi (ARCE 305, ARCE Dept. Cal Poly SLO). The tar material used is a Latex-ite Brand substance that has a general purpose of road-crack repairs found at a local department store. The flubber material was constructed with a recipe ratio of 3 teaspoons Borax that has been mixed with 2 cups Elmer's Brand glue and 5 cups water.

Tar Filler Material

Flubber Filler Material

Initial Testing:

The tar and flubber reacted in a fashion that can be categorized as a non-newtonian liquid. This is defined as a material that reacts similar to a solid upon impact forces and a liquid when applied with slow, gradual loading. The materials generally have poor shear capacity when given prolonged loading. Due to this, the experiment proved to be unsuccessful in acquiring data for axial compression since the materials provided no resistance against the buckling of the slender rods. The Rayleigh machine began to apply loading, but the significant slenderness of the 2 foot long rods was too small to be traced by the large machine. The rods gave way to significant displacements without providing any resistance to the forces.

Reading the Force-Displacements off the Machine

Initial Results:

The failures of the test specimen revealed a significant learning experience for the two of us. Going on into the structural engineering world, there is an understanding that some of the greatest feats learned in the community is what comes out of the failures of the past. Going into the experiment, we had an understanding that a viscous liquid held properties of resisting motion energy and providing damping. With this knowledge, we had hoped that a viscous liquid could also resist the motion of what it encases, similar to the qualities experienced when walking through a dense liquid and experiencing a significant strain to the human legs. What we failed to predetermine was that this stress from the liquid was not significant enough to provide a bi-axial compressive strength large enough to hold the zinc rods in place.

Tar Substance

Flubber Substance

Final Hypothesis:

The use of solely compressed aggregate to encase the steel rod may provide significant axial compressive capacities to the BRB system. The densities of the aggregate are the key to the overall compressive strength and comparing the specimens is the goal of the experiment. Even if the qualities are not as great as the grout substance, it will allow for these BRB members to be constructed under different prefaces to meet different project qualities.

Materials Utilized in the Experiment

Final Testing:

The same materials and setup were used with a change in the encasement materials. For the grout, the 3 parts sand to 1 part cement ratio with water still holds. For the aggregate, we tested two different sizes in the PVC. One aggregate we used was sand that we categorized as fine. The other consisted of small pebbles that we categorized as coarse. The method of constructing these specimen remained the same as the previously constructed test specimens.

Coarse and Fine Aggregate

Compression testing of the test specimens varied between 100lb increments for grout specimen and 50lb increments for aggregate specimens. The increased increment scale for the grout specimen was with the understanding that the grout substance was able to withstand a higher compressive load than the aggregates alone. Unlike the flubber and tar substances, the aggregates were able to take on significant loading and provide reasonable force-displacement data.

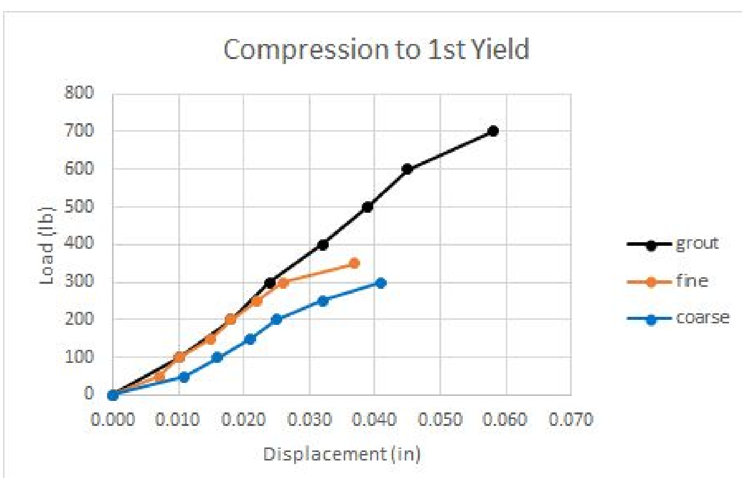
Once compression tests were cycled on each of the test specimens we had the machine switched from compression mechanics to tension. Once set up, we utilized the two clamping mechanisms on the Riehle machine that hold the ends of the member being stretched. In order for the rods to stay in place, we tightened nuts onto each end to give the clamps something to grasp to. Once the tests were completed, we observed the nuts and noticed they did not have any give to them. This ensured that they worked very well for our experiment. We took the members to their ultimate force and gathered their force displacements.

Compression Testing of Makeshift BRB

Tension Testing of Makeshift BRB

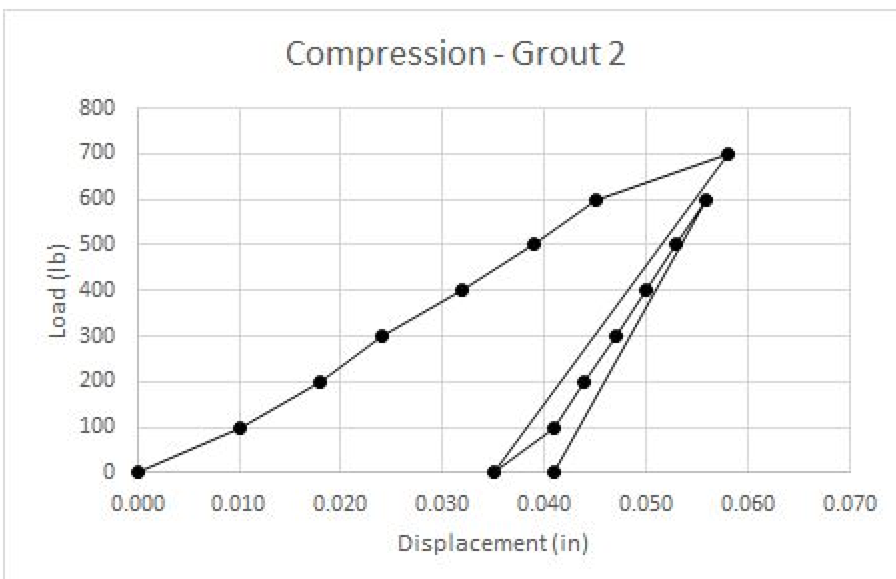
Final Results:

From the graph below, we concluded that the grout specimen performed the best compared to the fine and coarse aggregate. The grout specimen begins yielding around 600lbs while the fine and coarse aggregate begins yielding around 300lbs and 250lbs respectively. The fine aggregate and grout follow the same elastic curve as each other, however the fine aggregate specimen yields at a much lower force than the grout specimen. We found there to be a similar slope in the fine aggregate and the grout to be due to the fact that the fine aggregate is what was used in the creation of the grout specimens. As we had predicted, the grout material was able to perform significantly better than the fine and coarse aggregates in terms of ultimate loading capacity. However, the fact that the fine aggregate was able to hold the same stiffness as the grout material shows that it holds some significant quality of being an energy dissipating system. The coarse aggregate showed results that not only were weaker than the other two, but held much poorer properties. It remains a much less capable system, but is also able to provide some significant resistance. I would not overall count this out as a usable mechanism for future mechanisms.



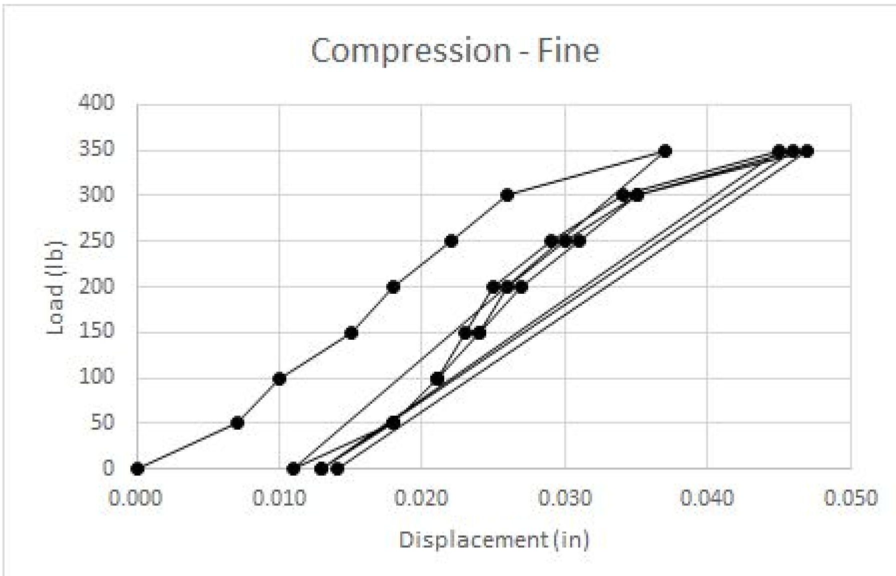
Graph 1: First Yield of All Specimens

Grout 2 shows a large displacement on the first segment of loading, followed by little displacement from then on. The large initial displacement is likely due to the fact that upon loading the system, the materials took some time to set into place before distributing the loads appropriately. After the initial loading, the stiffness of the specimen increased greatly. This would explain the great increase in displacement on the system after the first segment of loading from an initial state of 0” displacement to 0.035”. This could also be explained as the grout material actually having initially bonded to the rods encased. In that case, the initial loading on the specimen would have to be extracted from the analysis and the secondary loading would be our primary focus. In that case, the grout material would not only have provided a significantly greater compressive capacity than the other two specimens, but also would hold a much greater stiffness as well.

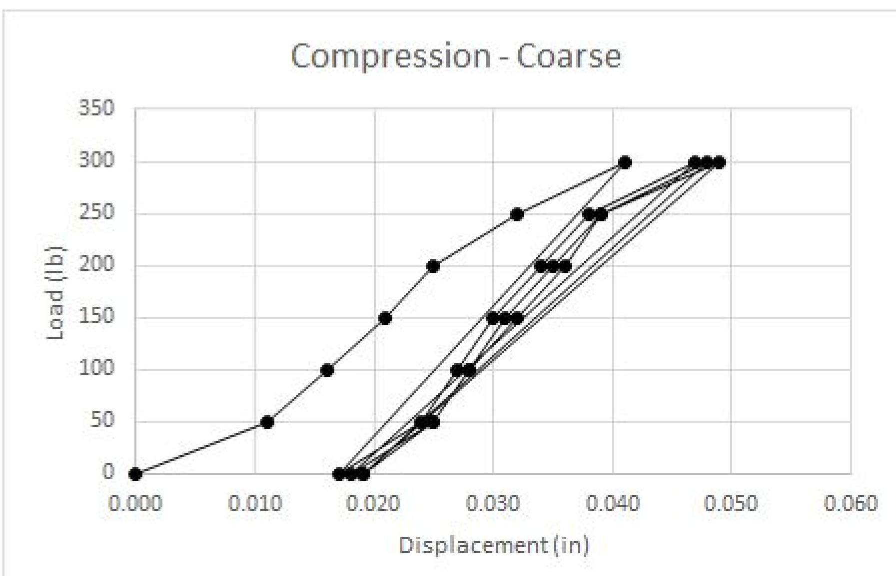


Graph 2: Grout 2 Specimen

Unlike the grout specimen, both fine and coarse aggregate show no change in stiffness between load tests which indicates proper set-up in the Riehle machine. Both aggregates have similar displacement patterns to each other, however the coarse aggregate deforms more than the fine aggregate. The coarse aggregate also yields at a lower force than the fine aggregate, while also deforming less than the fine aggregate past the yield point.



Graph 3: Fine Aggregate Specimen

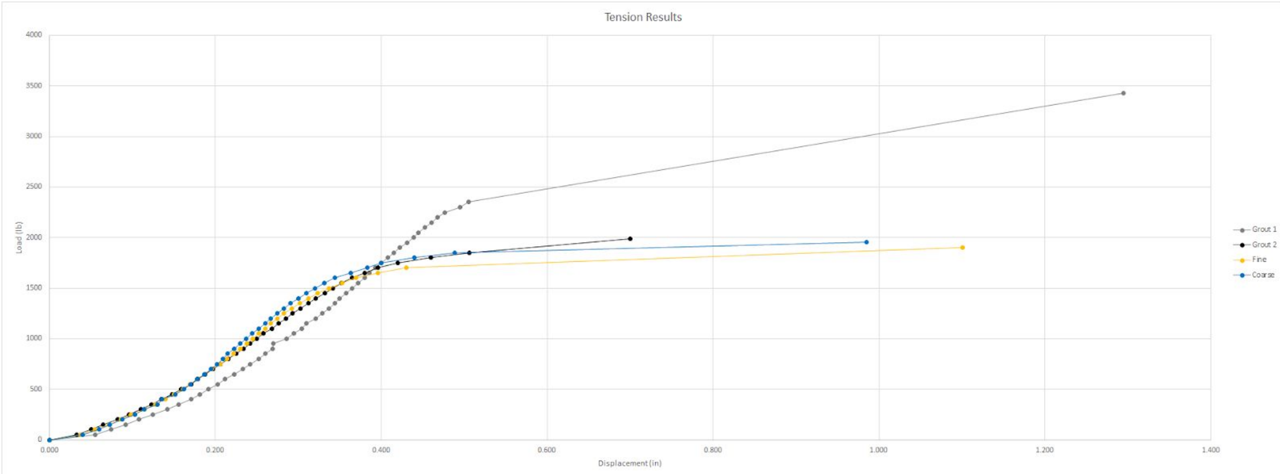


Graph 4: Coarse Aggregate Specimen

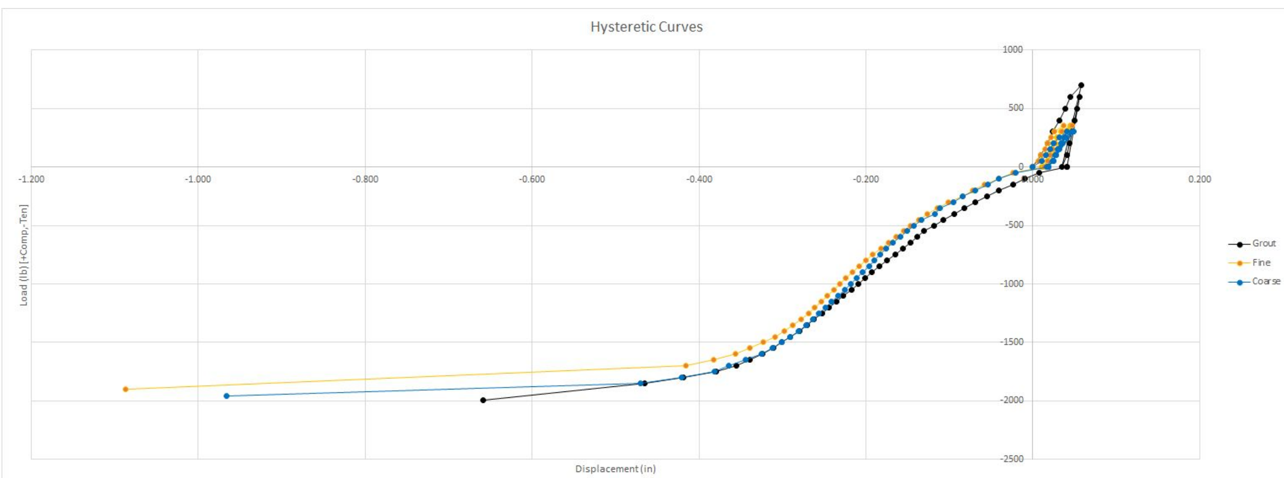
After testing for compression, we analyzed the tensile capacities of the systems. What we noticed was that there is no significant difference between the tensile capacity of the different BRB specimens. However, a common failure mechanism between each specimen was that the rod broke near the "joints" of the BRB.

Tension Rupture Locations for the Test specimens

Unlike an ideal BRB, the encased portion of the rods were not reduced compared to the exterior, therefore the location of failure were not controlled to be in the middle of the BRB. Although this had little effect on the results of the compressive capacities, it was reason for our tensile capacities to be relatively flawed. Another important thing to note is the tensile capacity of the grout 1 specimen. Due to the significant higher ultimate tensile strength of the rod, it became known that the grout 1 specimen used a steel rod instead of a zinc rod. Therefore, data from the grout 1 specimen was excluded in the overall analysis and comparisons.



Graph 5: Tension Testing



Graph 6: Full Force-Displacement Diagram

Sources of Error:

One of the possible sources of error is in the creation of the axial testing components. The alignment of the bottom and top plates are not certainly centered, therefore having some accidental eccentricity in the loading of the specimens is quite possible. This would allow for the members to buckle at a lower load than expected. However, as these force values may be skewed, they all underwent the exact same procedure so their values are still reasonable to compare. Another source of error existed in the precision of our values. The forces were read on a dial, while the deformations held a precision of the nearest thousandth of an inch. The deformations were so small that at least one more significant figure would have been good to track a more distinct force-displacement curve. Another source of error would be the usage of PVC pipe as the ultimate encasement boundary that we used. This material, as capable as it was to hold the encasement material in place, also exhibited elastic properties. That being said, it showed some give to buckling during our tests. If given the chance to go back and change the setup, I would have probably pursued a much stiffer exterior member than PVC. We also would have probably gone with full steel rods to see a lot more of the action being put in the encasement materials and to have very little worry as to the rod exhibiting failure mechanisms on us. Furthermore, we would have liked to use a method of debonding that was much more efficient than the grease. We believe that the rods were still able to bond to the encasement grout material which had effects on our initial data prior to debonding during loading.

Conclusion:

Given the results, the grout specimen is able to perform significantly better than the other two specimens. However, this does not rule out the usage of the other two aggregate materials as a potential for usage in projects that don't necessarily need such a significant load resistance. The fine aggregate was able to hold a similar elastic stiffness to that of the grout, leading us to believe that the aggregate in each system is pertinent to the stiffness of encasement on the slender rod inside. The factor that allowed for the higher loading capacity would be the bonding cement material that provided properties of preventing the aggregate from splitting away from each other under significant stress. The coarse aggregate performed poorly in comparison leading us to believe that a finer aggregate material is much more capable of remaining stiff to the stresses that is undergoes. The coarse aggregate also shows large initial displacements in the first loading scenario leading us to believe that it has a very high potential for slippage when given stress. We believe that this is due to the significantly low density of the material and the possibility for large air pockets to make way for the material to move to.

Future Impacts:

The concept of a BRB system is still young to this world, as is many of the lateral force resisting systems out there. The potential to extend this project further into research is still very open to optimization and testing to provide a greater understanding and ultimately be able to see the versatility in the system as structural engineers look to customize their lateral systems to the needs of their specific project. To anyone looking to further research on this concept, an idea that would be great to seek out are the different qualities of bonding materials in the aggregates. We have an understanding that cement is a very strong bonding material and is very unlikely to give way under significant stress. However, other bonding agents such as lime is something that could one day be pursued.