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Accessible Methods, Novel Arrangement: Developing Self-Centering Composite Structural Frame Systems for Highly Resilient Buildings

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Honors Thesis

ACCESSIBLE METHODS, NOVEL ARRANGEMENT:

DEVELOPING SELF-CENTERING COMPOSITE STRUCTURAL FRAME SYSTEMS FOR HIGHLY RESILIENT BUILDINGS

by
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ABSTRACT

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The benefits of self-centering systems for increasing building resilience are well documented and widely known. These systems are added to buildings to bring them back to “plumb,” or upright, position in the event of an extreme event. Benefits of their use are thus most notably that self-centering systems cut down on the repair, downtime, and/or demolition costs incurred after a structure encounters an extreme event. However, they are sometimes not used due to higher up-front costs incurred by the use of unconventional materials, methods, and construction details. This study developed a self-centering frame system that builds on established methods and utilizes common materials and standard construction details. The new system has the potential to make self-centering systems more affordable and accessible, encouraging the adoption of self-centering building designs.

This study explores the results of three tests run with the goal of designing a low-cost self-centering frame system in mind. Each test uses a slightly different iteration of the system developed, and each shows the results of that iteration from the perspectives of resilience, cost, and overall effectiveness of the system in withstanding extreme events. Successful concentration of damage into easily replaceable parts and self-centering of the structure was observed, as was cost reduction. The developed system is thus a viable one. This system should further the goal of developing civil infrastructure that is safer and less prone to damage when subjected to extreme events. Industry support is also anticipated due to the accessible nature of this system. Results of this research are specific to the system developed but could inform further research into innovative configurations of standard materials.

Keywords: self-centering, seismic design, restoring force, hysteretic behavior, resilient structural system

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CHAPTER 1. INTRODUCTION

This chapter defines the motivation for, objective, and scope of the research. The chapter also provides a summary of what is included in the report.

1.1 Background

In the construction of steel-frame buildings, moment frames are desirable for the preservation of building integrity in the event of an earthquake or windstorm. It is well known that the addition of self-centering technology to a moment frame reduces the risk of a building needing to be completely torn down due to residual drift should it undergo intense stresses. It is also well-known that within the development of self-centering beams, a concentration of damage into easily replaceable parts is desirable. However, there are a wide variety of approaches to the issue of developing effective self-centering buildings. Some of the parameters with which all approaches grapple (with the general benefits and effectiveness of self-centering beam systems borne constantly in mind) are:

- Uncommon field construction methods and materials
- Reconciliation of the self-centering (SC) system and the diaphragm (Maurya and Eatherton 2016)
- Cost efficiency

This section will explore how different approaches to the development and implementation of self-centering technology address these three issues. It will also consider the methods implemented by pre-existing systems for self-centering in order to:

- Self-center buildings; and
- Concentrate damage into easily replaceable parts

After reading this section, the reader should have a greater grasp of the issues facing the development of self-centering systems as well as an idea of the breadth of solutions already proposed.

1.1.1 The Need for Earthquake Resistance

It is of particular note that this research, while intended to benefit the world at large, is being conducted in America. Nearly half of all Americans are exposed to potentially damaging earth movements (USGS 2021). Such "damaging earth movements" as those described by this statistic tend to have a few distinctive effects on the areas in which they occur. When an earthquake hits a building, it applies a force to the base of the building, pumping energy up through the building's frame and leading to violent shaking. As this energy travels throughout the building, it is dissipated by damaging the braces, beams, and other elements of the building's frame. In other words, the earthquake causes significant damage to the affected building. Assuming that this damage doesn't harm the building to the point of requiring a teardown and rebuild, it typically takes significant amounts of time and money to repair. And yet, even in California, where a large proportion of those Americans exposed to such earthquakes live, only 2 of 10 homes and 1 of 10 commercial buildings have earthquake insurance (Fuller et al. 2020).

What's more, a recent federal study found that a full quarter of buildings in the Bay Area alone would be significantly damaged by a magnitude-7 earthquake (Fuller et al. 2020). This doesn't include the other 95% of California, which is riven by nearly 16,000 known faults and more than 500 active faults, with most residents living within 30 miles of an active fault risk (CEA 2020).

The majority of buildings in the United States that are constructed in earthquake-prone areas are called "moment resisting frame" buildings. These buildings fall in line with the human life section of current ASCE (American Society of Civil Engineers) standards, which call for a reduction in earthquake risks in order to mitigate "[devastation] to human life, infrastructure, and economy" (ASCE 2018). These buildings are designed to keep the people inside of them safe using engineered beam-column connections, and they do so effectively. Moment resisting frames will not collapse on top of residents in an earthquake scenario. However, these frames are prone to significant amounts of damage in important structural elements such as beams, columns, and the concrete core of the building—elements that are difficult to replace. Additionally, these buildings often hold "residual drift" after an earthquake, a phenomenon in which a building is left leaning as a result of an earthquake's shaking. If large enough levels of residual drift are present, the building must be completely torn down. While moment resisting frame buildings are safe, they are not sustainable. What's more, while not as expensive to construct as more fully earthquake-proofed buildings, they tend to incur high costs in repair and/or teardown and rebuild after an earthquake. Moment resisting frame buildings do not adequately fulfill ASCE's admonition to mitigate earthquake impact on infrastructure and economy.

Several methods for earthquake resistance are available—all of which are more expensive to construct than a typical moment resisting frame building (Huang et al. 2018). While the "pay-off time"[1] of many of these buildings generally falls within the building's standard service lifetime, the extra up-front cost still makes for a hard sell. A federal study in Memphis, Tennessee, even concluded that the economic benefits to earthquake-resistant buildings were not worth the initial investment (NIST 2016). Additionally, the uncommon construction methods often associated with earthquake-resistant buildings are intimidating and difficult to complete (Maurya and Eatherton 2016). Thus, although the benefits of earthquake-resistant buildings are well-documented (Herning et al. 2009), they are rarely used in practice, and moment resisting frames are widely favored.

The United States in general suffers from a relative lack of concern for earthquakes, with not only more lax seismic building codes than other countries but fewer earthquake-resistant buildings constructed on average (Fuller et al. 2020). This may be due in part to the cost premium in labor and materials alike associated with constructing earthquake-resistant buildings. As such, this system has the potential to highlight the way forward for earthquake-resistant construction in this country.

1.1.2 Self-centering Defined

The first order of business in a discussion of self-centering beam systems is to define "self-centering." Self-centering is a term used to describe engineered elements which create a couple to maintain the effect of a moment frame via connections between columns and beams and post-tensioned elements. In other words, via self-centering, all of

[1] "Pay-off time" is defined by Qindan Huang, et al. as the time when the extra upfront cost of an earthquake resisting building is paid off by mitigating seismic loss over time.

the earthquake-resisting and safety benefits of a moment frame are preserved and, additionally, the building is brought back to plumb position after an extreme event. This is generally achieved by allowing a gap to form somewhere in the building's frame, and then employing post-tensioning to create a couple that closes the gap. The damage that, in a normal moment frame, would run along beams and columns is concentrated into easily replaceable "fuse" elements.

With a basic understanding of what is meant by "self-centering," the issues facing the development of self-centering (SC) beams take on a new importance. These issues are discussed in the sequence mentioned above.

1.1.3 Uncommon Field Construction Methods and Materials

It is an unfortunate reality of SC systems that at least one piece of uncommon field construction is almost always going to be included, namely, post-tensioning (PT) procedures. In SC systems, gaps are allowed to form between the beam and column as earthquake-type forces are applied, which are then closed using steel post-tensioning strands or bars. There are several different gap-formation methods, including at the base of a frame; at beam-column joints; and between telescoping concentric tubes and anchorage plates (Maurya and Eatherton 2016). In all of these methods, the most common practice is to use steel post-tensioning elements to close the gap, or, in other words, to self-center the frame. (It is worth noting that some SC systems rely on shape memory alloys or gravity loads (Maurya and Eatherton 2016), but as these both comprise or entail uncommon field construction methods or materials of their own, they will not be discussed in depth as a method/material to be addressed.)

As mentioned, one of the ways in which gaps are formed in SC systems is by allowing a gap to form at the base of the building frame. To close this gap, several vertical PT strands are placed either at the center of the frame or at the column lines. The steel frame rocks back and forth as a result of the lifting of one side of the frame and the PT system's pulling it back to plumb position. This in and of itself is, naturally, an uncommon field construction method, and would be difficult to adapt to shop construction. There is also the conscious allowance of rocking to contend with, as this (thankfully) is not a typical part of building construction. Finally, the fuse plates are placed either at the base of a single rocking frame or between two rocking frames. This, too, comprises an uncommon field construction method (Eatherton et al. 2014).

One way in which the developers of SC systems attempt to circumvent setting post-tensioning strands and/or bars in the field is to rely on shop fabrication, thus increasing accessibility for the construction industry. The self-centering beam (SCB) system developed by Maurya and Eatherton is an example of this approach. It is true that more conventional field construction methods can, in general, be implemented if putting this system into a building. Thus, one of the issues of uncommon field construction is circumvented. However, in this SCB system, a claw or finger joint is used to connect the beam and columns. This joint was created in-shop and, while an effective method for allowing vertical movement of the beam-column connection, is not therefore a common construction material. Custom coping on both sides of the beams is required in this method to house a second pin connection at the bottom of the beam and the self-centering technology that this method utilizes. That technology comprises two concentric tubes, a free-floating anchorage plate, and post-tensioned strands. These tubes are themselves uncommon materials, and their installation on the moment frame would require somewhat specialized construction methods (Maurya and Eatherton 2016).

1.1.4 The SC System and the Diaphragm

As mentioned in the previous section, SC systems rely on steel post-tensioning strands or bars as one half of a couple that functions as a restoring force mechanism. The other side of the couple comes from the gap that is allowed to form between pre-compressed elements when an earthquake or windstorm force is applied to the system. There are a wide variety of methods for forming this gap, and it is in the formation of this gap that incompatibilities arise between the SC system (comprising the beams, columns, and PT strands) and the diaphragm (or gravity framing, for our purposes comprising mainly floor systems). Thus, as a precursor to discussing the ways in which given SC systems address the issue of beam expansion vs. diaphragm expansion, the SC systems themselves (or the gap allowed to form) must be further explored.

In SC systems using vertical PT strands and rocking, compatibility issues between the SC system and the diaphragm are nowhere to be found. This is because the diaphragm rocks along with the beams and columns, as one unit (Eatherton et al. 2014). It is rigid at the connection points, and so there is no difference in the damage done to the beams and that which the floor system sustains.

In one of the newer SC systems, the gap is formed at the bottom of the beam—and hardly has any impact on the beam-column system itself at all. In the system researched by Maurya and Eatherton, the gap opening is relegated to the two concentric tubes which are allowed to slide relative to one another as the building uncenters and recenters itself. A bit of coping at the bottom of the beam allows for the free-floating anchorage plates to move back and forth from their neutral position, or where they lie when the building is in plumb position.

The benefit here, as far as the compatibility of the SC system and the diaphragm goes, is that the beam itself does not help form the gap. This SC system was shown to have a very large deformation capacity (up to a 6% story drift, with no damage to end connections, the SC body, or columns (Maurya and Eatherton 2016)), and the design itself "eliminates deformation incompatibility with the gravity framing system" (Maurya and Eatherton 2016). While the tests conducted on this SCB did not include a floor system, the conclusion remains reasonable when examined bearing the reasons for deformation incompatibility, (e.g. the floor system is more rigid than the frame and/or doesn't allow for movement of the frame) in mind.

1.1.5 Cost

One effective method for reducing the cost of SC systems is to reduce the use of uncommon field construction methods and materials, as more common materials and methods tend to cost less than novel ones. Thus, a creative configuration of pre-existing construction details and methods is ideal. At present, most SC systems rely on at least one unconventional method or material. As mentioned in section 1.1.2, the Maurya and Eatherton system uses concentric, telescoping tubes, the fabrication of which would be quite costly. This system also requires the shop fabrication of finger joints, a more costly endeavor than using pre-existing or commonly used joints. Granted, the researchers for this SCB were well aware of the cost premium the system would carry with it, stating that there would likely be a reduction in cost premium if the SCB was redesigned for production. The system simply was not designed or detailed for economy (Maurya and Eatherton 2016).

Likely, the perceived difficulty in removing fuse plates detailed in section 1.1.6 is the result of this fact.

Another type of system that presents cost and downtime difficulties is that which relies on the rocking of precast concrete walls and braced frames. In these systems, an entire building is constructed to self-center itself, rather than merely the connections between beams and columns being engineered to self-center the building as a whole. This presents quite the cost as construction and design begins. The fuse plates in these systems also tend to be rather difficult to access (almost as difficult to get to as beams and columns, so it seems), which makes replacement of the fuse plates potentially difficult (Eatherton et al. 2014). This, in turn, contributes to the downtime, (the costly shutdown of a building in order to complete repairs), required for a building to recuperate after an extreme event.

1.1.6 Damage Concentration and Replaceable Parts

In standard moment frame buildings, the damage incurred from an earthquake or windstorm is directed through the beams. As the beams reach yield stress, damage occurs, dispensing energy and keeping the building stable enough to be safe. However, the obvious drawback is that the beams are then damaged. Beams are difficult to replace, requiring a good amount of downtime to fix a building back up after it experiences a traumatic incident. If the damage is severe enough, the building may need to be torn down completely. While the people who may have been inside of it are safe, the building is a loss.

Damage to and/or the complete loss of a building is also a risk that must be addressed in developing SC methods. Self-centering systems rely on the formation of a gap somewhere along the joint between beam and column. Without post-tensioning to bring the building back to its original position by closing the gaps, the building would need to be torn down due to residual drift. However, without some other method for damage concentration and energy dispersal, an SC building is exactly the same as a normal moment frame building: the beams will be damaged, downtime incurred, and losses experienced. It is common practice in the development of SC systems to use fuse plates to concentrate damage and disperse the energy of the earthquake or windstorm. These plates are allowed to experience tension and compression as the beams and columns move, and, after the event has passed, are generally able to be easily replaced. It is certainly less costly to replace a small plate than an entire beam, and it would take less time.

However, these fuses are not always easily accessible. While it is still more feasible and practical to use fuse plates than to simply let beams be damaged, inaccessible fuse plates can lower the overall efficiency of an SC system. In rocking SC systems, for example, fuse plates are located either as yielding shear elements between two rocking frames or are simply placed near the base of a single rocking frame, flanking the PT strand. These fuses effectively dissipate the energy acting on the structure, and so limit the forces (Eatherton et al. 2014). They are also replaceable units, which one could, in theory, remove and replace with little issue. The location of the fuses does not seem to completely facilitate easy removal, however, as they are so integrally connected to the very frame of the building they are in.

In the Maurya-Eatherton system, the fuse is connected to the inner tube on one end and to the outer tube on the other. It deforms axially as the tubes shift and telescope, thus experiencing damage and dissipating energy. The damage is concentrated effectively, with the exception of some damage to the post-tensioning strand, which is to be expected and may very well be just another unfortunate given of SC systems. Designers can control only so much of the self-centering capability of an SC system, due simply to the materials one has to work with (Maurya and Eatherton 2016), but the replacement of the fuse plate presents an issue. The fuse is *inside* the outer tube, making it somewhat difficult to access for repair purposes and indicating that a building utilizing this system may incur more downtime than is ideal. This is, again, likely due to the fact that the design is not optimized for economy use.

1.1.7 Self-centering Systems

Here is where the bits and pieces that have been discussed in the preceding sections are brought together to give a brief overview of the self-centering systems currently in use or development in the industry. To begin, look to Maurya and Eatherton. The self-centering beam (SCB) they developed creates a couple in the usual way: with a gap and post-tensioning (PT) strands. The gap and PT strands are contained in two concentric tubes, with the larger one welded to the bottom of the beam. As the system moves, the inner tube (connected to the columns), moves relative to the beam, and thus the gap (the compression component of the restorative couple) is formed. The beam is coped at the bottom corners to allow the gap to form, as in this way the free-floating anchorage plate is able to slide easily over the brace connection. The PT strands strung through the tubes provide the final, or tensile, component to the moment, restoring the columns to plumb position. The damage is concentrated into energy dissipation fuses within the tubes, one end connected to the inner tube and one end to the outer tube. Thus, as the tubes move, the *fuse* is damaged rather than the beam, columns, or SCB system. The beam and column are connected by a finger joint at the top of the beam, (which allows for some rotation), and a shear tab with elongated slots, (which allows for some lateral movement and rotation). This is a more novel SC system, and one that has not yet been optimized for industry use or production (Maurya and Eatherton 2016).

Another system which has been heavily researched includes rocking steel frames and/or concrete walls. In these systems, the post-tensioning strands run parallel to and within the walls rather than along the beams. The gap is formed at the building's base, and fuse elements are generally located either as yielding shear elements between two rocking frames or near the base of a single rocking frame, flanking the PT strand. These fuses effectively dissipate the energy acting on the structure, and so limit the forces (Eatherton et al. 2014), but are rather less accessible than they could be. (Interestingly, this type of self-centering has also been applied to mass timber construction with fairly good results (Ganey et al. 2017).)

1.2 Solution

Now, having discussed what an SC system is, it is time to move on to what could be. The system proposed in this study addresses the various problems and difficulties involved in SC systems with one overriding goal in mind: accessibility. As a self-centering beam system is being developed, issues of safety and effectiveness are givens; accessibility is where the greatest difficulty lies. For the purposes of this study, "accessibility" is made manifest primarily by 1) reduction in cost, and 2) use of common materials, standard construction details, and more common field construction methods.

The method in which this new system addresses the use of uncommon field construction methods and materials is ensuring that the majority of the construction utilizes common materials and details such as seat angles, concrete, and cross-laminated timber panels. The concrete flooring system is created and attached to the beam using conventional methods (e.g. headed shear studs and a steel deck), but many elements go through the flooring system to facilitate the self-centering action. Specifically, six PT strands and two struts run the length of the concrete flooring, with the fuse plates embedded into the concrete flooring on either end. To embed these elements, four cuts along the length of the metal decking for the concrete floor are required. Aside from post-tensioning (which, again, is a necessary step in most SC systems), the fabrication of the concrete floor comprises the most "uncommon" method utilized in this system. Shop fabrication might help to alleviate some of the strain on field construction. In particular, the fuse plates can be produced in-shop fairly easily. Notwithstanding some uncommon methods, the materials used to produce this system are commonly seen in construction of steel moment frame buildings without SC technology, and as such do not constitute "uncommon" materials.

As far as reconciliation of the SC system and the diaphragm, the system explored in this study uses a method similar to the SCB developed by Eatherton and Maurya. The newer system sees a gap formed at the top of the beam, between the column and the beam, right near where the PT strands are located. The beam is coped at the top, where this gap occurs, which negates the deformation of the beam as a result of the column's movement. In addition, there is a gap between the column and the beginning of the flooring system (or gravity framing). Thus, here again, the SC system and the diaphragm are compatible. Given that this system builds off of the work done by Maurya and Eatherton, it is expected to have a similar capacity for deformation. It also stands to reason that, with the beam and diaphragm alike unaffected by the column movement, there would be no issue of deformation incompatibility. Granted, this relies in part on the successful engineering of the fuse plates embedded into the flooring system such that the gravity framing will suffer no ill effects from the extreme forces the system will be subject to; but that is a topic to be addressed later.

Mitigating up-front costs is one of the central goals of this SC system. As previously discussed, the system proposed in this study relies on common pieces such as seat angles, copes, slotted shear tabs, and common materials including steel, concrete, and cross-laminated timber panels. Thus, the up-front cost is likely to be reduced. In addition, the placement of the fuse plates has been conceived for the express purpose of easy removal and replacement. They are to be placed vertically in the flooring system, such that replacement will be quick. This will reduce the amount of downtime imposed upon structures using this SC system, proving cost-effective in the long- and short-run alike.

The fuse plates utilized in this system have been mentioned several times already. In order to facilitate damage concentration and easy replacement alike, these fuse plates are to be embedded vertically in the concrete flooring system, flanking the PT strands and struts running through the floor. The concrete will encase the more slender section of the plate, forcing it into high-mode buckling when the plate is in compression. As such, the plates will yield in both tension and compression, taking the damage and dissipating energy. As mentioned in the above section, the orientation of these fuse plates will also ensure that the plates are easily replaceable. What's more, a simple bolted connection is utilized to connect the fuse plates to the columns of the system. This connection is easily created and removed, again facilitating easy replacement of the fuse elements.

Finally, in the method of self-centering which this system proposes, the gap forms at the top of the beam, and the flooring system contains the PT strands which round out the restorative couple. These PT strands will be contained in hollow-structural links in the floor system itself. The flooring system also contains fuse plates, which will absorb the damage caused by the earthquake or windstorm force. The beam and column are connected by a seat joint at the bottom of the beam, (which allows for some rotation), and a shear tab with elongated slots, (which allows for some lateral movement and rotation). Thus, this SC system persists in using common materials and standard construction details, reducing up-front costs while ensuring the longevity of buildings in which it is installed.

1.3 Hypothesis

It is predicted that during this experimentation, an effective self-centering system will begin to be developed. For the purposes of this study, an "effective" self-centering system is one which:

1. Achieves levels of 4% story drift without significant damage to the system.
2. Is able to bring the system back to plumb after reaching 4% story drift.
3. Dissipates energy without damage to the frame or flooring system.

It is also predicted that the system will prove cost-effective and comparatively accessible for contracting and construction purposes. When compared to the concentric-tube system researched by Maurya and Eatherton in 2016, described in earlier sections, this system is predicted to have lower material costs as well as lower labor costs. This is due in part to the fact that this system relies less on shop-fabricated pieces and emphasizes the use of standard construction details.

Finally, it is predicted that the development of this system will represent a step forward in cost-effective seismic-resisting research, as well as a step toward more sustainable building in the United States in particular. Given its higher levels of accessibility in terms of cost as well as construction methods, the system has the potential to be more appealing to contractors and builders in the United States.

1.4 Thesis Organization

This thesis is organized into five chapters:

- Chapter 1 provides the motivation for the research and defines the objective and scope of research. It also provides a summary of what is included in the thesis.

- Chapter 2 describes the process of design for the two frame systems tested for this research, and offers explanation for the choices made in the design. It also provides some rationale for the testing frame and identifies which parts of the frame system were most heavily tested.

- Chapter 3 describes the full-scale test campaign. It describes the methodology, including the details of the frame system preparation and assembly, cyclical loading test apparatus, instrumentation, and data reduction. The chapter also presents the measured and observed results from the cyclical loading tests. Finally, it presents the results of a cost comparison between the system under examination and a comparable system.
- Chapter 4 contains a summary of the test campaign, the analytical study, and the results. Principal findings are summarized, and areas for future research are identified. As this research is intended as a proof-of-concept experiment, an analysis of what changes future researchers might make is also included.

CHAPTER 2. DESIGN OF THE FRAME

This chapter describes the process of design for the two frame systems tested for this research and offers explanation for the choices made in the design. It also provides some rationale for the testing frame and identifies which parts of the frame system were most stringently tested.

2.1 The Self-Centering System

The essential components of a self-centering system are the gap-formation, restorative, and damage dispersing or “fuse” elements. These are the pieces of the self-centering system which, in testing, were under closest observation. The gap formation in the system under study occurs as a result of post-tensioning: of the end plate for the post-tensioning system and the strut design in one case, and at the top of the beam-column connection in the other. As the building moves back and forth, two “wings” or tabs attached to the ends of the struts within the flooring system press against the end plates for the post-tensioning strands, and thus the gap is formed. This arrangement is shown in Figure 1. At the top of the beam-column connection, the gap forms as a result of the movement and the connections used to attach the beam and column to one another. At the bottom of the beam is a standard all-bolted 8”x8”x1” seat angle, which allows for some rotation about the bottom of the beam-column connection. Additionally, the web of the beam is connected to the flange of the column by a slotted shear tab, (see Figure 1), which is welded to the column and bolted to the beam. The slots in the shear tab provide for additional rotation, and thus the gap at the top of the beam-column connection forms.

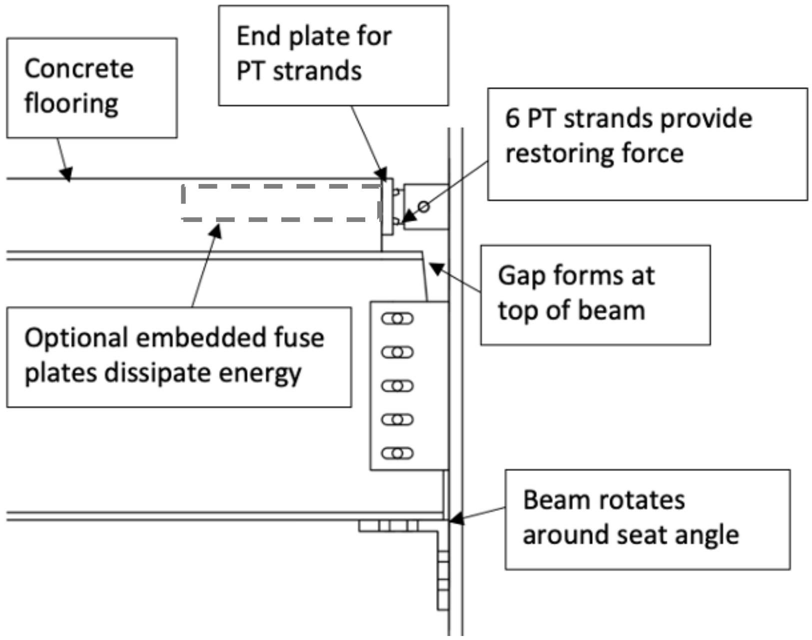

Figure 1 Diagram of the self-centering system beam-to-column connection.

The restorative force is provided by a series of post-tensioning strands which run the length of the flooring system. They function much like a rubber band, pulling the building back to its starting, plumb position after being stretched by the seismic force. In the self-centering system, the free-floating plates at the ends of the floor slab act as the fingers, stretching the post-tensioning strands apart. The movement of these plates is caused by the sliding of the struts running along the length of the floor slab and bolted to the columns of the framing system. Small tabs welded onto these struts (see Figure 2) hit and push out the plates, to which the post-tensioning strands are anchored to. Thus, the "gap" is formed and the strands engaged, enabling them to pull the system back to plumb position after the seismic force has passed. (See Figure 6 for a visualization of this force transfer.) Due to the different widths of the two flooring systems, six post-tensioning strands were used in the concrete flooring system while only four were used in the wood flooring system. In placing these strands in the concrete flooring system, consideration was given to the need to allow concrete to flow around the casing for the post-tensioning strands. The strands were layered such that there would be sufficient space between and around them for the concrete to flow around the form.

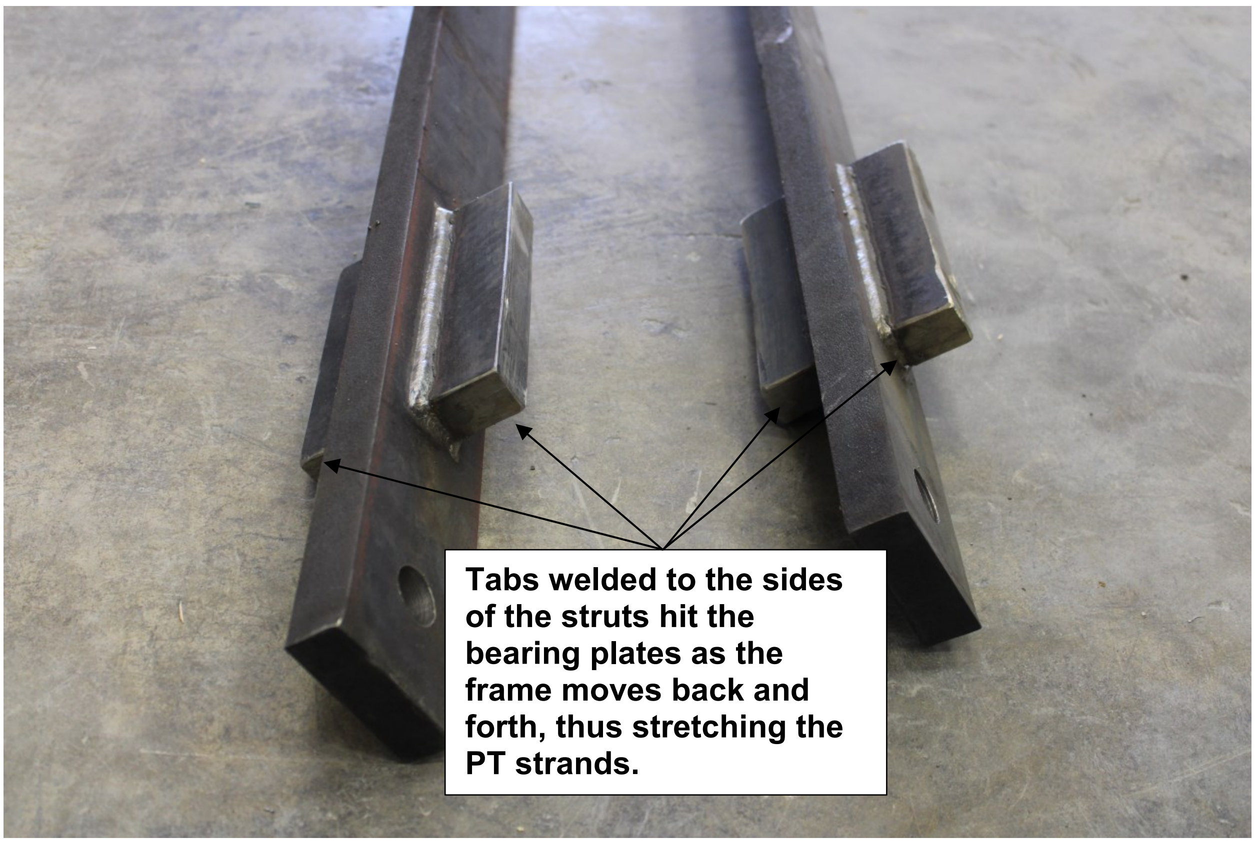

Figure 2 Tabs welded onto the struts.

Finally, the damage-dispersal or “fuse” elements of this system come in the form of z-shaped steel plates, shown in Figure 3. These elements are designed to be lowered into slots cut in the flooring system and bolted to the flange of the columns. Sections on each fuse plate narrow to only three inches wide, and are therefore much weaker than surrounding steel and flooring. As the building moves, they are stretched and the narrow sections are damaged. After a seismic event, these elements can be unbolted, slid out of their slots, and replaced easily. The basic layout of these elements was the same for both the concrete and wood flooring systems. For the layout of the elements within the flooring system pre-concrete pour, see Figure 4. For a view of the beam-column and strut-column connections, see Figure 5.

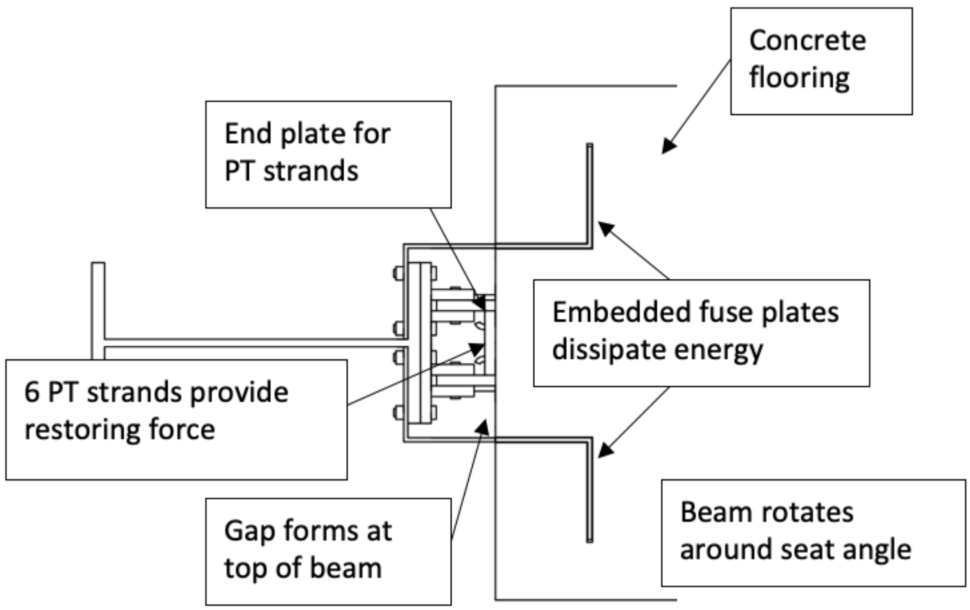

Figure 3 Plan view of the self-centering system.

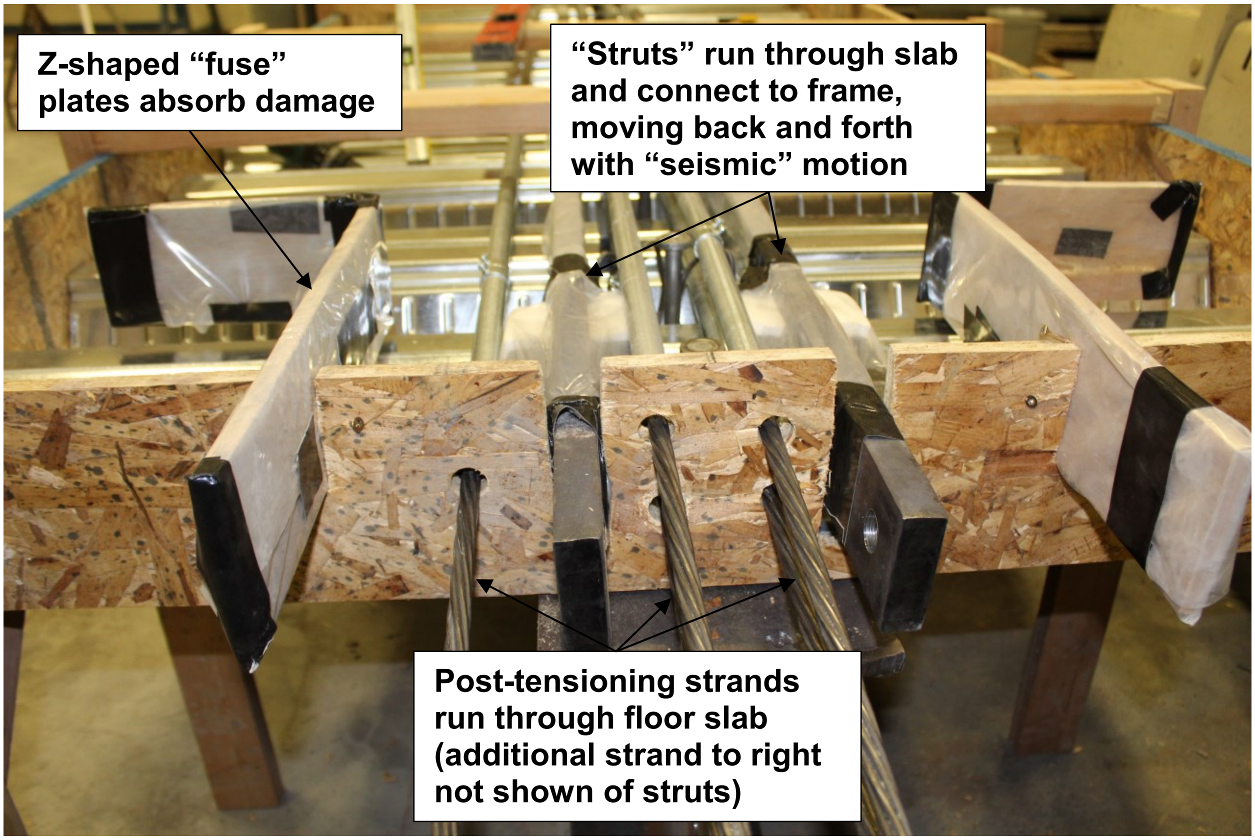

Figure 4 Layout of post-tensioning elements prior to pouring the first concrete floor.

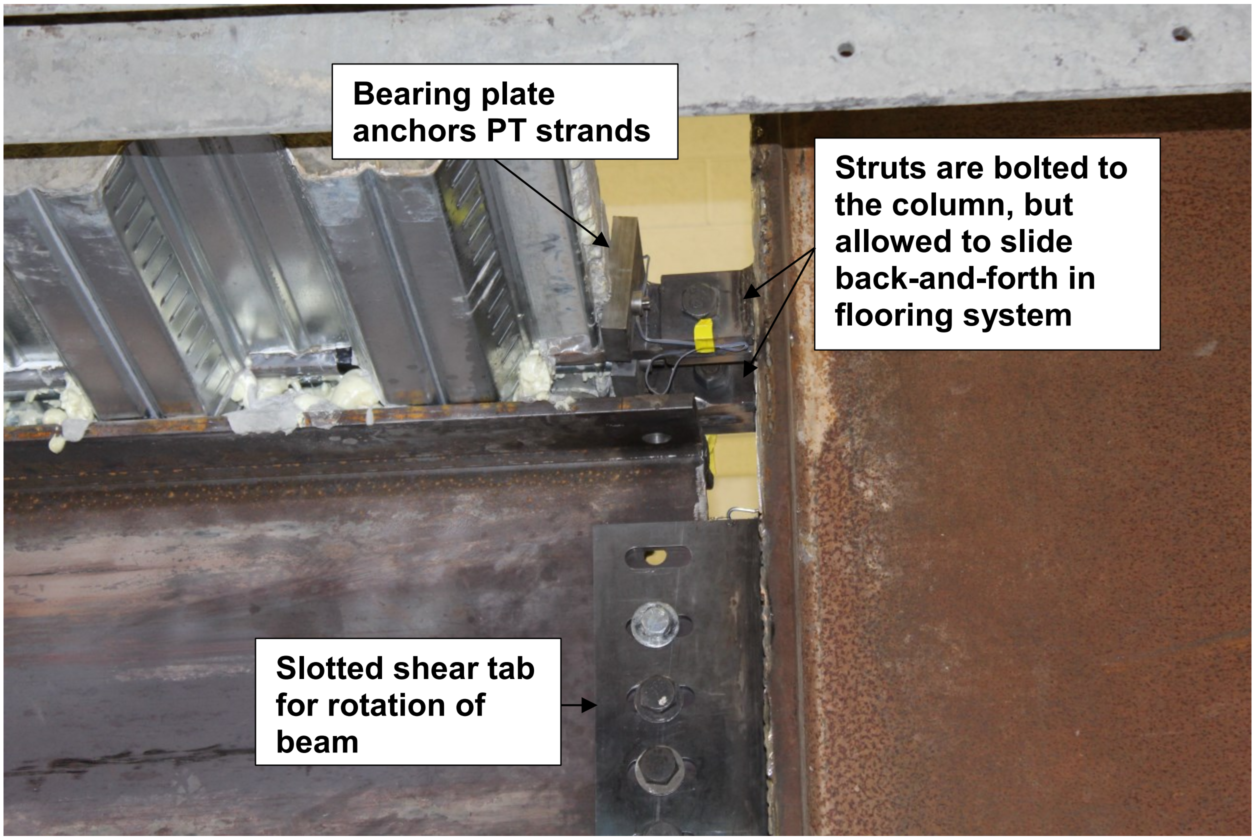

Figure 5 Beam-column and strut-column connections.

The design of the frame had to be modified from the example steel moment frame in AISC 341-16 Chaps. E, F, on which it was originally based, due to the constraints of the testing facility and availability/cost of materials. The basic frame consisted of a one-story one-bay steel moment frame with a W24x76 A992 beam and W30x191 A992 columns. While the beam size is the same as that specified in the AISC Seismic Design Manual, the columns were sized up. However, the target flexural strength of the beam-column connection was not altered, remaining at 249.3 kip-ft, and the columns used in testing had the same flange thickness as the ones in the manual. As such, the design and sizing of the elements was the same. It is also worth noting that the flooring systems ended up being several feet shorter than the frame in the seismic construction manual, possibly leading to non-conservative results during testing (e.g. the struts may be more prone to buckling if longer).

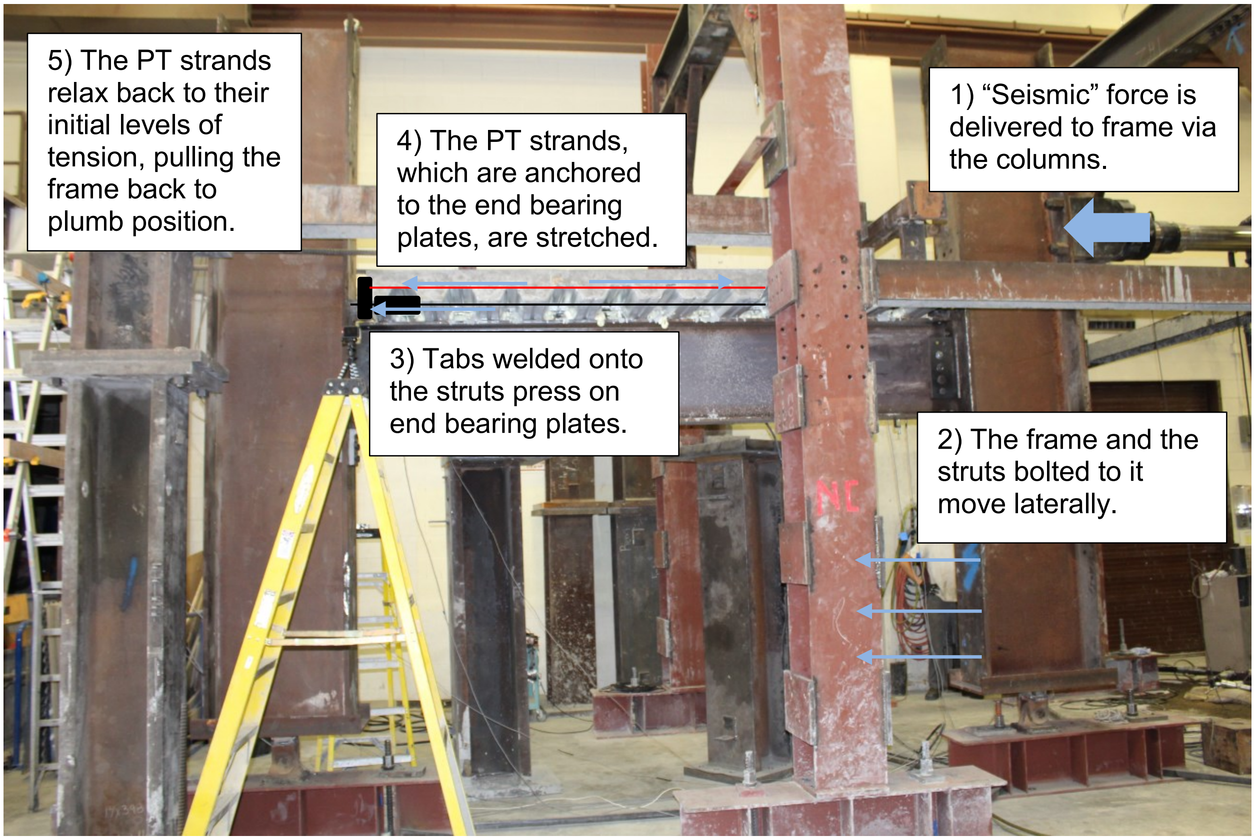

Figure 6 Force transfer and mechanisms of the self-centering system.

2.2 Concrete Floor System

Light-weight concrete with a specified compressive strength equal to 4 ksi was used to construct the concrete floor system. The base of the floor was a three-inch, 18-gage metal deck, which was fastened to the top flange of the beam using 5/8" diameter by 5-3/16" long headed shear studs. The decision to use a metal deck in the concrete flooring system, rather than no deck, was reached due to the emphasis on this research on incorporating traditional construction methods and materials. A metal deck and HSA studs is the typical system for securing concrete floors to beams, so that is what was used in this design. The floor was designed to contain two struts, the fuse plates, and the post-tensioning strands. Thus, in designing the concrete flooring system, it was imperative to leave enough concrete above the struts to prevent them from buckling upwards when stressed. It was decided that leaving one inch of concrete above the struts would be sufficient to restrain them from above. However, to withstand a moment of 120 kips, these struts had to be three inches tall and one inch wide. This necessitated cuts to the metal decking for the concrete floor, which allowed the struts to sit with one inch of concrete above them and, below them, some space to move up and down during testing. Cuts were also made for the lowest two post-tensioning conduits to sit in. While these cuts are not a typical part of concrete flooring construction, they were not considered difficult to do by the lab techs who completed them, and did not take too much time.

It is important to note that the geometry of the elements inside of the flooring system was carefully considered in development. By putting as many elements as possible in the flooring system, the system is simplified and made more viable in construction. However, it does lead to some congestion at the ends of the flooring system closest to the column connection, hence the consideration afforded to the placement of elements within the system. This is shown in Figure 1 It also led to congestion at the column-strut connection itself. A simple bolted connection between the struts and tabs welded to the columns was used, rather than a direct weld between strut and column, to facilitate rotation of the column while the struts remained roughly horizontal during testing. But, as seen in Figure 1 and discussed in section 3.5.1, the presence of the strut tabs led to congestion of the space between the flooring system and the column, and the column flange alike. A picture of the completed full-scale model is given in Figure 7.

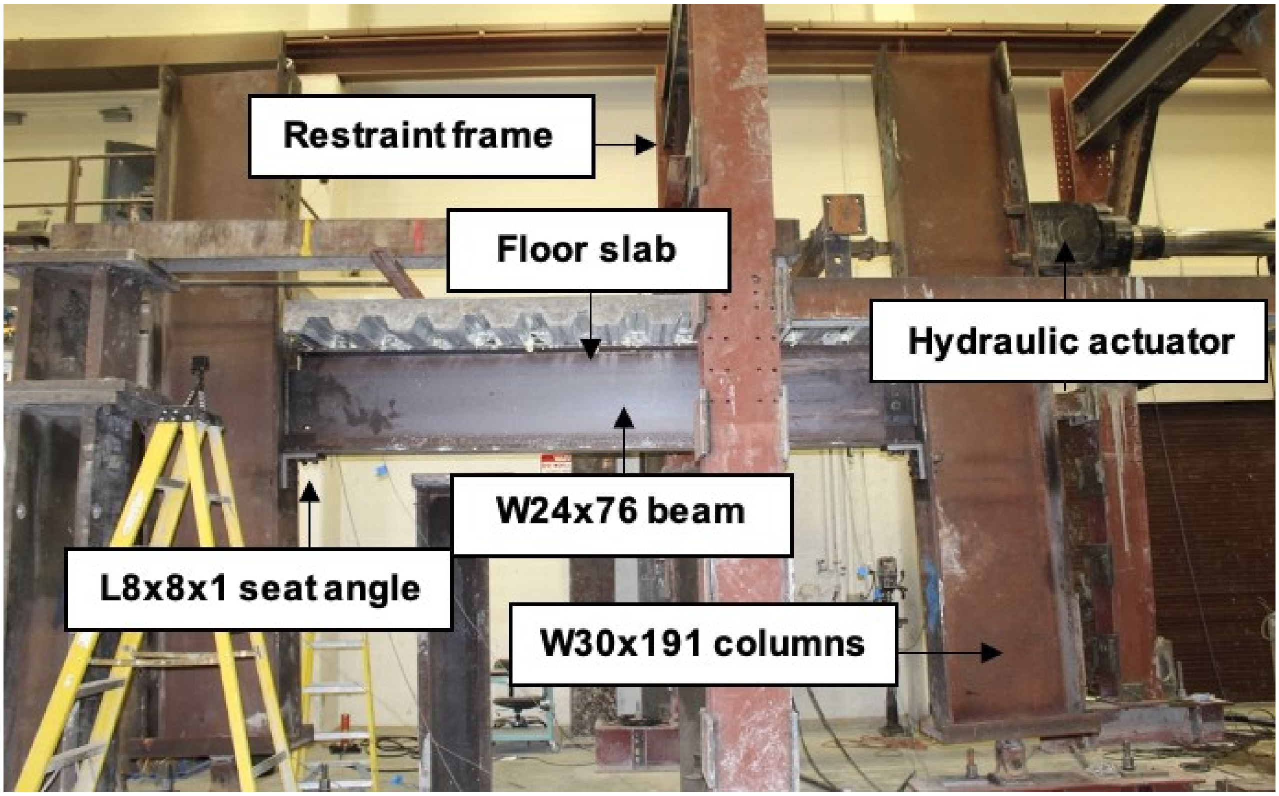

Figure 7 Concrete flooring self-centering frame system.

For the initial test of the frame with the concrete flooring system, three 8-inch tall, 4-inch diameter cylinders were poured at the same time as the concrete flooring system, using the same concrete mix. The cylinders were able to cure for the same amount of time as the floor, (28 days), and were then tested in the customary fashion, loading at 0.2 inches per minute. Figure 8 shows the concrete samples before and after testing. Table 1 shows the results of the tests.

Table 1 Results of concrete strength tests, first test

Test No.	Yield Strength (lb)	Yield Strength (kips)	Cylinder Area (in^2)	Yield Stress (psi)	Yield Stress (ksi)
1	57665	58	12.56	4591	4.59
2	60450	60	12.56	4813	4.81
3	37255	37	12.56	2966	2.97

Pre-Test Post-Test

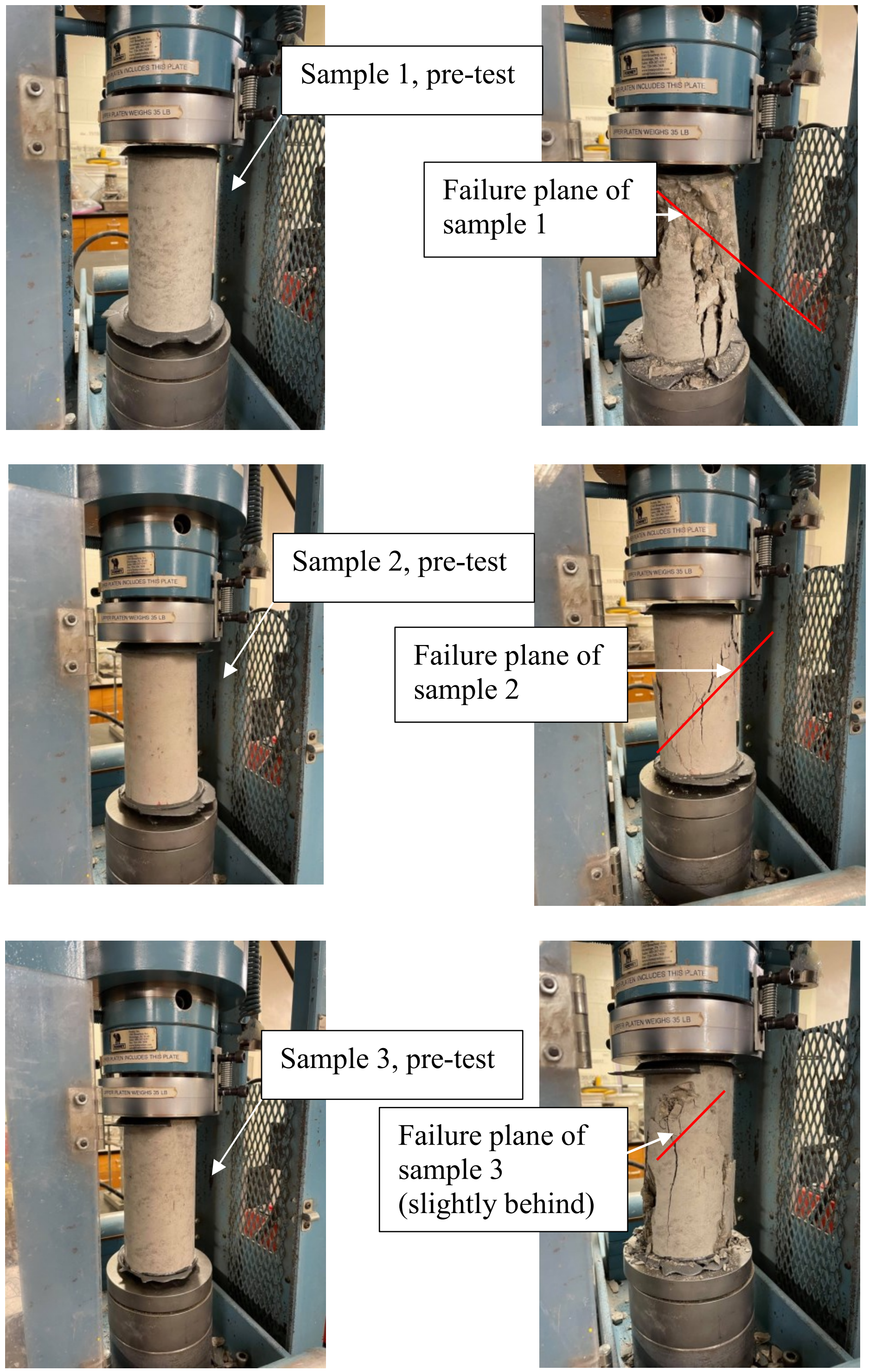

Figure 8 Pictures of concrete samples pre- and post-yield

In our analysis, it was ultimately decided to remove test number three as the sulfur cap on this sample was a bit uneven on one side. We did our best to compensate for the incongruity when testing the cylinder by tilting the machine base. However, the fact of this specimen's yield strength being significantly lower than the other two leads us to believe that we were unable to fully compensate for the previously incurred user error. As such, this test was thrown out of our final analysis, the results of which are tabulated in Table 2.

Table 2 Analyzed results of concrete strength tests, first test

Avg. Yield Strength (lb)	Avg. Yield Strength (kips)	Avg. Yield Stress (psi)	Avg. Yield Stress (ksi)
59058	59	4702	4.70

These results are consistent with what was expected of the concrete, and, as the average yield stress is greater than 4 ksi, the concrete is sufficient for our purposes.

For the second test of the frame with the concrete flooring system, the concrete was significantly weaker. This is likely due to the fact that concrete was being poured for several projects on that day, which could have led to less careful mixing. The results of the concrete strength tests are shown in Table 3.

Table 3 Results of concrete strength tests, second test

Test No.	No. Days	Yield Strength (lb)	Yield Strength (kips)	Cylinder Area (in^2)	Yield Stress (psi)	Yield Stress (ksi)
1	27	33990	34	12.56	2706	2.71
2	27	37320	37	12.56	2971	2.97
Average	27	35655	36	12.56	2839	2.84

As shown by this table, at just one day shy of the typical 28 days that concrete takes to fully cure, the second batch of concrete was 40% weaker than the first. This difference was an important factor to consider as we analyzed the results of our second test with the concrete flooring system in place. It is also worth noting that the second test began when the concrete had been curing for 25 days, meaning that the concrete would have been slightly weaker.

2.3 Wooden Floor System

The design of the wooden floor system was undertaken primarily by Tate Baird and Ethan Brown. This flooring system was primarily constructed using cross-laminated timber blocks from the structures lab which had previously undergone strength testing for a separate research project. These blocks were attached to the beam by screws, and not connected to one another due to time constraints. This flooring system needed to house all of the same elements as the concrete flooring system, minus the fuse plates and two post-tensioning strands. Cuts for the struts were made in the bottom of the blocks, and the blocks were then lowered over them and the other internal elements. As such, the addition of metal fins to the beam below the cuts, (see Figure 9 of the wooden floor system), was necessary to restrain strut buckling in the downward direction. Finally, the wooden floor system was narrower than the concrete flooring system, and didn't include cuts for the fuse plates. Aside from the flooring system itself and the changes detailed above, no changes were made to the basic frame in the construction and testing of the wooden floor system.

This test employed glued laminated timber blocks made from Douglas Fir (*Pseudotsuga menziesii*) for the flooring system, simply because this material was on hand in the lab. For this material, the compressive strength for short-term loading is 2.56 ksi (AWC 2018).

Figure 9 Bottom of the wooden floor used in the wooden flooring system

CHAPTER 3. FULL-SCALE TESTS

This chapter describes the full-scale test campaign. It describes the methodology, including details of the concrete and wooden floor system preparation and assembly, instrumentation, and data reduction. It also presents the measured and observed results of the quasi-static fully-reversed cyclic loading protocol and the results of cost comparison.

3.1 Methodology

3.1.1 Assembly Details

Assembly of the frame took place over several months. The first step was acquisition of the required materials, as detailed in the Appendix. Based on drawings produced in AutoCAD by the researcher, and on markings made by the researcher on the various steel components, lab technicians cut, welded, and assembled the steel frame. They also made the necessary cuts to the steel decking and poured the concrete for the concrete flooring system, and made cuts in the cross-laminated timber blocks for the wooden flooring system.

Once the basic frame was constructed, assembly of the concrete flooring system took longer than that of the wooden flooring system simply due to the curing time required for the concrete floor. Assembly of the wooden flooring system was accomplished over a span of a few days.

One of the most important parts of assembly was the post-tensioning of the post-tensioning strands. This is also one of the aspects of our research that was different between the several tests. For the first test with the concrete flooring system, an Enerpac air-powered hydraulic pump was used to post-tension each strand. The strands were tensioned up to 20 kips, and then naturally relaxed down to 12.5 kips for each strand. It is partially due to this observed relaxation of the strands that two post-tensioning strands were added to the design of the concrete flooring system: initially, we planned to bring each of the four strands up to 20 kips of tension, giving us a total of 80 kips' resistance on each side of the frame. With each strand relaxing down to 12.5 kips, adding two more was necessary to provide 75 kips of resistance on each side. In the second test with the concrete floor system, each strand was pulled to 25 kips, allowed to relax, and pulled again to give 15 kips of tension per strand, for a total of 90 kips on each side. Finally, for the wooden floor test, each of the 4 PT strands was initially tensioned to 28 kips, then dropped to 20-22 kips, for 80 kips on each side.

In assembly, other changes to the design were necessary simply due to the construction process. As highlighted in Figure 10, not all of the bolt holes made in the slotted shear tab ended up being used. As it happened, we discovered during assembly and in calculations that the seat angles alone would adequately hold up the beam and flooring system. The bolts were also sized such that only using four on either side would not prove fatal to the structural integrity of the system. In addition, due to measuring errors, the holes did not line up and we ended up needing to use only four of the five available slots. Initially, five slots were planned due to the factor of safety associated with the slotted shear tab. This element could be refined in future research because we now know that only four bolts will sufficiently hold up the frame.

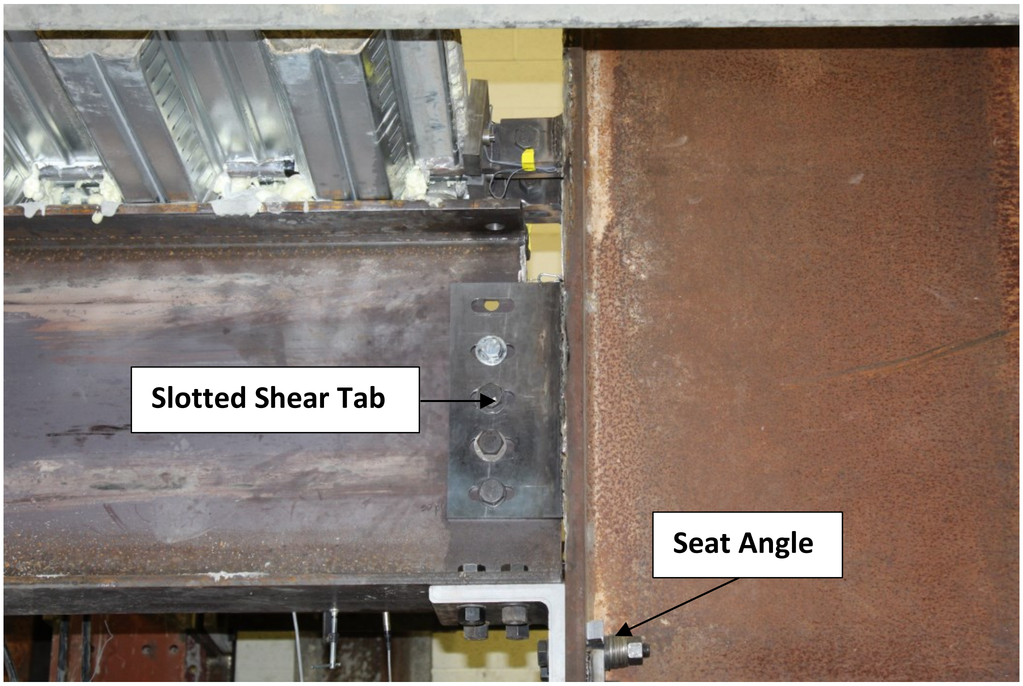

Figure 10 Image of the slotted shear tab.

We also found in assembly that the fuse plates didn't fit perfectly into the cuts made for them in the concrete flooring system. This led us to believe that in practice, it would be ideal to leave a bit more space for the fuse plates when pouring the concrete, possibly by wrapping them in foam.

In preparing each of the flooring systems, we needed to ensure that the metal struts inside of the floor would be able to slide back and forth within the flooring system and thus facilitate gap-opening without taking on the force of the actuator/moment. In the first iteration of the concrete flooring system, this was accomplished by wrapping the struts in a layer of plastic: while the plastic adhered to the concrete, the struts were able to remain free-floating. In the second iteration, the struts were simply greased to prevent their adhering to the concrete. This difference may have had an impact on the test results, which will be discussed later. In the wooden floor system, it was unnecessary to grease or wrap the struts as the design of the wooden system allowed for movement and as the wood would not adhere to the struts.

3.1.2 Testing Notes

Before moving forward, it is important to know that this research ended up covering only the initial stage of testing due to time constraints on the project. The initial plan was to test the frames without the fuse elements, and then to add them in for a second stage of testing. However, we were only able to conduct the tests where the fuse elements were not included. Thus, although details for the tests in which the fuse plates would have been in place are included in this chapter, these plans were not ultimately tested. That work is left to future researchers.

3.2 Cyclical Loading Test Setup

3.2.1 Loading Protocol, Initial Tests

The loading system used in testing was adapted from the cyclic Loading Sequence for Beam-to-Column Connections in chapter K of AISC 341-10 (AISC 2010) as well as that used by Abhilasha Maurya for her tests of another self-centering beam system (Maurya 2016). In the first test, the loading progresses quite slowly as this test was conducted without the fuse plates installed. As such, the frame was at its most delicate, and with the goal in mind of stopping the test before incurring damage but still being able to observe the reactions of various frame components, a slow loading protocol was deemed prudent. Figure 11 presents a graphic representation of the loading protocol used in the initial test, while Table 4 shows all of the relevant information connected to the protocol.

Table 4 Description of loading protocol for the initial test

Test 1*				
Story drift (%)	Displacement (in)	Height (in)	# cycles	Rate (in/min)
0.25	0.2925	117	6	1
0.5	0.585	117	6	1
0.75	0.8775	117	6	2
1	1.17	117	4	2
1.5	1.755	117	2	3
2	2.34	117	2	3
3	3.51	117	2	3
4	4.68	117	2	3
5	5.85	117	2	3
6	7.02	117	2	3
Total Time	1 hr	48 min	2 sec	
*For this test, the actuator should be halted prior to any structural damage being incurred by the frame.				

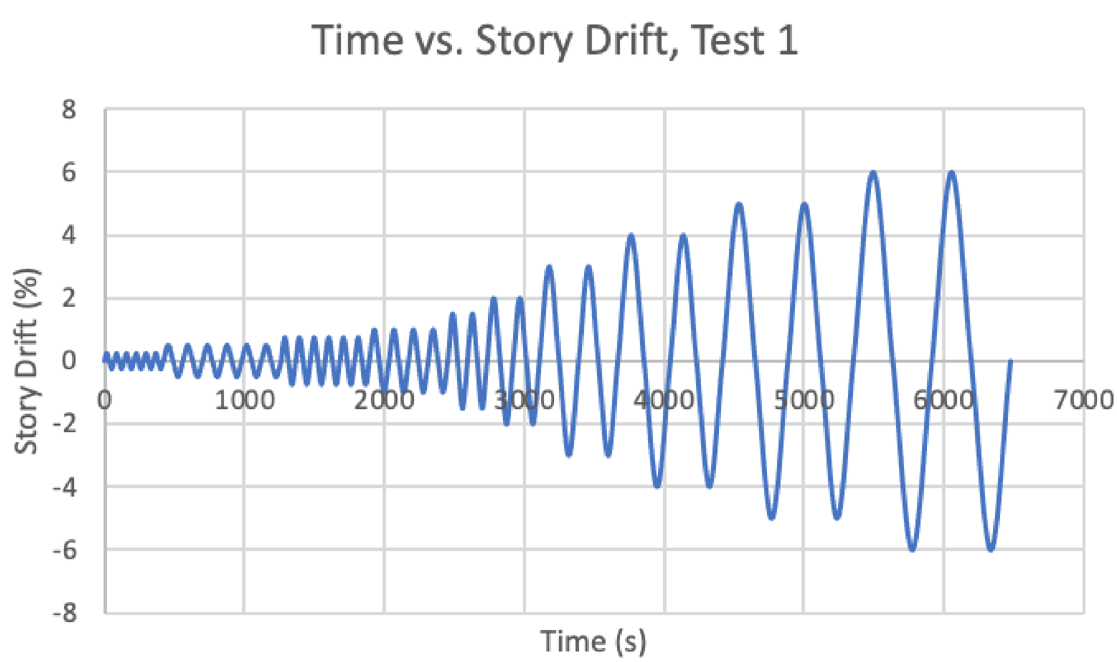

Figure 11 Time versus story drift in the loading protocol for initial test

3.2.2 Loading Protocol, Test 2

For the second stage of testing, the fuse plates would have been installed, allowing for a more robust loading protocol. After 6% story drift, the actuator was extended monotonically until failure. Table 5 and Figure 12 present the information pertinent to this test.

Table 5 Description of loading protocol for the second test

Test 2**				
Story drift (%)	Displacement (in)	Height (in)	# cycles	Rate (in/min)
0.25	0.2925	117	4	2
0.5	0.585	117	4	2
0.75	0.8775	117	4	2
1	1.17	117	4	2
1.5	1.755	117	2	3
2	2.34	117	2	3
3	3.51	117	2	3
4	4.68	117	2	3
5	5.85	117	2	3
6	7.02	117	2	3
Total Time	1 hr	48 min	1 sec	
**After 6% story drift is achieved, the actuator is to be extended monotonically until failure, unless failure has occurred during the previous cycles.				

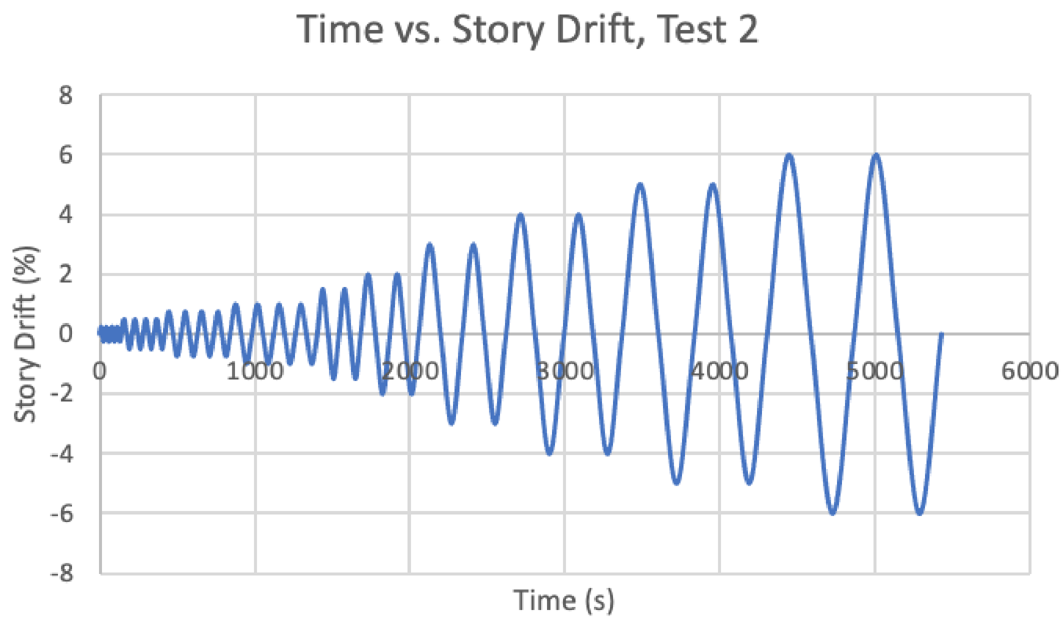

Figure 12 Time versus story drift in the loading protocol for the second test

3.3 Instrumentation and Data Reduction

The instrumentation for both tests comprised strain gauges on concrete and steel, string pots, and the actuator. The layout of this instrumentation is given in Figure 13 and Figure 14, with a description of the purposes of each element of instrumentation.

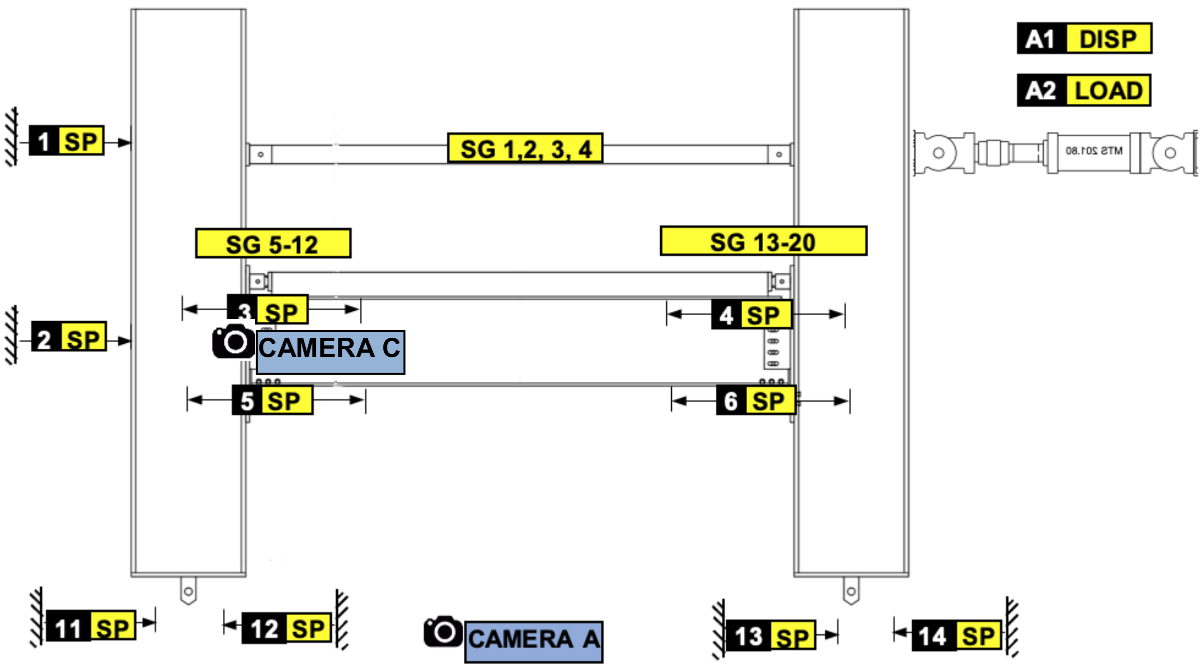

Figure 13 Elevation view of instrumentation on test frame

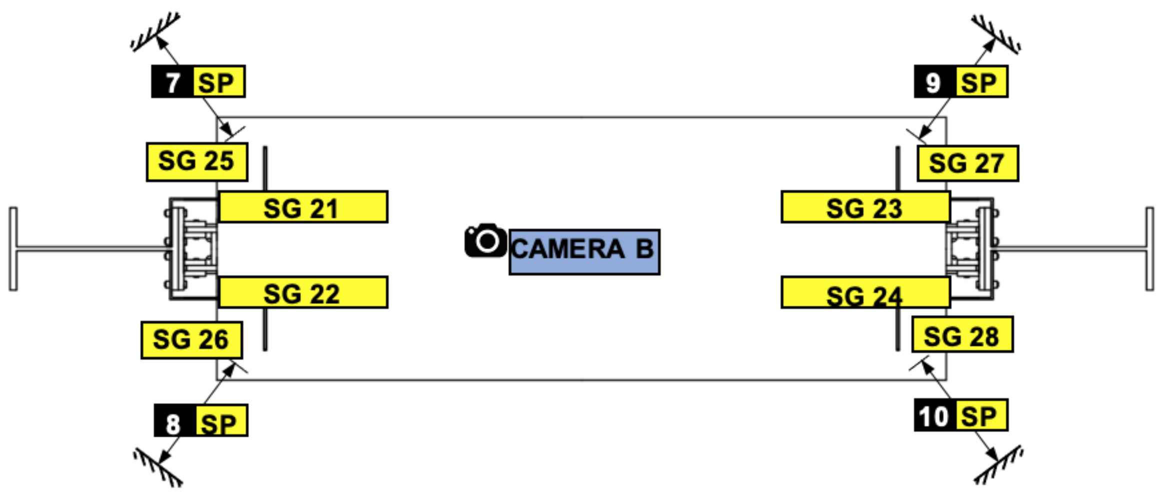

Figure 14 Plan view of instrumentation on test frame

Table 6 Purpose description for elements of instrumentation

Symbol	Measurement / Purpose
A1	Actuator displacement
A2	Actuator load
SG 1, 2, 3, 4	Strain in top strut
SG 5-12	Strain on left struts
SG 13-20	Strain on right struts
SG 21, SG 22	Strain on left fuse plates
SG 23, SG 24	Strain on right fuse plates
SG 25, SG 26	Strain on concrete, left
SG 27, SG 28	Strain on concrete, right
SP1, SP2	Frame drift
SP3, SP4	Gap displacement, right and left
SP5, SP6	Bottom beam movement, right and left
SP7, SP8, SP9, SP10	Fishtail measurement (Could place on top strut if more effective)
SP11, SP12	Base displacement parallel/perpendicular to beam, left
SP13, SP14	Base displacement parallel/perpendicular to beam, right

3.3.1 Mounting Notes

In the above instrumentation plan, the following notes regarding the mounting of certain instruments merits further explanation. First, SG 21-24 were to be mounted on the tops of the fuse plates, attached to the section which was narrowed to encourage damage. Since the tests were run without the fuse plates installed, these strain gauges were also not in use during that test. Additionally, SG 25-28 were placed on the face of the concrete floor in the area encompassed by the fuse plates, as these areas were under the most stress due to the movement of the frame and the cuts made for the fuse plates. These strain gauges were not included in the instrumentation of the wooden flooring system, as strain gauges used on wood were unavailable and this weak spot was not included. (There were no cuts made for the fuse plates in the wooden flooring system.) Finally, SP 7-10 and SP 11-14 extended out to steady reference points on the steel framing surrounding the test frame, providing a reading of any fishtail or base displacement which could affect other results. For each test, strain gauges and string pots were mounted between a week and 24 hours prior to testing. String pots were mounted using securely tightened clamps, with the strings extending to hooks attached to either strong magnets (on steel) or to hooks epoxied to the pertinent surfaces (on concrete). While nothing significant was noted in data reduction, it is worth mentioning that the magnets and clamps may have moved if a sufficient force was applied to them. However, for the purposes of expediting our testing, and since the risk of such a force was small, magnets and clamps were judged to be superior to bolts in securing the string pots.

3.3.2 Visualization Plan

In the instrumentation plan detailed in Figure 13 and Figure 14, CAMERA A is positioned on one side of the test frame and is the primary view. CAMERA B gives a view from above, allowing us to see the concrete and fuse plates during the tests. CAMERA C was positioned close to the top of the beam-column connection on the non-actuator side of the frame and allowed us to get a closer look at the gap formation during testing. It also helped us to identify points where the congestion of this part of the design were problematic.

3.4 Testing Process and Observations

Prior to conducting full-scale tests, the system was racked back and forth several times to ensure that the struts were sliding adequately. No problems were noted during this preliminary test, and that being the case, testing was commenced in earnest.

3.4.1 Concrete Floor, Test 1

This test was conducted without the fuse plates in place, using the loading protocol described in section 3.2.1 Loading Protocol, Initial Tests. Instrumentation went smoothly, with the exception of one strain gauge, (SG 11), which needed to be remounted due to damage. The test ran for one hour and seven minutes. SG 8 moved into the concrete at one point, damaging it temporarily, but the strain gauge came back online soon enough. When we reached 3% story drift, the system began losing load due to the strut tabs hitting the compression plate and cracking the concrete. As the concrete was crushed, the load the system was able to take decreased. During the initial positive displacement for the 4% drift cycle, an issue with the actuator was noted and the test was paused for three minutes to fix it. Once it was fixed, and the test resumed, the system failed in earnest as the concrete under SG 25 was broken completely and the concrete was compressed to the point of severe cracking. At this point, the test was paused and then the actuator was brought back to a point of zero displacement and observation commenced. During observation, it was discovered that the limiting factor in this test was the amount of space between the strut tabs and the bearing plates. CAMERA C’s footage showed that when the strut tabs ran into the bearing plates, it caused compression that had not been accounted for or planned in design, leading to the crushing of the concrete.

Eight days after this test, the damaged system was subjected to the loading protocol up to 4% story drift once more, with the bearing plates and post-tensioning strands removed in order to give the system more room to move. The goal of this test was to ascertain whether or not load was being generated by friction and other difficult-to-control factors. As the levels of load were very low, we decided that while some load was generated by friction between the struts and the concrete, it was not enough to compromise the test. However, this discovery led us to adopt a different method of friction reduction between the concrete and the struts in subsequent tests. We also noted that the bending of the seat angles likely contributed a bit to the force felt by the system. Finally, given that the strut tabs did not run into the concrete flooring with the bearing plate removed, we were able to formulate a plan for the next test.

3.4.2 Concrete Floor, Test 2

In the second test of the concrete flooring system, the bearing plate was situated such that it was flush with the end of the concrete flooring system, as shown in Figure 15, to avoid crushing the concrete once more. The struts were also greased rather than wrapped in plastic in an attempt to further mitigate friction between the struts and the concrete. Due to lab scheduling, testing on this specimen began a month and a half after the conclusion of the previous tests. As noted in section 2.2.1, the concrete used to pour the floor system in this test was much weaker than previous tests, and cracks on the top of the concrete (running along the top of the struts) were noted prior to beginning the tests. Additionally, it was noted that, as the beam was being lifted into position to be bolted to the columns, the corner where SG 25 would have been placed was cracked to the point of not being connected to the rest of the floor. As such, SG 25 was not installed.

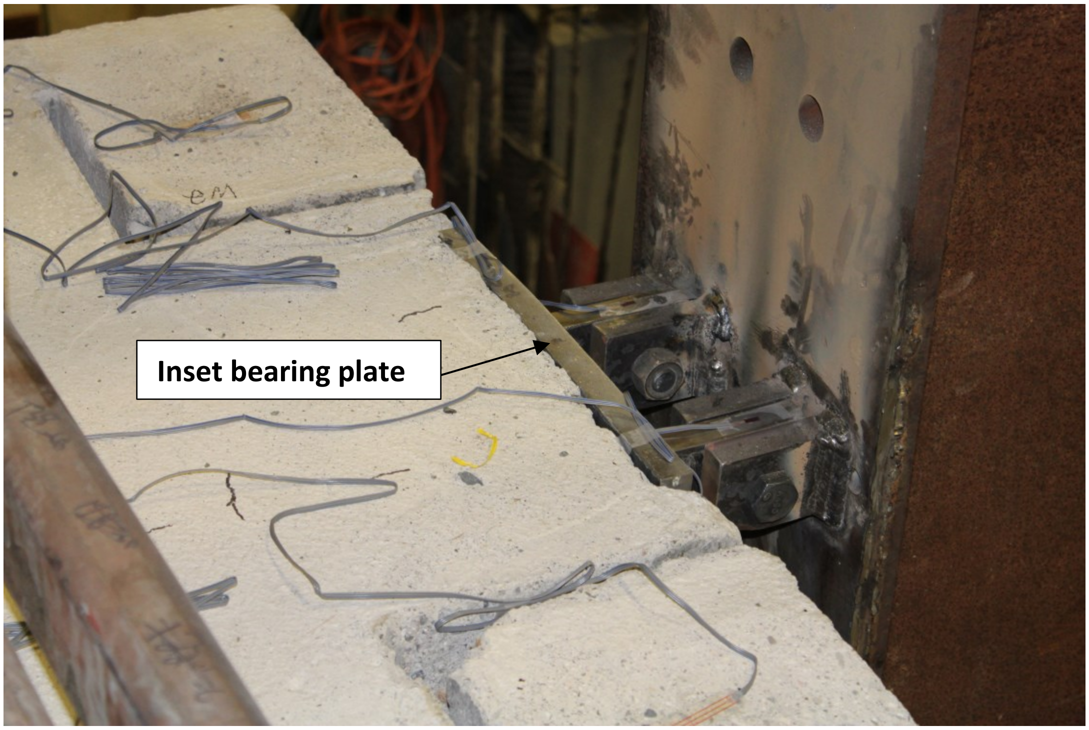

Figure 15 Configuration of the second concrete flooring test.

This test was run over the course of two days. On the first day, the loading was proceeding with standard increases in load when, after the actuator's initial 2% drift excursion, there was a pop and testing was paused. This occurred when the test had been running for approximately 40 minutes. It was found that a weld at the bottom of the actuator-side column had given out. A safety weld had been put in place, in case such a problem occurred, so there was no other damage to the system or any injury. However, we did have to wait for two days to repair the weld and recommence testing.

Upon the failure of the weld, the actuator was brought back to zero load, and this is where testing began. The goal of this test was to complete the 2%, 3%, and 4% story drift loading protocols. There was a false start initially, with the actuator beginning the 3% story drift protocol rather than 2%, at which point the system hit its maximum level of load for the test. When the test was restarted, the next peak was hit during the 3% story drift protocol. After that, as the concrete cracked and was crushed, more lateral movement was allowed and so the load relaxed. After completing the 4% story drift protocol, we found that the limiting factor and cause of failure was simply the weakness of the concrete, possibly combined with the higher levels of post-tensioning, leading to a tendency to fracture.

3.4.3 Wood Floor Test

Just under a month after the conclusion of the concrete floor tests, the wood flooring system was tested. During instrumentation for this test, the strain gauges attached to the beam running across the top of the frame needed to be replaced the morning of testing due to damage incurred (they had been used for all previous tests, and so had been there for some time), and they were therefore not fully cured. However, no problems were noted as a result of this. In this test, we were concerned that, since the wooden blocks were not connected to one another, they may buckle at the joints, or that the bearing plates (placed the same distance from the strut tabs as they were for the second concrete flooring test) might end up crushing the wood. However, these issues were not noted during actual testing.

In testing, the system ultimately failed due to bending of the bearing plates, which had been reused for all tests conducted.

3.5 Test Results

Based on the results of the tests conducted, it is concluded that the overall design of the self-centering system is fairly effective in reaching required levels of story drift and flexural strength. While different tests encountered different limiting factors, when all are taken together, it is reasonable to conclude that this system provides a basis for the full development of a low-cost self-centering system.

3.5.1 Concrete Floor Tests

The moment versus rotation plot for the initial concrete test is shown in Figure 16. For this plot, the moment at the beam-to-column connection was calculated based on force equilibrium and geometry, with the beam rotation determined based on the displacements at the top and bottom of the left end of the beam. This plot shows that the system exhibited somewhat asymmetric self-centering behavior, with a maximum moment of 240 kip-ft at 4% story drift in the positive direction. The maximum moment in the negative direction was 324 kip-ft at 3% story drift. Based on these data, from the initial concrete floor test we can conclude that the frame reached the target flexural strength in one direction (negative) and the story drift for highly ductile steel frames (per AISC 341-16) of 4% in the other direction (positive). It is worth noting that, while the frame was not able to reach the story drift for highly ductile steel frames in the negative direction, it was able to reach the target story drift for moderately steel ductile moment frames. Failure in this test was caused by insufficient space between the bearing plate and the column.

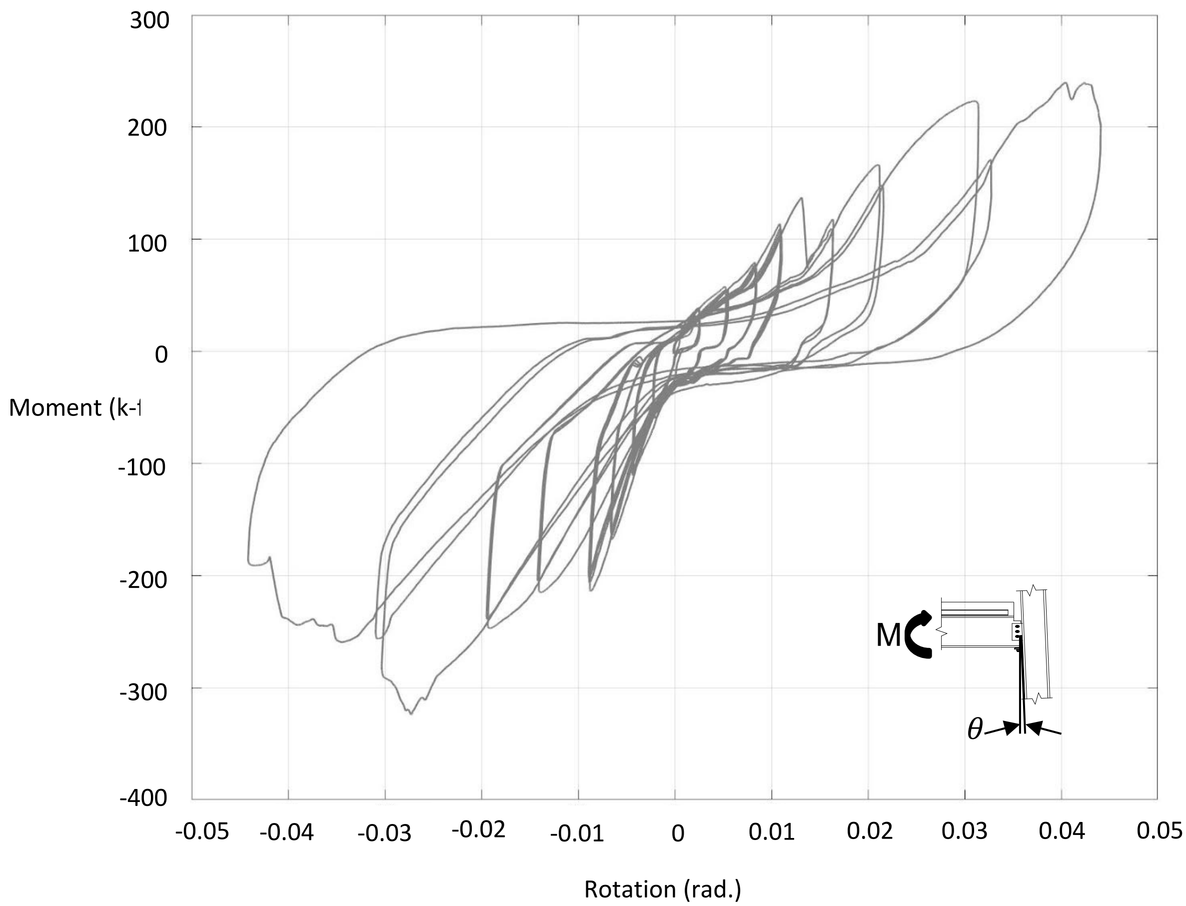

Figure 16 Moment-rotation plot for the first concrete flooring test.

The second test run on the initial concrete floor, without the bearing plates and post-tensioning strands in place, found that the system was only able to reach about 30% of the maximum flexural strength achieved in the first test. However, this indicates that several aspects of the system contributed to the flexural strength, such as the friction between the struts and the slab, bending of the seat angles, and bolt bearing on the shear tab hole(s).

In testing the second concrete floor, the system exhibited more symmetric self-centering behavior up to the point of failure. This is exhibited in Figure 17, in which moment and beam rotation were determined in the same manner as for the first concrete test. In this test, the maximum moment in the positive direction was 289 kip-ft at 2% story drift, with a maximum of 4% story drift achieved with lost flexural strength prior to failure. In the negative direction, the system achieved a maximum moment of 224 kip-ft at 3% story drift, going on to reach 4% story drift before failure. In this test, the concrete failed without contacting the column tabs, indicating that the new design allowed for sufficient space between the column and floor slab. It is predicted that the more symmetric behavior of the hysteresis in the second concrete floor test was due to decreased friction between the beams and the concrete, as in this test the beams were greased rather than wrapped in plastic. Failure likely occurred due to a combination of weaker concrete and stronger post-tensioning, with the concrete's strength insufficient to withstand the post-tensioning and applied forces.

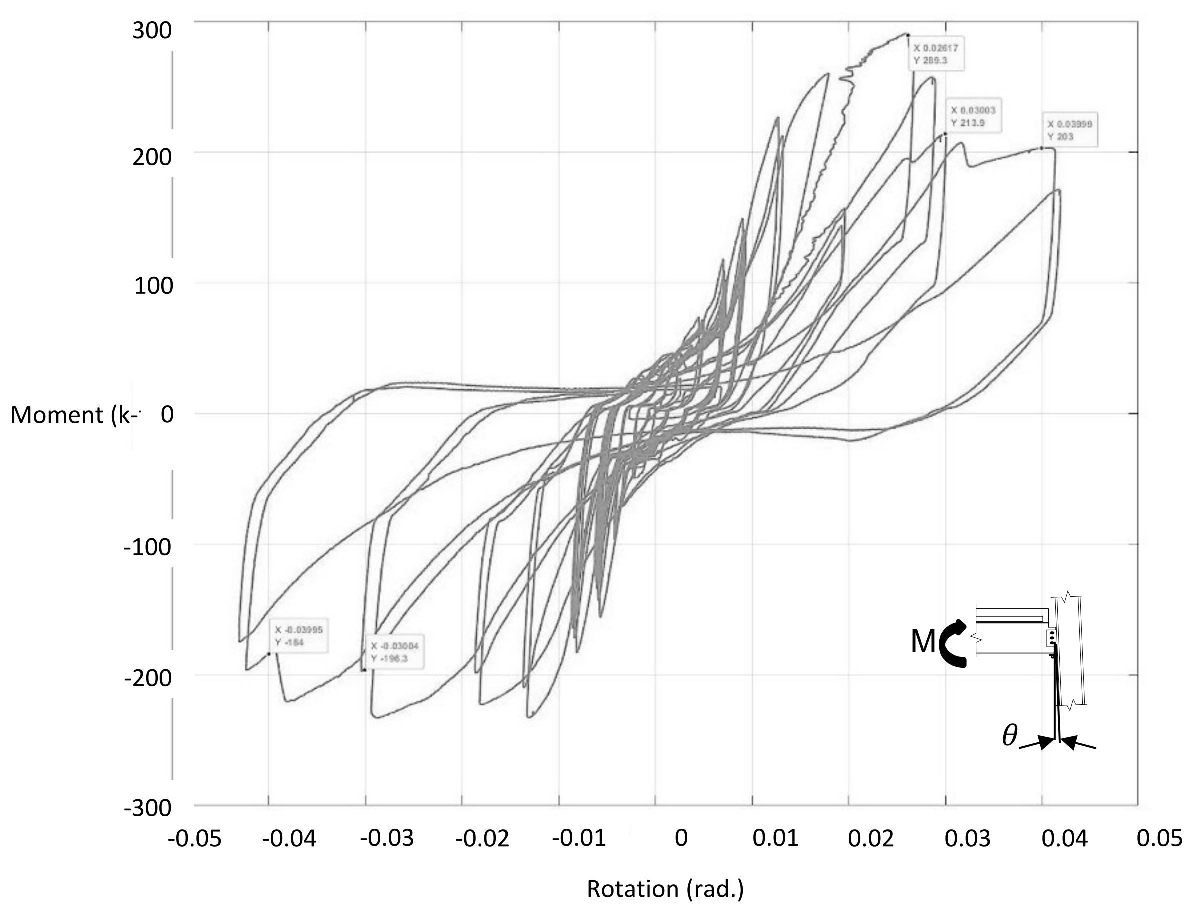

Figure 17 Moment-rotation plot for the second concrete floor test.

3.5.2 Wood Floor Test

The object of the wood floor test was to provide proof of concept for further research, as the use of mass timber is gaining traction in the construction world. Traditionally, mass timber structures use timber products such as cross laminated timber panels, glued-laminated timber beams, or other timber products for roofs, floors, and walls. Structures constructed in this way are attractive in appearance, relatively light-weight, and are a sustainable building solution, among other benefits (WoodWorks 2021). The use of a mass timber roof or floor system in combination with a conventional concrete or steel lateral system can also be advantageous (AISC 2022). Structures thus constructed can be an efficient solution in buildings where wider floor spans are desired or where a moderately or highly ductile lateral system is needed. The investigation of wooden floors with the self-centering beam system is thus a project worthy of further study.

As shown in Figure 18, the self-centering behavior of the wooden floor system was more consistent than that of previous specimens. This is likely due to the fact that friction within the system was severely reduced: the beams in the wooden floor system were essentially "free floating," without any adhesion to the floor itself. The system eventually failed due to the bending of the bearing plates, which had been used in the concrete floor tests as well, as shown in Figure 19. However, the drift capacity and strength were much lower, with a maximum moment of 148 kip-ft in the positive direction at 3% story drift and of 150 kip-ft in the negative direction at 3% story drift. While these flexural strengths and drift levels are below what is expected for moderately steel ductile moment frames, this test nonetheless provides proof of concept for a wooden floor system in that the results display sufficient evidence of self-centering behavior.

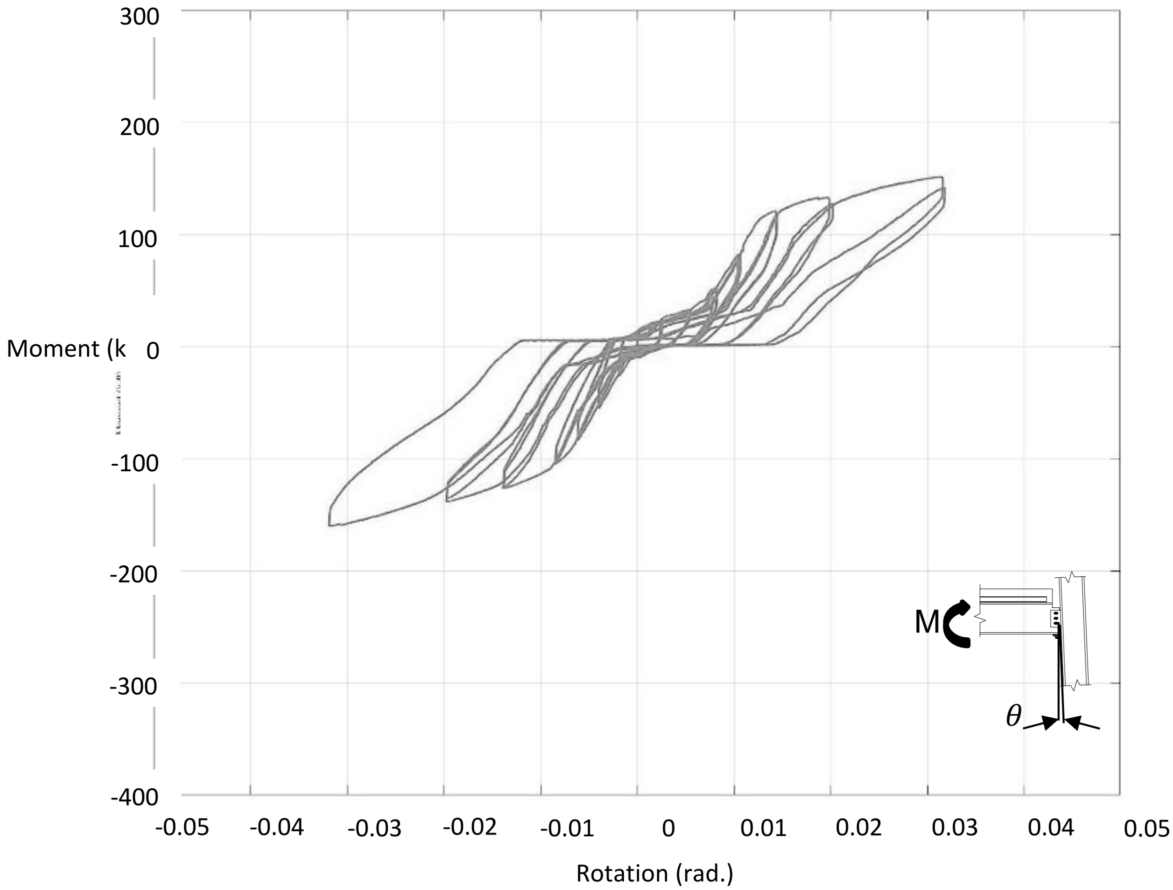

Figure 18 Moment-rotation plot for the wooden floor test.

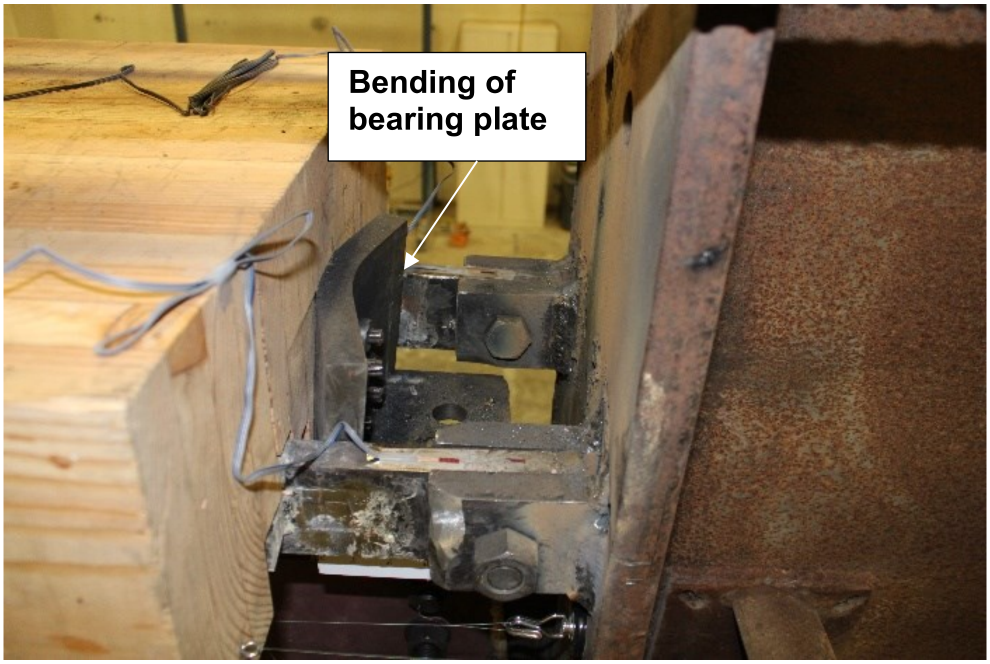

Figure 19 Bending of bearing plates.

3.5.3 Cost Comparison and Analysis

In order to determine the economy of the system, estimated labor and material costs were compared to the conventional self-centering system developed by Abhilasha Maurya (Maurya 2016). In this comparison, only the key unique elements were compared, as items such as beams, columns, flooring systems, etc. are standard in any and all buildings. We also excluded items that are common among self-centering systems, such as the PT strands and pin connections. The cost of these components is roughly equivalent across self-centering systems, and so does not bear on the cost comparison analysis. In the self-centering system developed by Maurya, the primary material costs were the telescoping HSS members (19.89 in^2/ft). While both systems require slotted shear tabs, pin connections for the struts, and a coped beam, contributing to labor costs, the system being researched also requires the initial up-front effort to cut slots in the metal deck and block out the floor slab. Maurya's system, on the other hand, also requires cutting the web at the flange junction along the entire length of the W-shape, welding the HSS members to the beam web, and fabricating a finger connection. The system being researched is thus estimated to be ten times less expensive than conventional self-centering systems in terms of added material costs alone, with additional reductions in cost when comparing labor costs. This comparison was conducted based on the fabrication process for the concrete flooring system, as the wooden flooring system cost would not be included in cost analysis regardless and that is the biggest difference between the two systems.

CHAPTER 4. CONCLUSIONS

This chapter contains a summary of the test campaigns, the analytical study, and their results. The principal findings are summarized, and areas for future research are identified.

4.1 Summary

In this research, the goal was to prove that an effective self-centering system comprised of standard construction details and created using standard construction methods was possible. Specifically, testing was designed to ascertain whether the system was able to:

1. Achieve levels of 4% story drift without significant damage to the system.
2. Bring the system back to plumb after reaching 4% story drift.
3. Dissipate energy without damage to the frame or flooring system.

Design of the system itself was calculated so as to mitigate costs while providing the gap-formation, restoring force, and damage dispersal elements essential to a self-centering frame. Three specimens were tested: two using concrete floors, and one using wooden. In the initial concrete floor test, the limiting factor proved to be design-based, with the frame exhibiting asymmetric self-centering behavior and achieving the required flexural strength in one direction and the required 4% story drift in another. Failure occurred when tabs attached to the column rammed into the bearing plates, compressing and cracking the concrete floor. The second concrete floor test was limited by the concrete itself, which proved to be weaker than expected and weaker than the previous specimen. In this test, more symmetric hysteretic behavior was exhibited, though, due to cracking and fracture of the concrete, neither the required flexural strength nor the target story drift was achieved. However, congestion in the area where the tabs hit the concrete slab was not an issue in this test. As such, it is expected that, with the improved design and stronger concrete, the system would successfully reach the target flexural strengths and story drifts.

The wooden floor test provided adequate proof of concept for further development of a wood flooring self-centering system, with fatigue on the bearing plates proving to be the limiting factor while effective self-centering behavior was exhibited.

4.2 Principal Findings

4.2.1 Overall Effectiveness of the System

This system, overall, exhibited moderately effective self-centering behavior. In the concrete floor tests, the geometry of the system was refined such that the system was able to reach the target 4% story drift without compromising the system. Additionally, the frame was able to reach the required levels of story drift and flexural strength (4% story drift and 300 kip-ft moment) at least once during testing. Thus, the system was able to achieve 4% story drift. As far as damage goes, it is predicted that given the refined geometry of the system and stronger concrete, these levels of story drift would be achievable without significant damage; however, this hypothesis remains untested. The system thus half-meets the first requirement for effectiveness in self-centering.

The second requirement for the system was that it be able to bring the frame back to plumb position after achieving 4% levels of story drift. This is difficult to evaluate, due to the use of the actuator and the fact that all specimens were tested to failure. While it is predicted that the system would do so, as it is predicted that the refined system would be able to reach the required levels of story drift, etc., it is ultimately inconclusive.

Finally, the system was expected to dissipate energy without significant damage to the frame or flooring system. The design of the flooring and self-centering systems ensured that incompatibilities between the two would not be present. The system, too, was able to reach high levels of story drift and flexural strength before taking damage even without the fuse elements. However, the fuse elements themselves remain untested. There are two trains of thought when attempting to make any predictions about the behavior of these elements within the system(neglecting the design of the fuse elements themselves, which, untested as it is, is simply predicted to work based on other researchers' efforts). The first holds that the slots cut in the concrete to house the Z-shaped fuse plates creates a weak zone right where the system is at its most congested. As such, the design of the plates within the system requires more thought, because it ultimately contributes to failure and damaging of the system. The second train of thought posits that, were the fuse plates in position during the tests, filling the slots cut in the concrete, the weak zone would be negated or reduced. Either way, the question of energy dissipation remains unanswered at this time.

Figure 16, Figure 17, and Figure 18 back up the conclusion made above, that the system exhibits moderately effective self-centering behavior, with the greatest success in the wooden flooring system.

4.2.2 Economic Evaluation

Based on the cost comparison detailed in section 3.5.3, the system being researched is estimated to be ten times less expensive than conventional self-centering systems in terms of added material costs alone, with additional reductions in cost when comparing labor costs.

4.2.3 Overall Conclusion

A full-scale prototype of this self-centering structural frame system with concrete flooring was constructed and tested twice in the lab using a quasi-static fully reversed cyclic loading protocol. In between these two tests, the prototype was again tested to determine the inherent flexural capacity of the system. One test was also conducted on the prototype with a wooden flooring system in place. The test results for the concrete floor tests showed that in the positive direction, the system achieved the required story drift for a highly ductile steel moment frame and was within 4% of meeting the target flexural strength. The limiting factor in this test was congestion at the strut-column connection, leading to the bearing plates compressing the concrete upon ramming into the strut tabs. In the second test, more even self-centering and loading behavior was noted, but the concrete was weaker than usual. It is predicted that, with the changes in geometry between the first and second tests and with sufficiently strong concrete, the target story drifts and flexural strengths would be met. The wooden floor test provided sufficient proof-of-concept for further investigation, limited only by fatigue on the bearing plates. The system also proved significantly less expensive and labor-intensive than a typical self-centering system. As such, the self-centering system investigated is viable and merits further development.

4.3 Recommendations for Future Research

In continuing the research and development of this self-centering system, one of the more obvious steps to be taken is the testing and refinement of the energy-dissipating fuse elements. This could be undertaken via testing of the flexural strength of the members outside when removed from the system as well as within a full-scale prototype. These elements have the potential to increase the safety potential and earthquake-resisting capacity of the system. Another element that has the potential to be refined is the slotted shear tab, which was found to be somewhat over-designed and over-conservative. It would also be beneficial to undertake more stringent development and testing of the wooden flooring system, preferably using fresh parts.

Another aspect of researching this system that would be beneficial is seeking industry input, asking industry leaders about the likelihood of their actually implementing such a system and potentially further refining the system based on their feedback.

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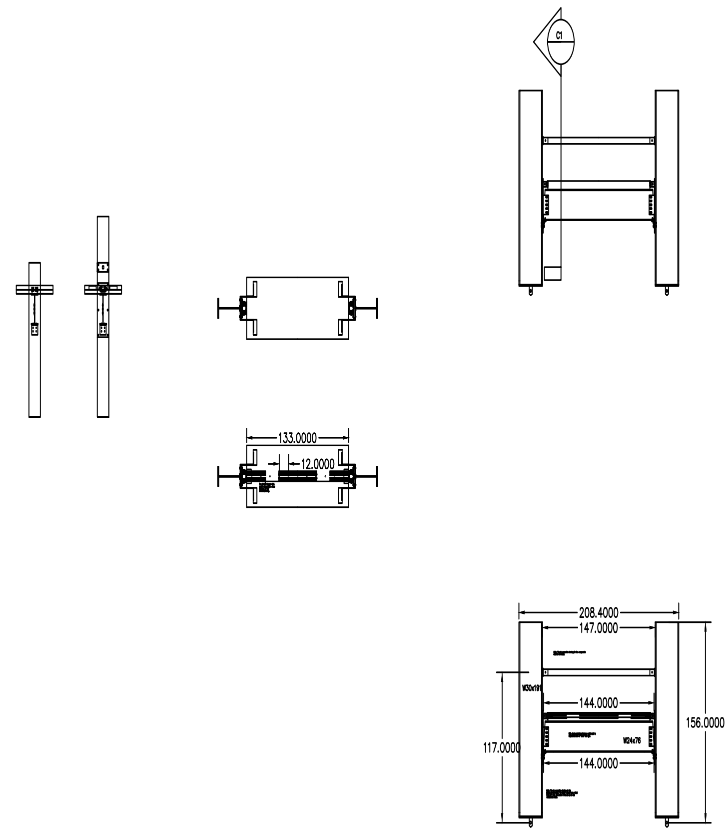
APPENDIX A: SELF-CENTERING SYSTEM DESIGN DRAWINGS

This appendix contains the final drawings of the test specimens which were used for fabrication and construction of the testing apparatus. Drawings were produced using AutoCAD for the concrete floor system. For the wooden floor system, fitting the self-centering system into the floor was figure out in the shop and using materials from previous wooden flooring tests.



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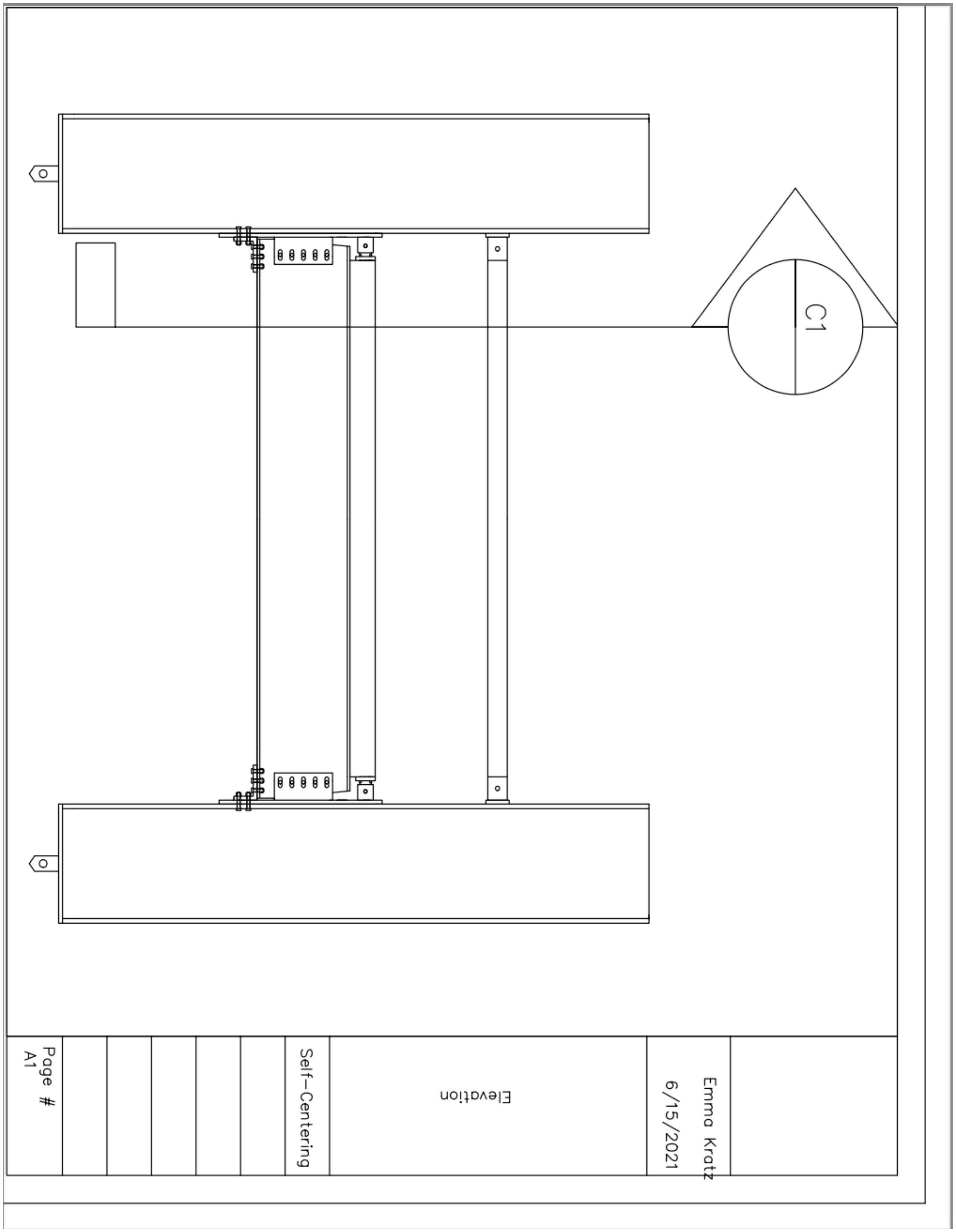
Cover Page
Self-Centering
Page # AA


C1
Page #
A1
Self-Centering
Elevation
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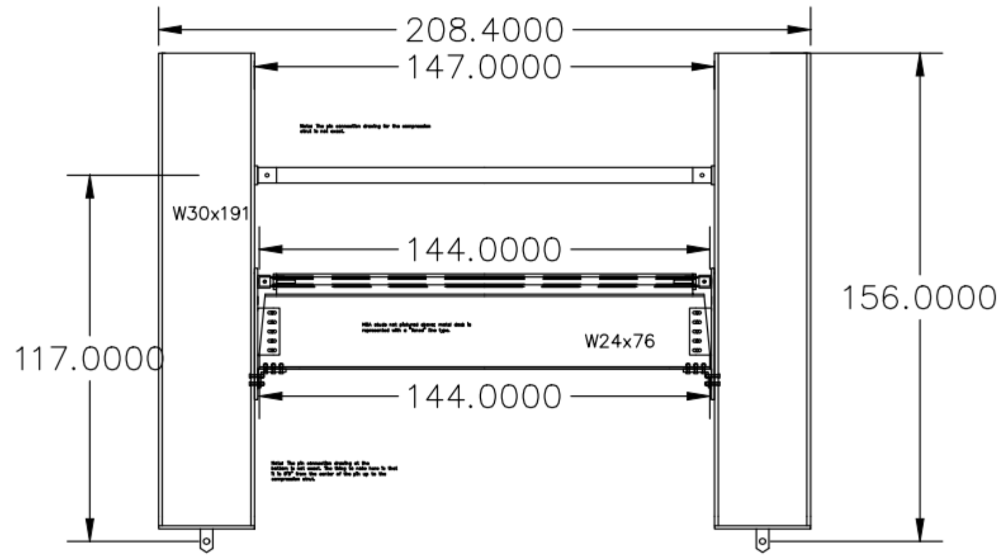

HSA studs not pictured above; metal deck is represented with a "fence" line type.

Note: The pin connection drawing at the bottom is not exact. The thing to note here is that it is 9'9" from the center of the pin up to the compression strut.

Note: The pin connection drawing for the compression strut is not exact.

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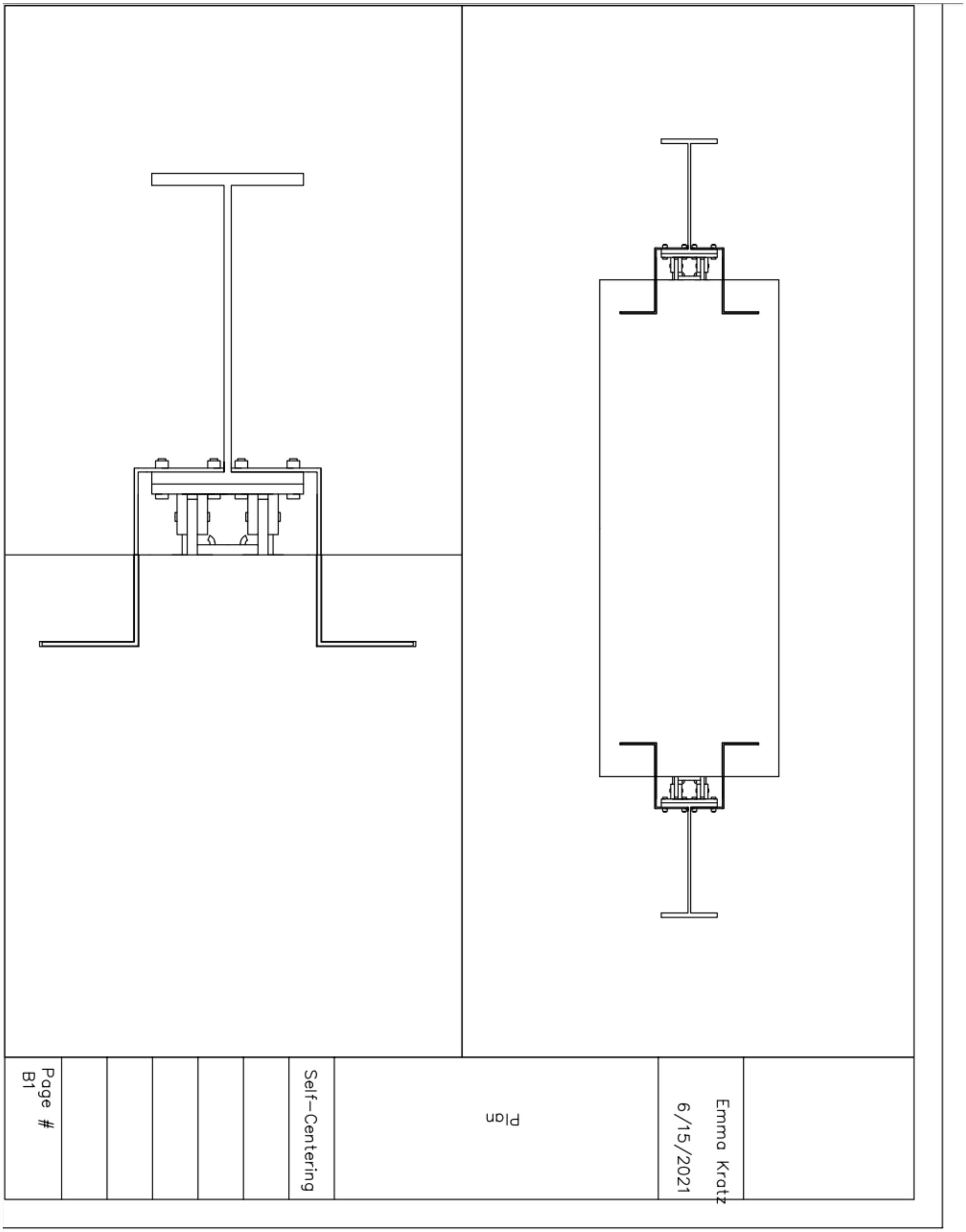
Dim. Elevation

Self–Centering

Page #
A2


Page #
B1
Self-Centering
Plan
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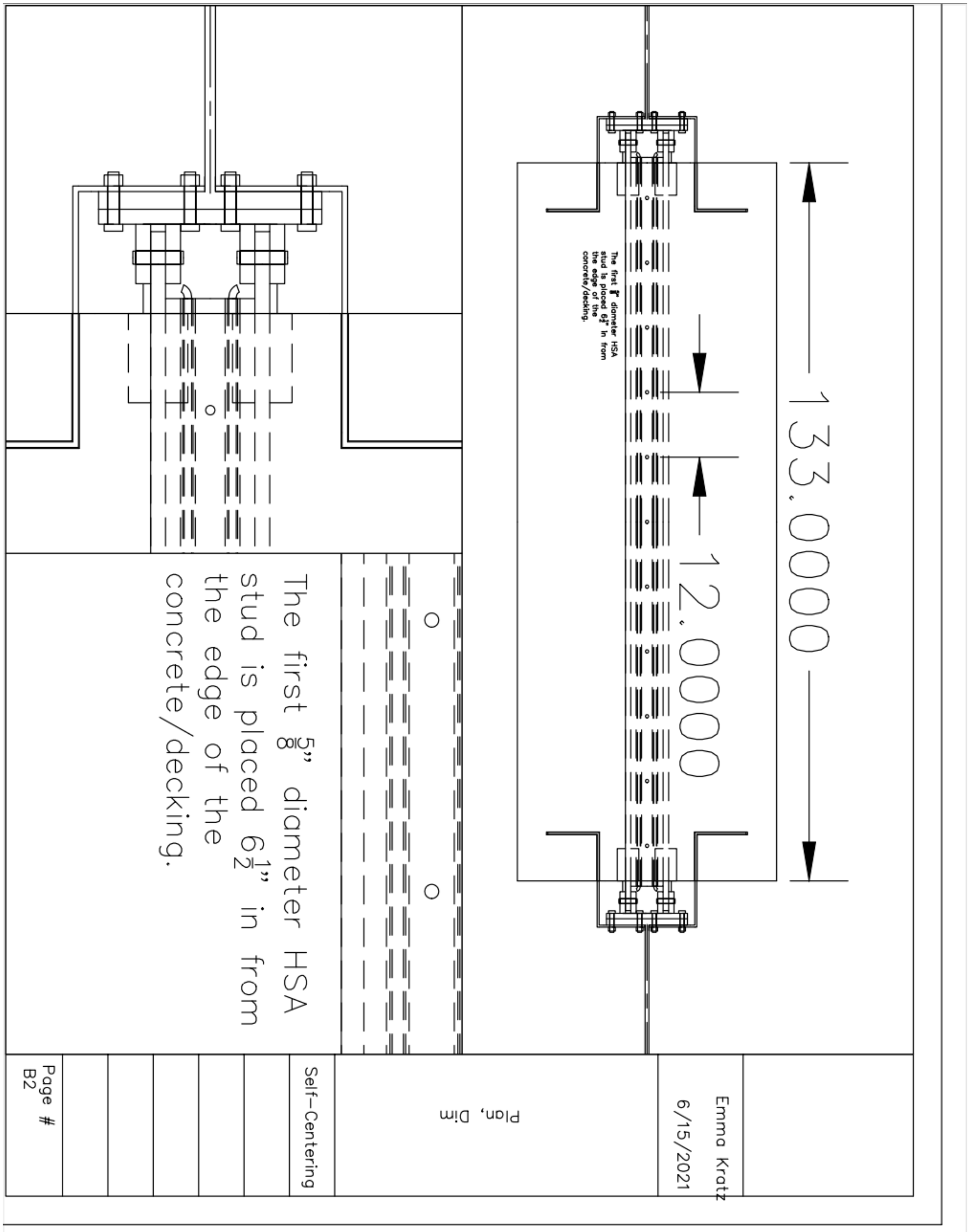
133.0000
12.0000
The first 5/8" diameter HSA stud is placed 6 1/2" in from the edge of the concrete/decking.
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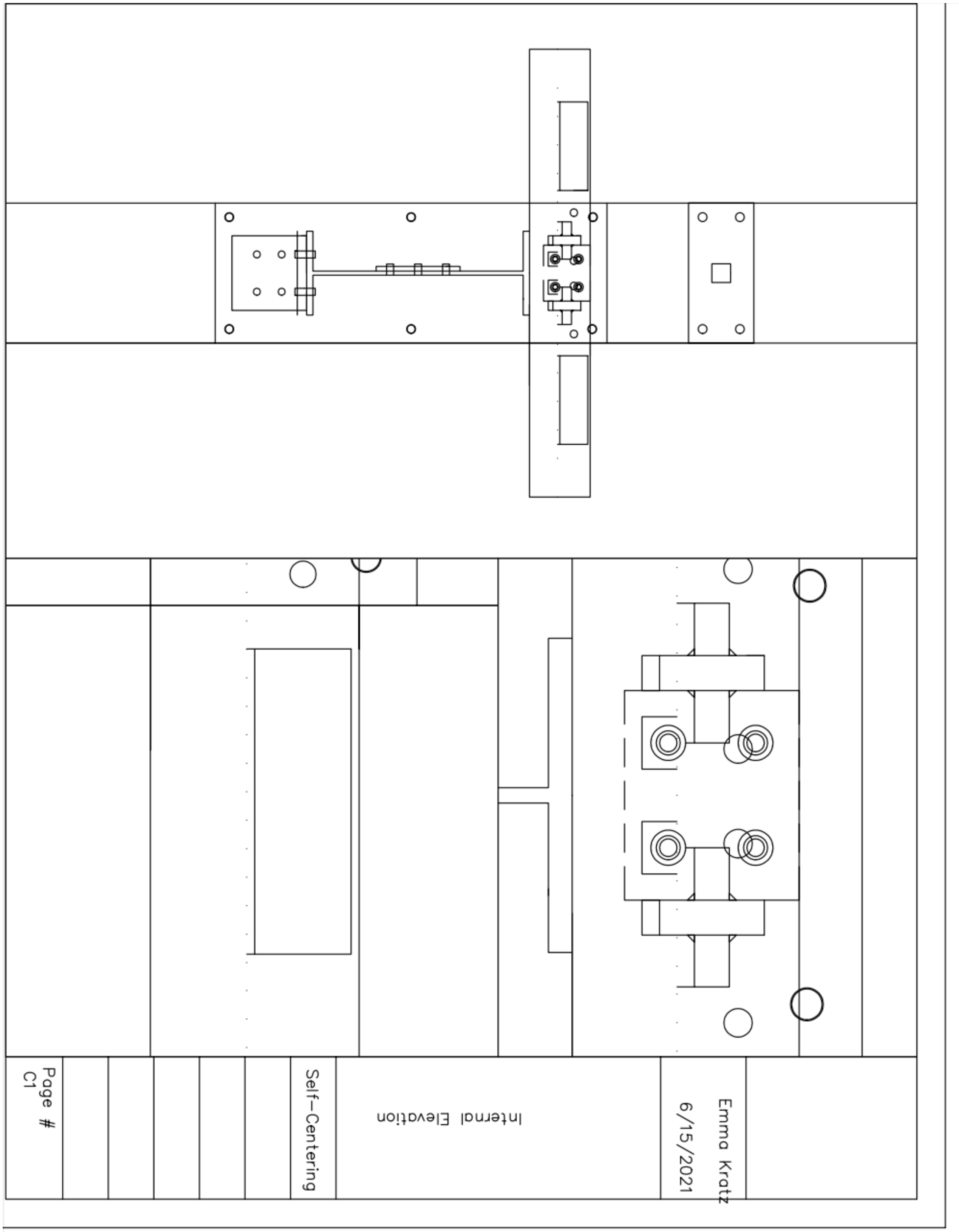
Plan, Dim
Self-Centering
Page #
B2


Emma Kratz
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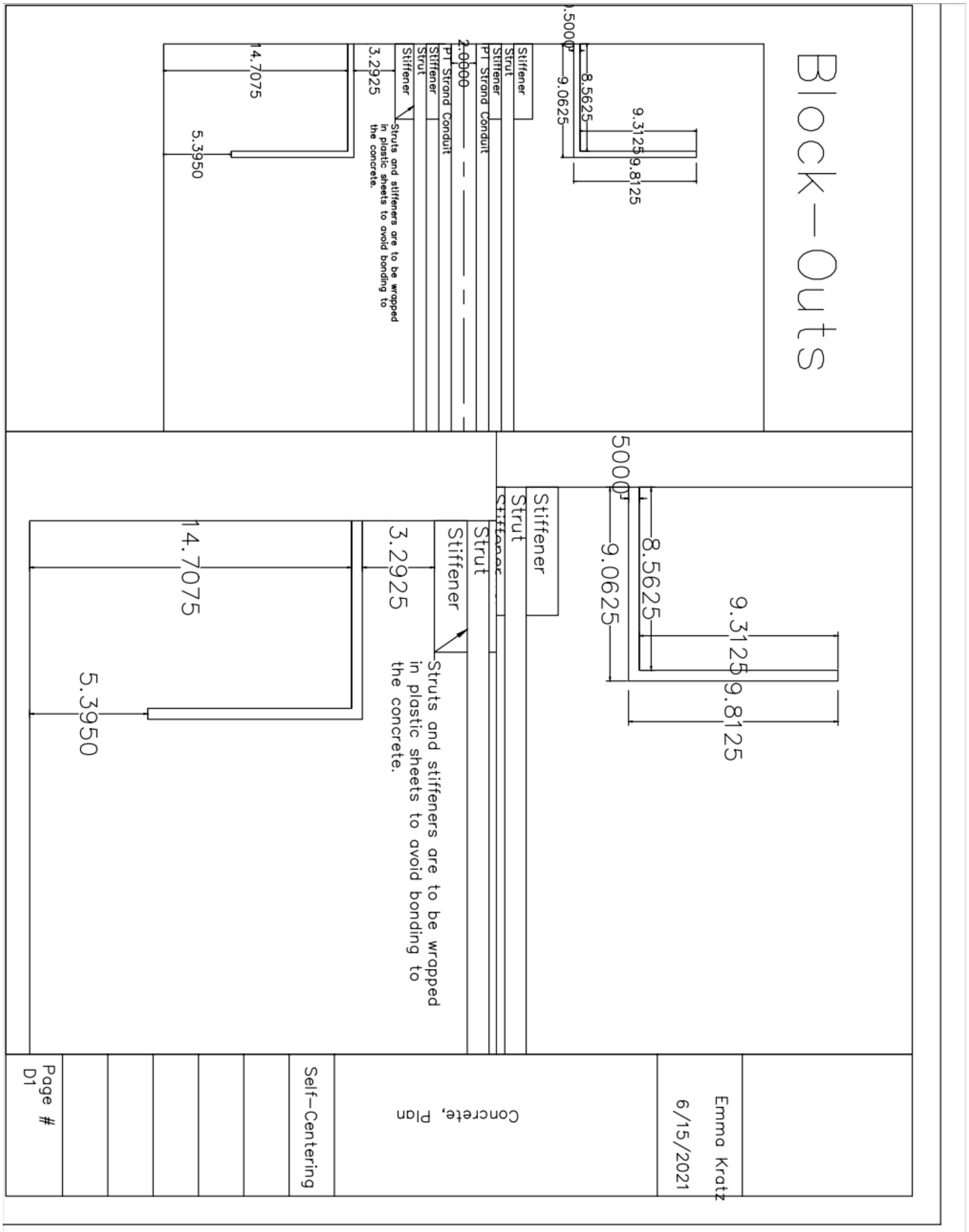
Internal Elevation
Self-Centering
Page #
C1


Block-Outs
Stiffener
Strut
PT Strand Conduit
2.0000
.5000
8.5625
9.0625
9.3125
9.8125
14.7075
3.2925
5.3950
Struts and stiffeners are to be wrapped in plastic sheets to avoid bonding to the concrete.
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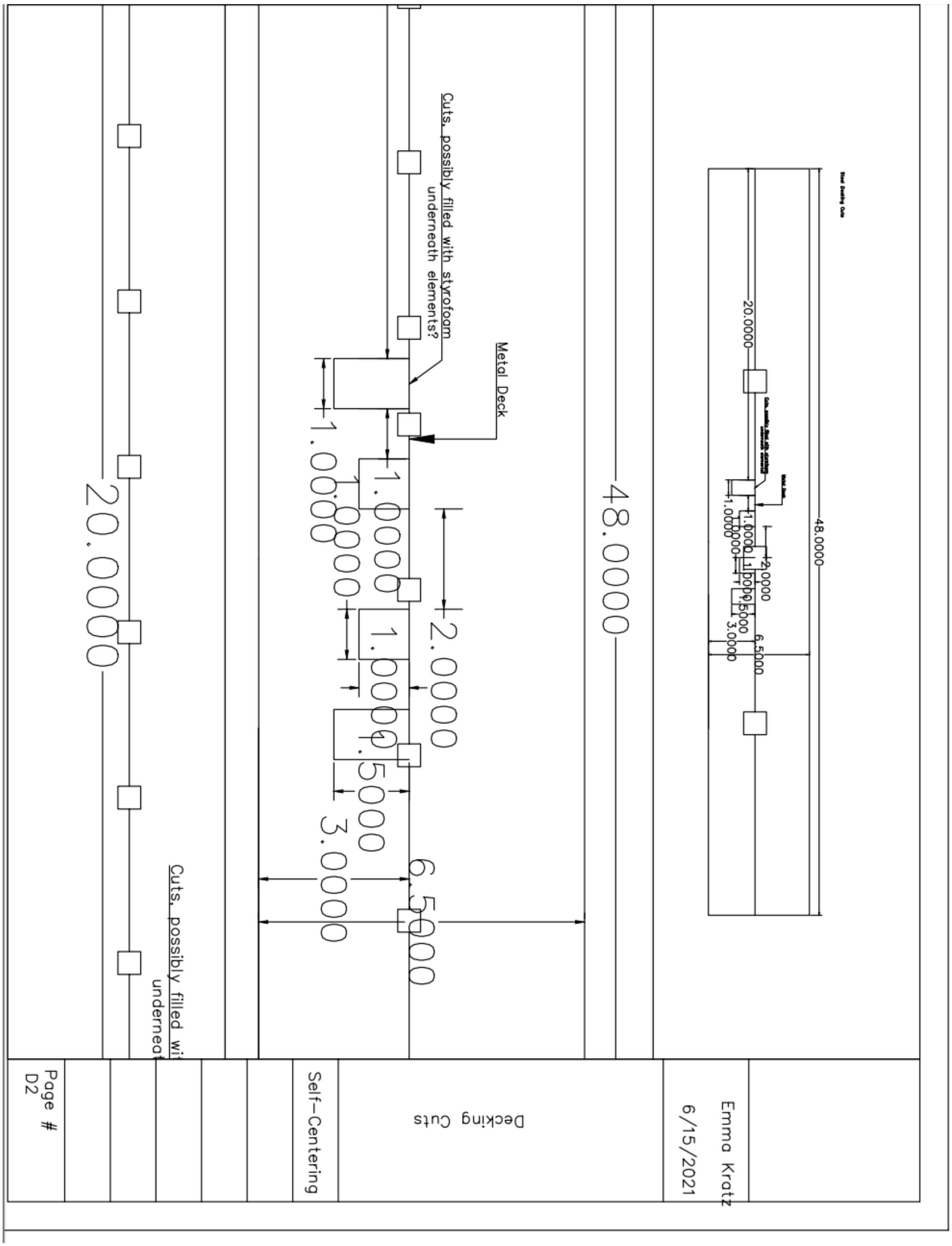
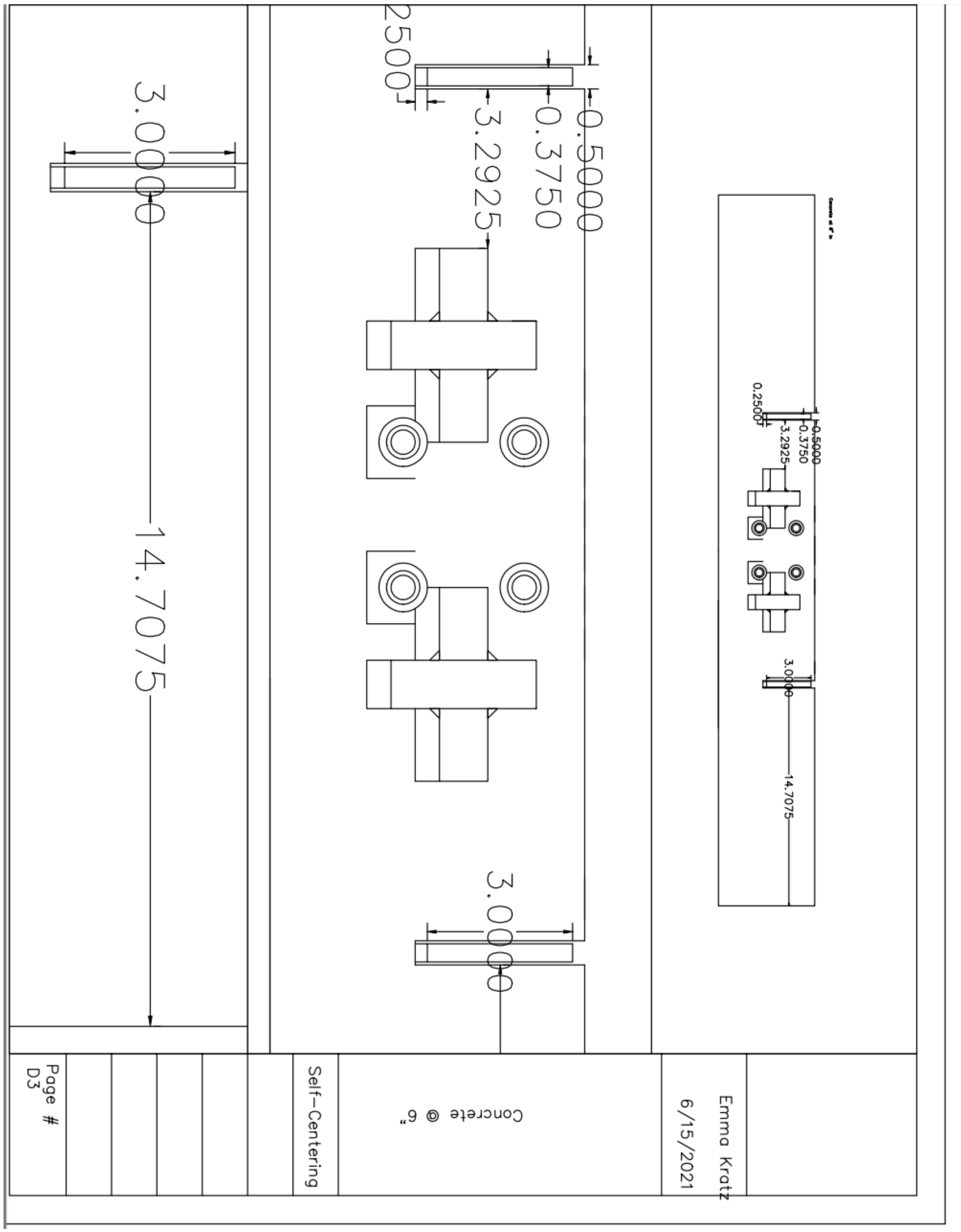
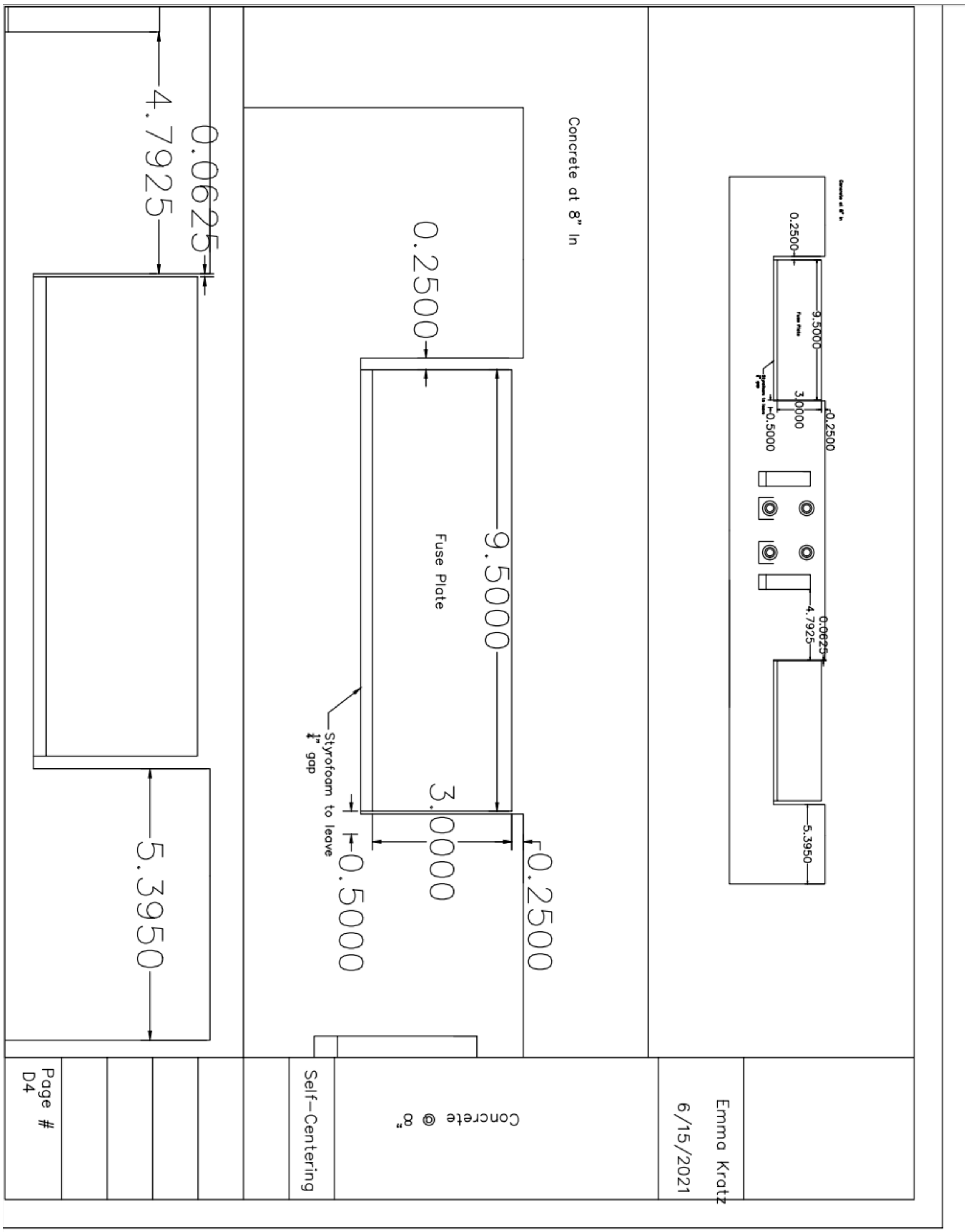
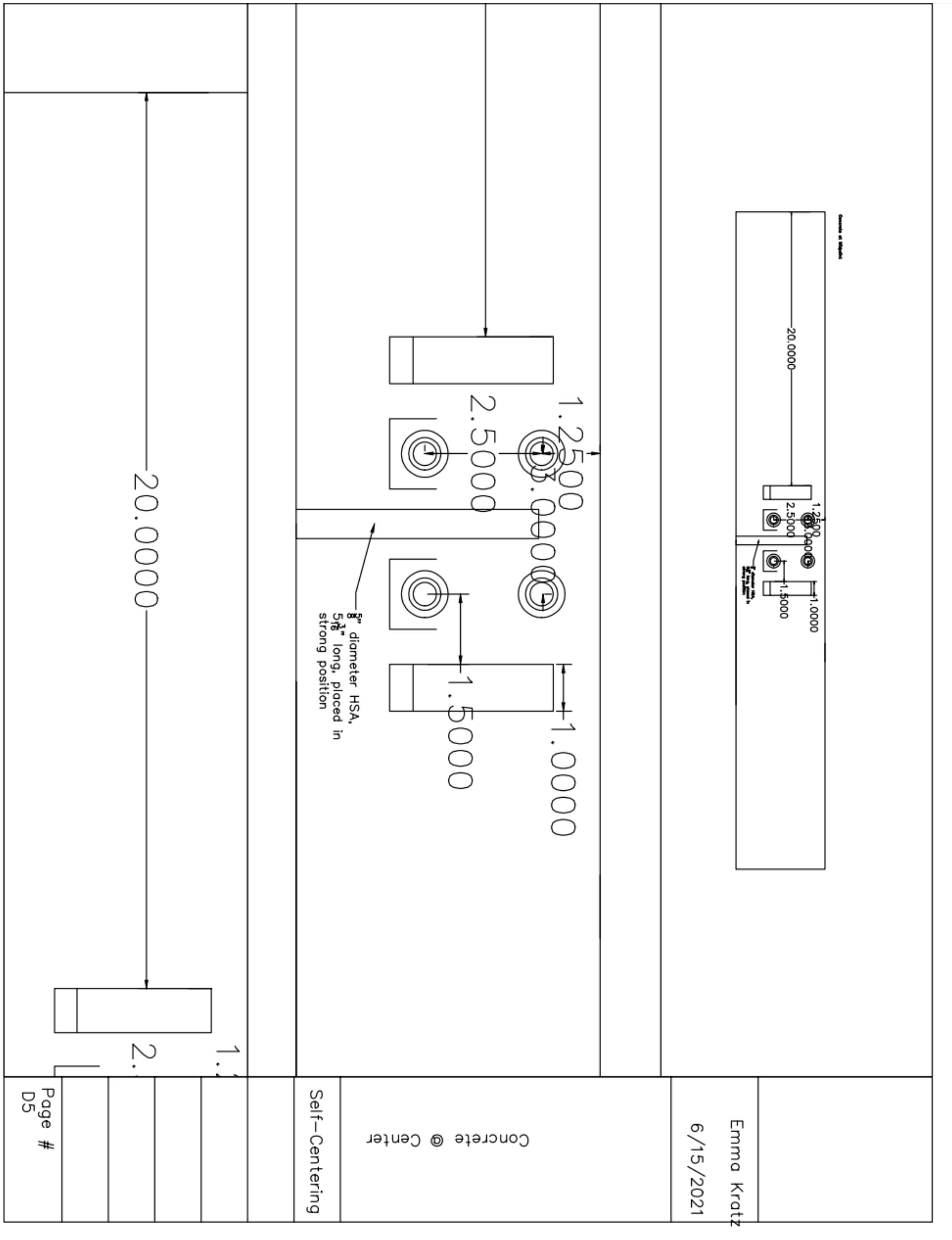
Concrete, Plan
Self-Centering
Page #
D1

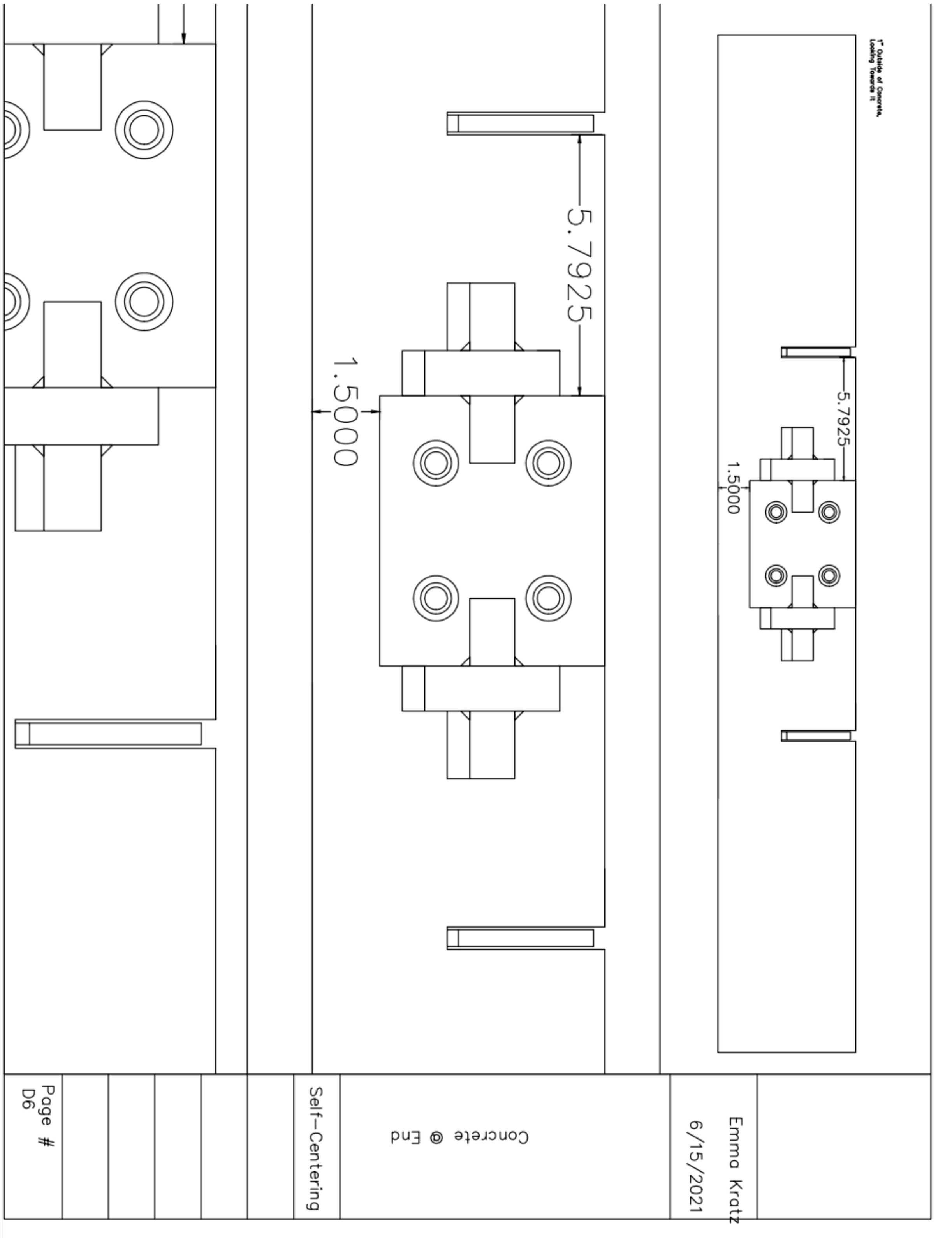

Cuts, possibly filled with styrofoam underneath elements?
Metal Deck
48.0000
20.0000
1.0000
1.0000
1.0000
2.0000
1.0000
1.5000
3.0000
6.5000
Cuts, possibly filled wi
underneat
Emma Kratz
6/15/2021
Decking Cuts
Self-Centering
Page #
D2

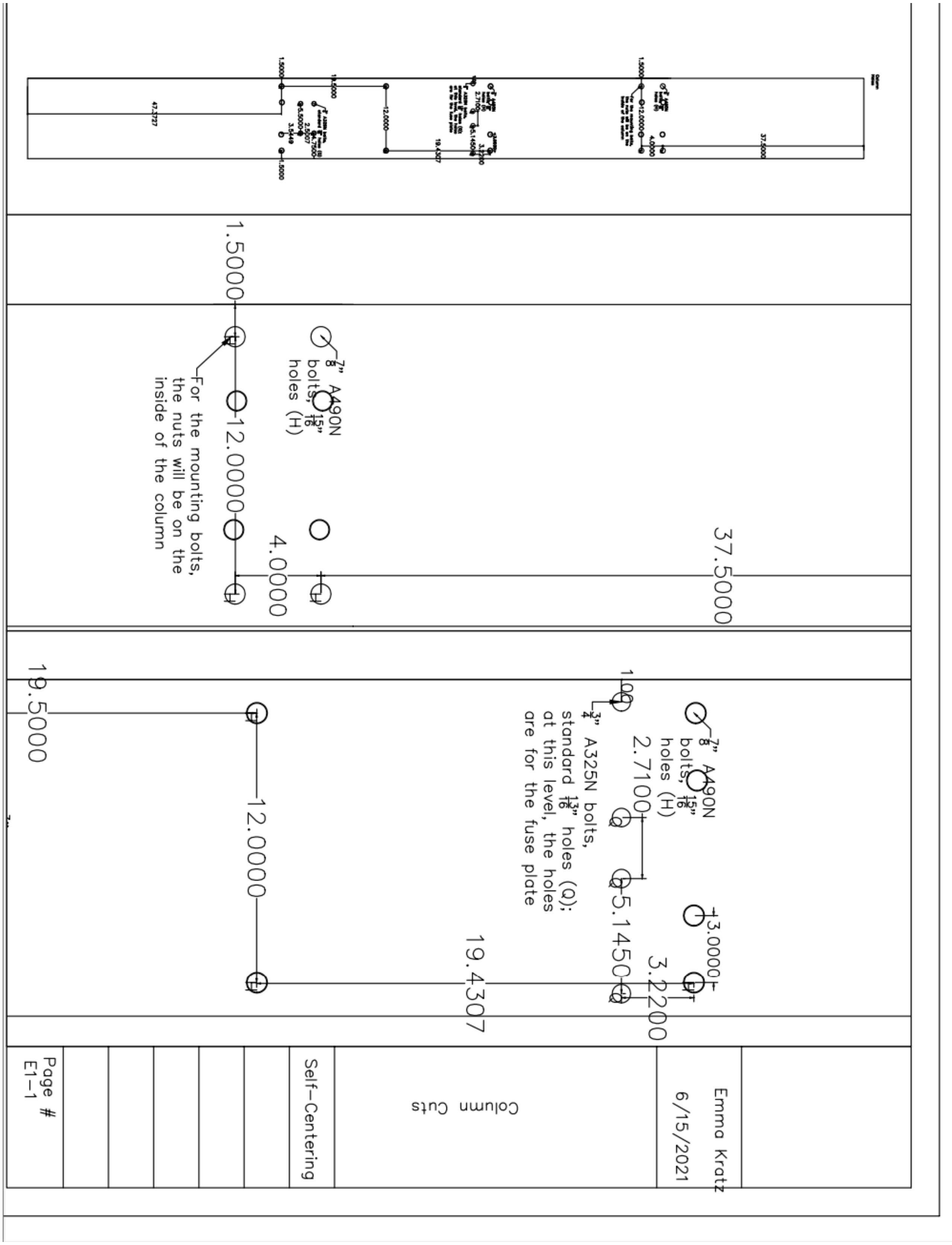

0.5000
0.3750
3.2925
0.2500
3.0000
14.7075
3.0000
Emma Kratz
6/15/2021
Concrete @ 6"
Self-Centering
Page #
D3



Concrete at 8" In
0.2500
9.5000
Fuse Plate
Styrofoam to leave 1/4" gap
3.0000
0.5000
0.2500
0.0625
4.7925
5.3950
Emma Kratz
6/15/2021
Self–Centering
Concrete @ 8"
Page #
D4


20.0000
1.2500
3.0000
2.5000
1.5000
1.0000
5/8" diameter HSA,
5 3/16" long, placed in
strong position
Self–Centering
Concrete @ Center
Emma Kratz
6/15/2021
Page #
D5


1" Outside of Concrete,
Looking Towards It
5.7925
1.5000
5.7925
1.5000
Emma Kratz
6/15/2021
Concrete @ End
Self–Centering
Page #
D6



37.5000
1.5000
7/8" A490N bolts, 15/16" holes (H)
12.0000
4.0000
For the mounting bolts, the nuts will be on the inside of the column
19.5000
1.00
7/8" A490N bolts, 15/16" holes (H)
2.7100
3/4" A325N bolts, standard 13/16" holes (Q); at this level, the holes are for the fuse plate
5.1450
3.0000
3.2200
19.4307
12.0000
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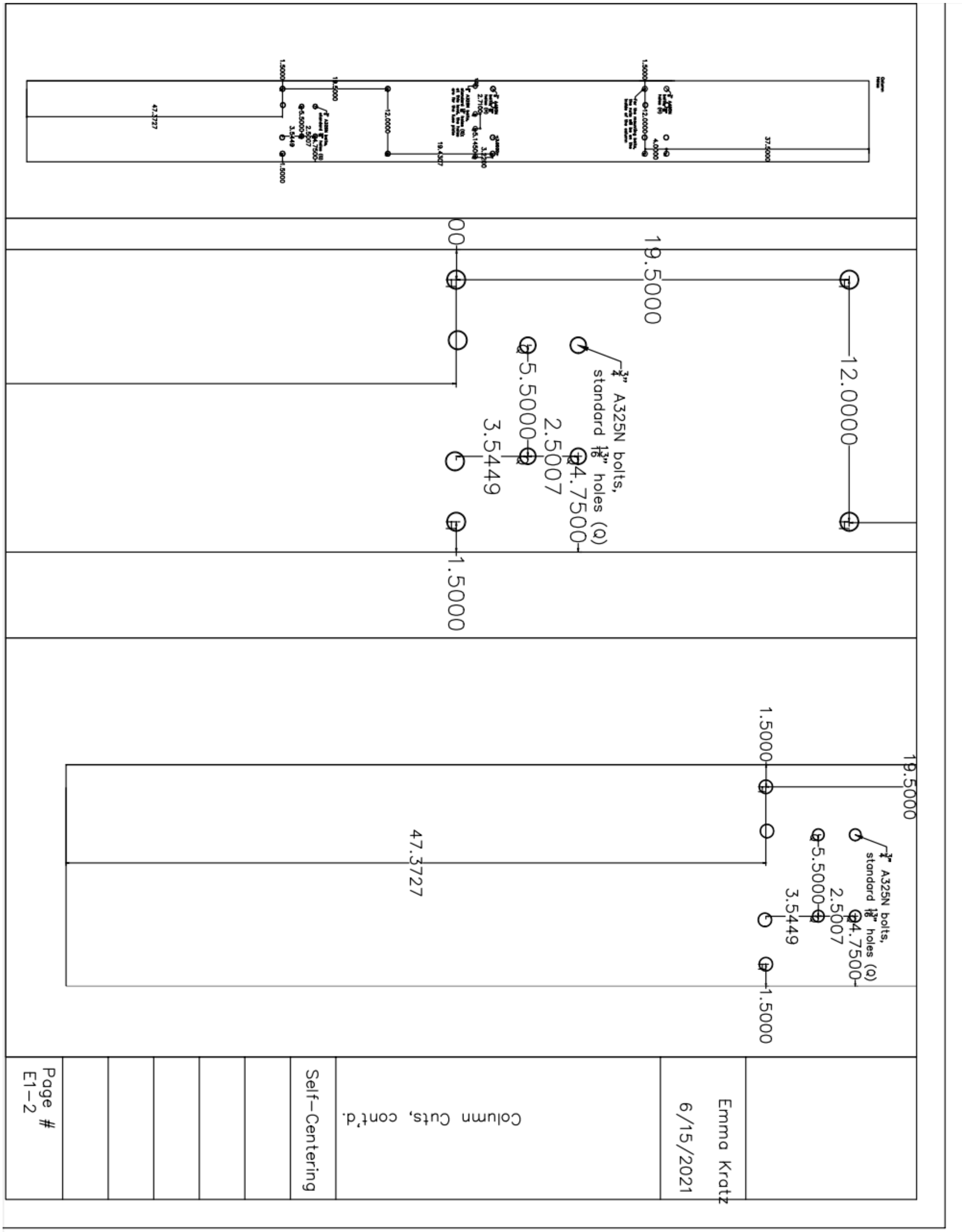
Column Cuts
Self-Centering
Page #
E1-1


19.5000
12.0000
3/4" A325N bolts, standard 13/16" holes (Q)
5.5000
2.5007
4.7500
3.5449
1.5000
47.3727
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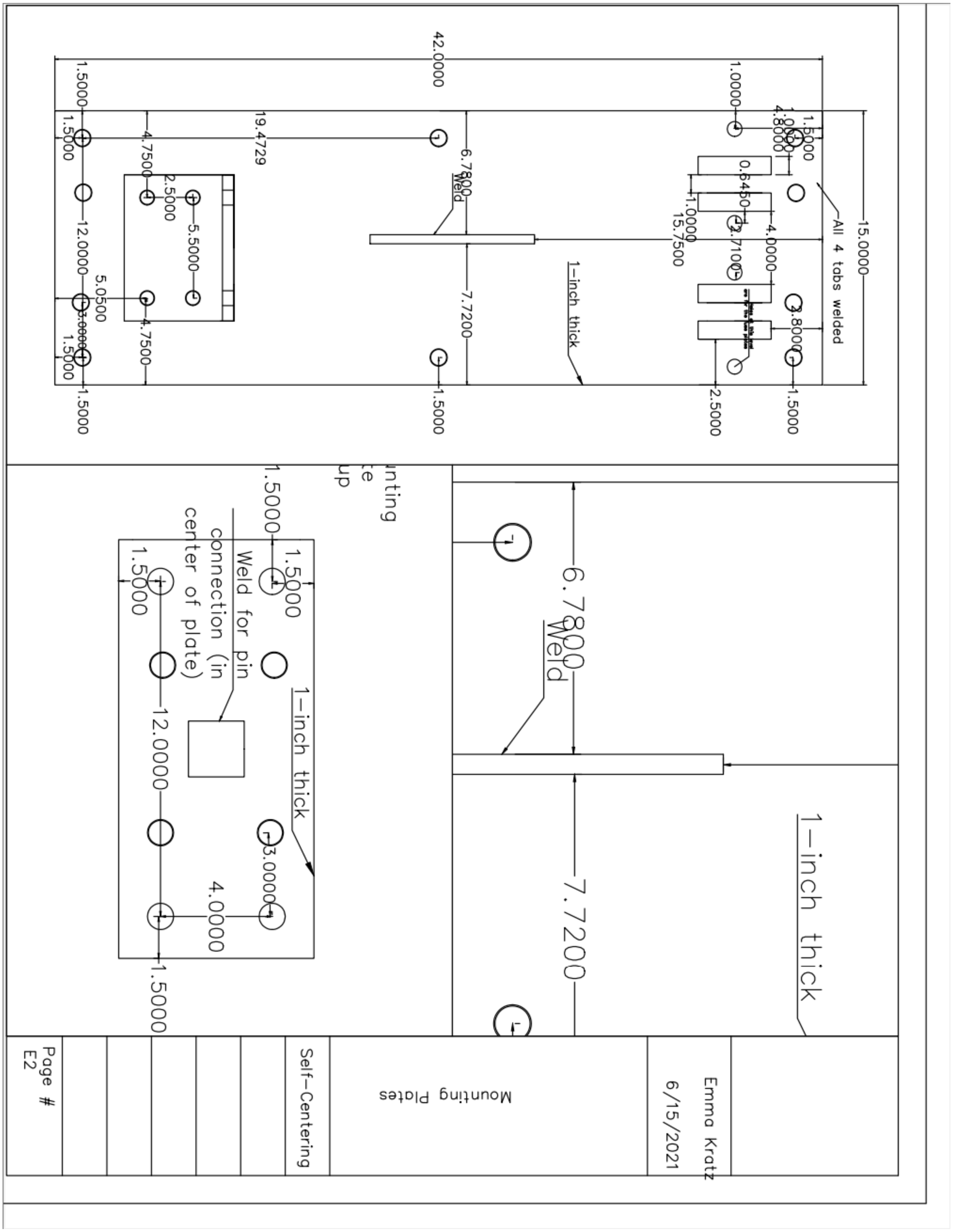
Column Cuts, cont'd.
Self-Centering
Page #
E1-2


All 4 tabs welded
1-inch thick
Weld
Weld for pin connection (in center of plate)
42.0000
15.0000
19.4729
6.7800
7.7200
12.0000
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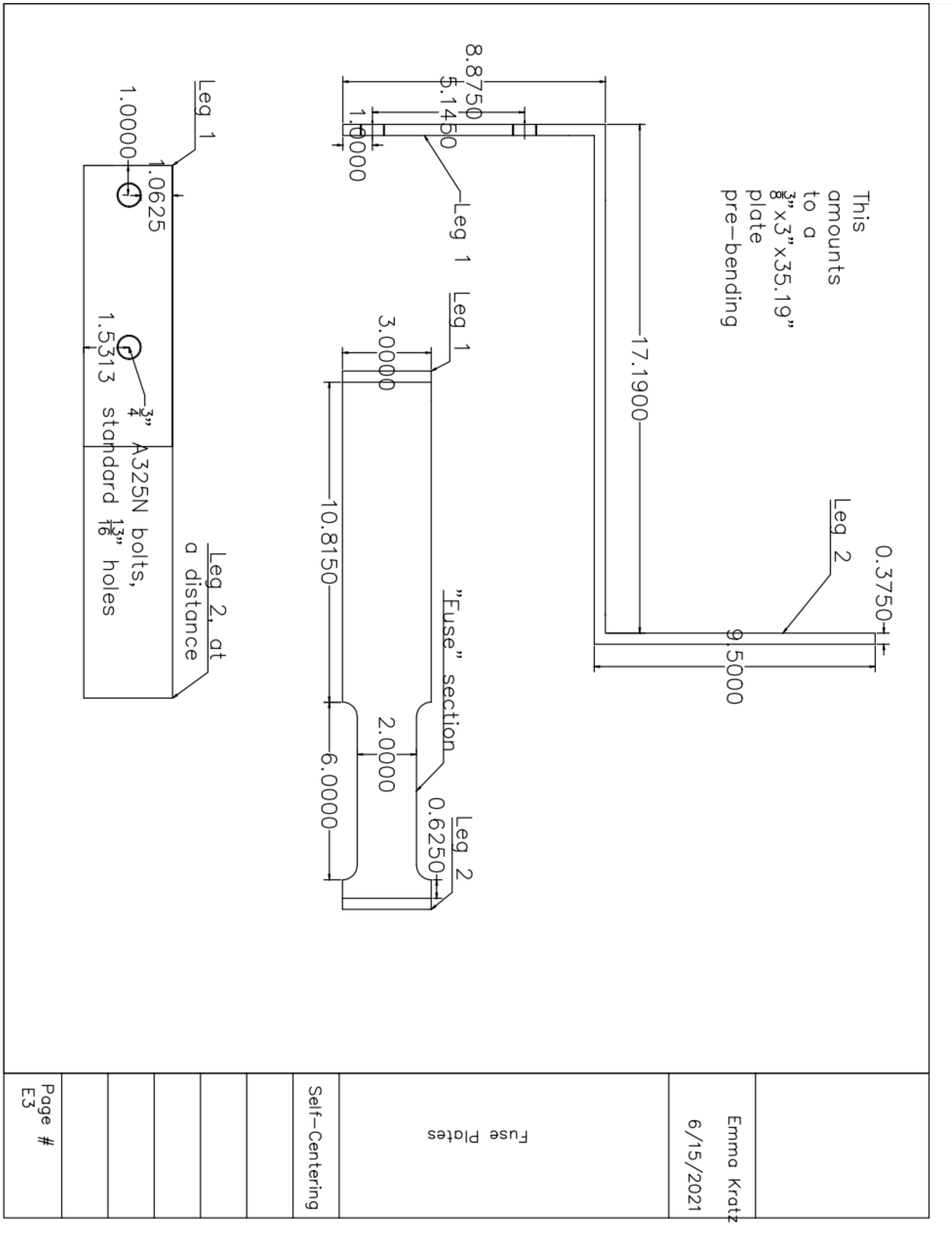
Mounting Plates
Self-Centering
Page # E2


This amounts to a 3/8"x3"x35.19" plate pre-bending
8.8750
5.1450
1.0000
Leg 1
17.1900
Leg 2
0.3750
9.5000
Leg 1
3.0000
10.8150
"Fuse" section
2.0000
6.0000
0.6250
Leg 2
Leg 1
1.0000
1.0625
1.5313
3/4" A325N bolts, standard 13/16" holes
Leg 2, at a distance
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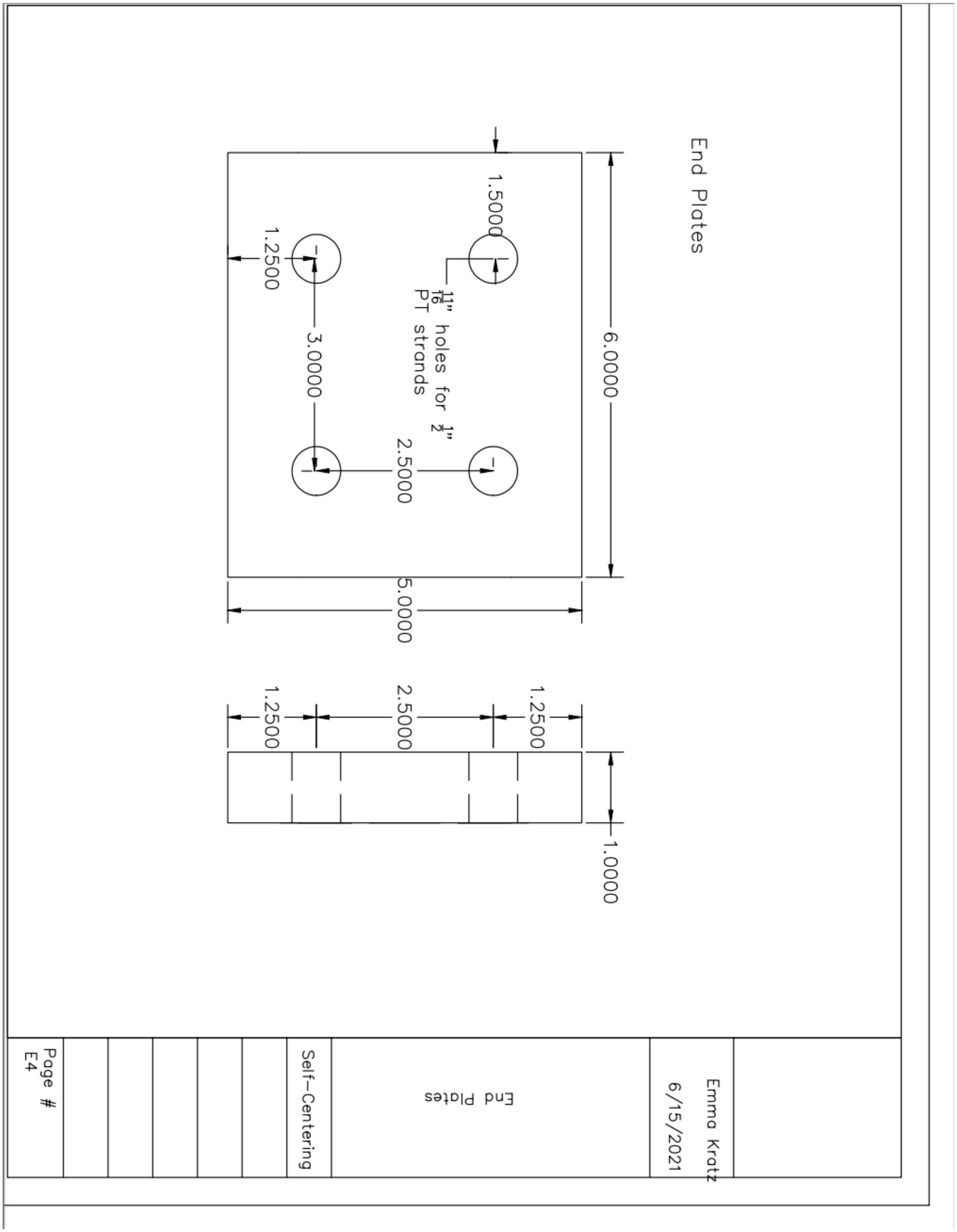
Fuse Plates
Self-Centering
Page # E3


End Plates
1.5000
1.2500
$\frac{11}{16}$" holes for $\frac{1}{2}$" PT strands
3.0000
2.5000
6.0000
5.0000
1.2500
2.5000
1.2500
1.0000
Page #
E4
Self-Centering
End Plates
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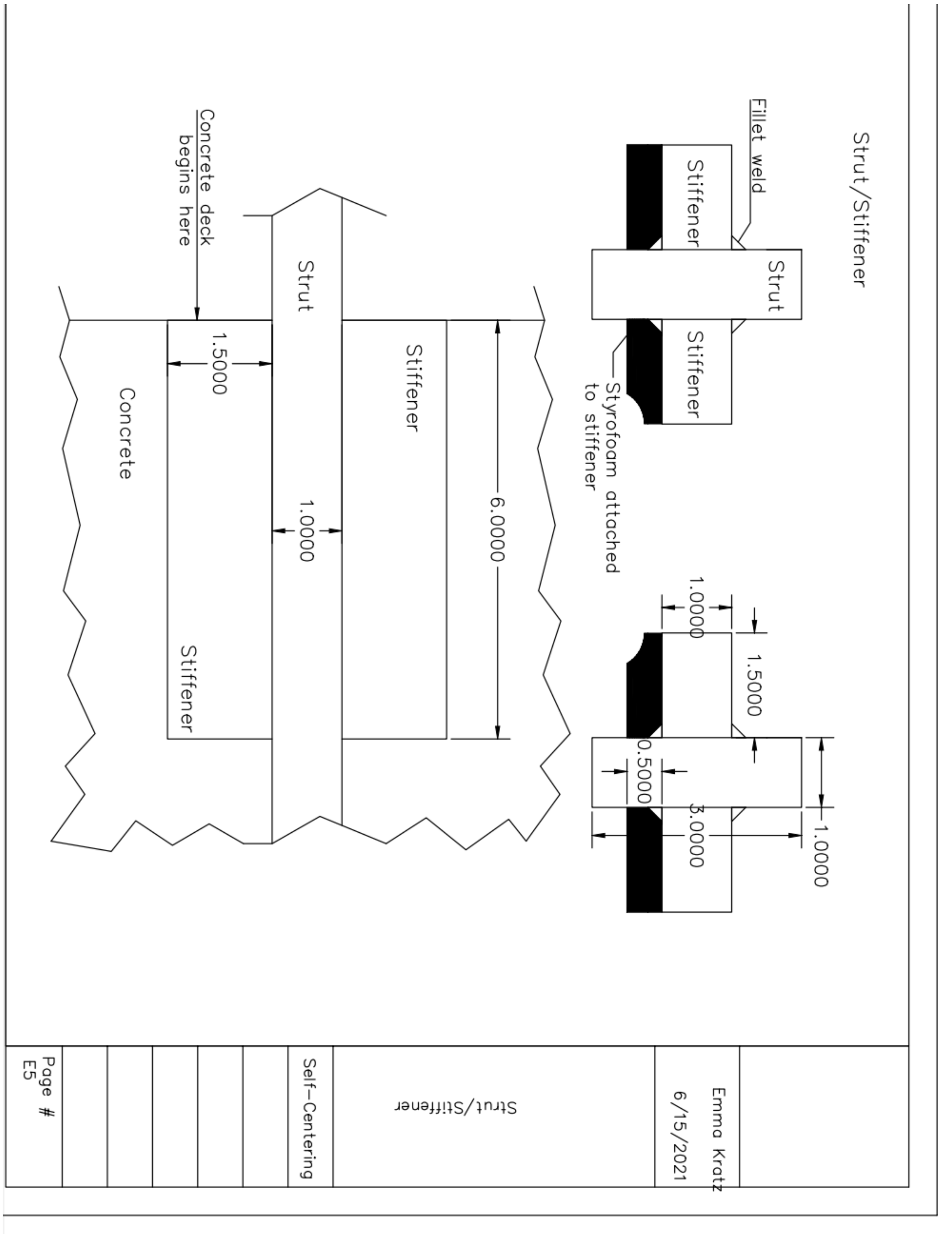
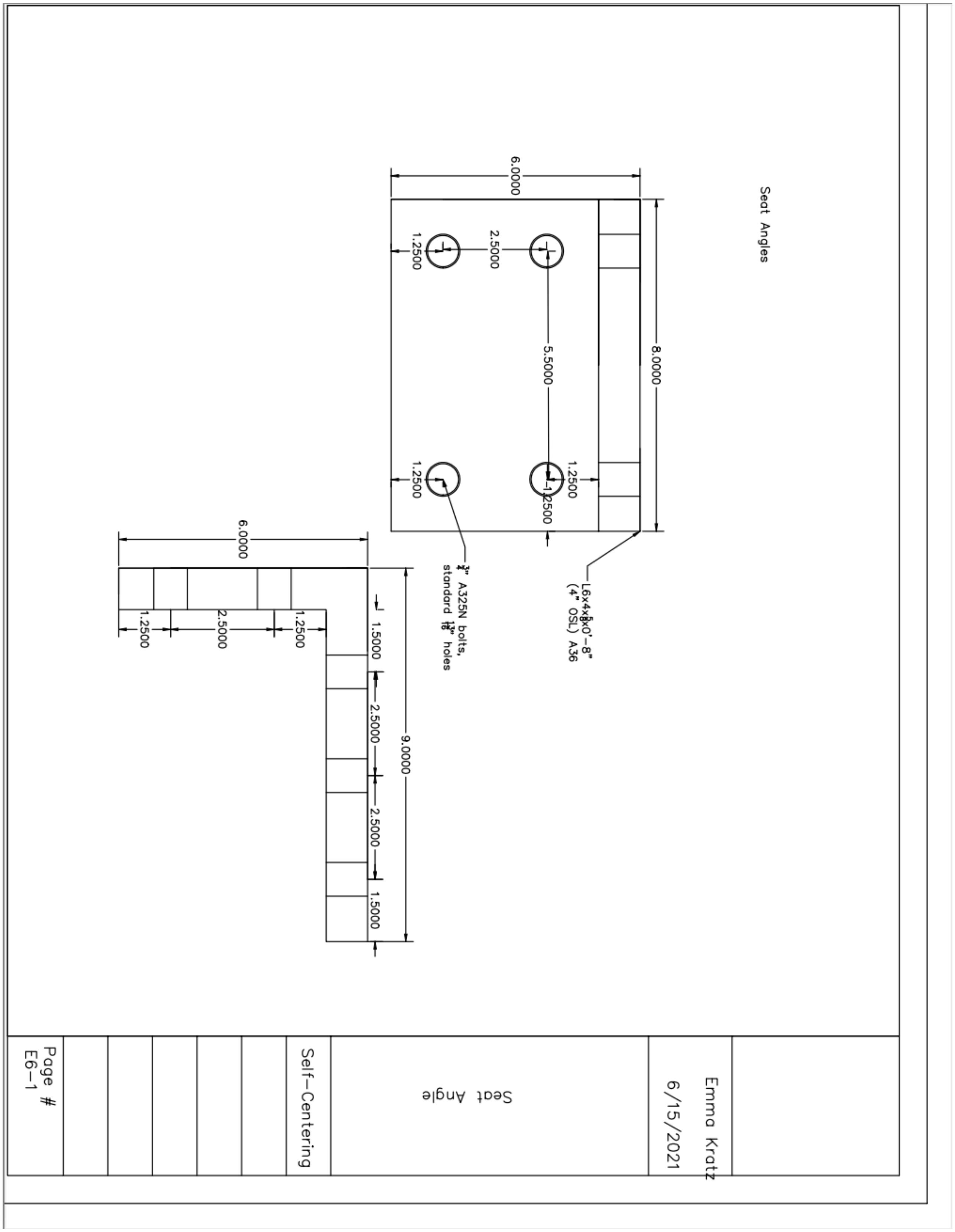
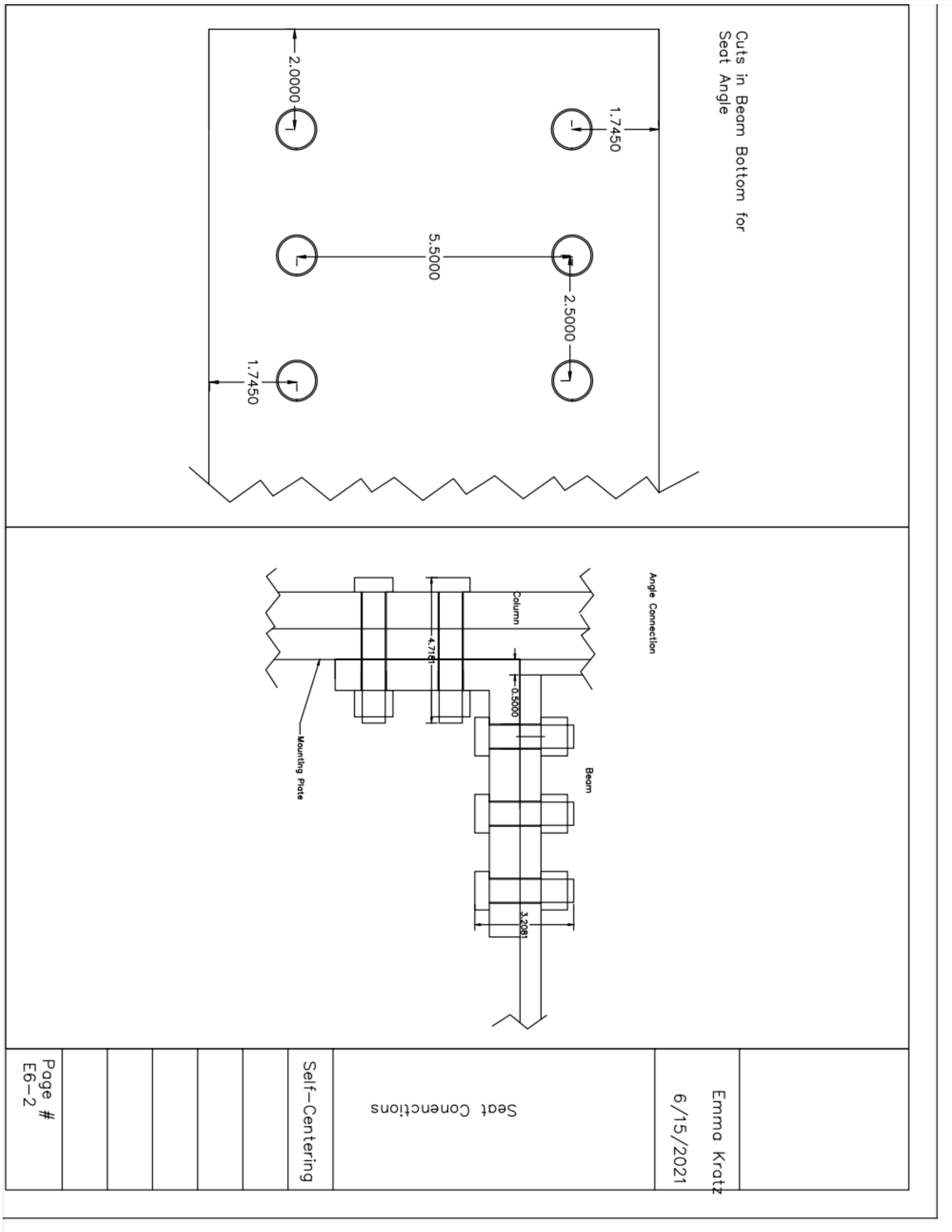

Strut/Stiffener
Fillet weld
Stiffener
Strut
Stiffener
Styrofoam attached
to stiffener
1.0000
1.5000
0.5000
3.0000
1.0000
Concrete deck
begins here
Strut
Stiffener
1.5000
Concrete
1.0000
6.0000
Stiffener
Page #
E5
Self-Centering
Strut/Stiffener
Emma Kratz
6/15/2021



Seat Angles
6.0000
8.0000
1.2500
2.5000
5.5000
1.2500
1.2500
1.2500
L6x4x5/8x0'-8"
(4" OSL) A36
3/4" A325N bolts,
standard 13/16" holes
6.0000
1.2500
2.5000
1.2500
1.5000
2.5000
9.0000
2.5000
1.5000
Emma Kratz
6/15/2021
Seat Angle
Self-Centering
Page #
E6-1



Cuts in Beam Bottom for Seat Angle
1.7450
2.0000
5.5000
2.5000
1.7450
Angle Connection
Column
4.7181
0.5000
Beam
Mounting Plate
3.2081
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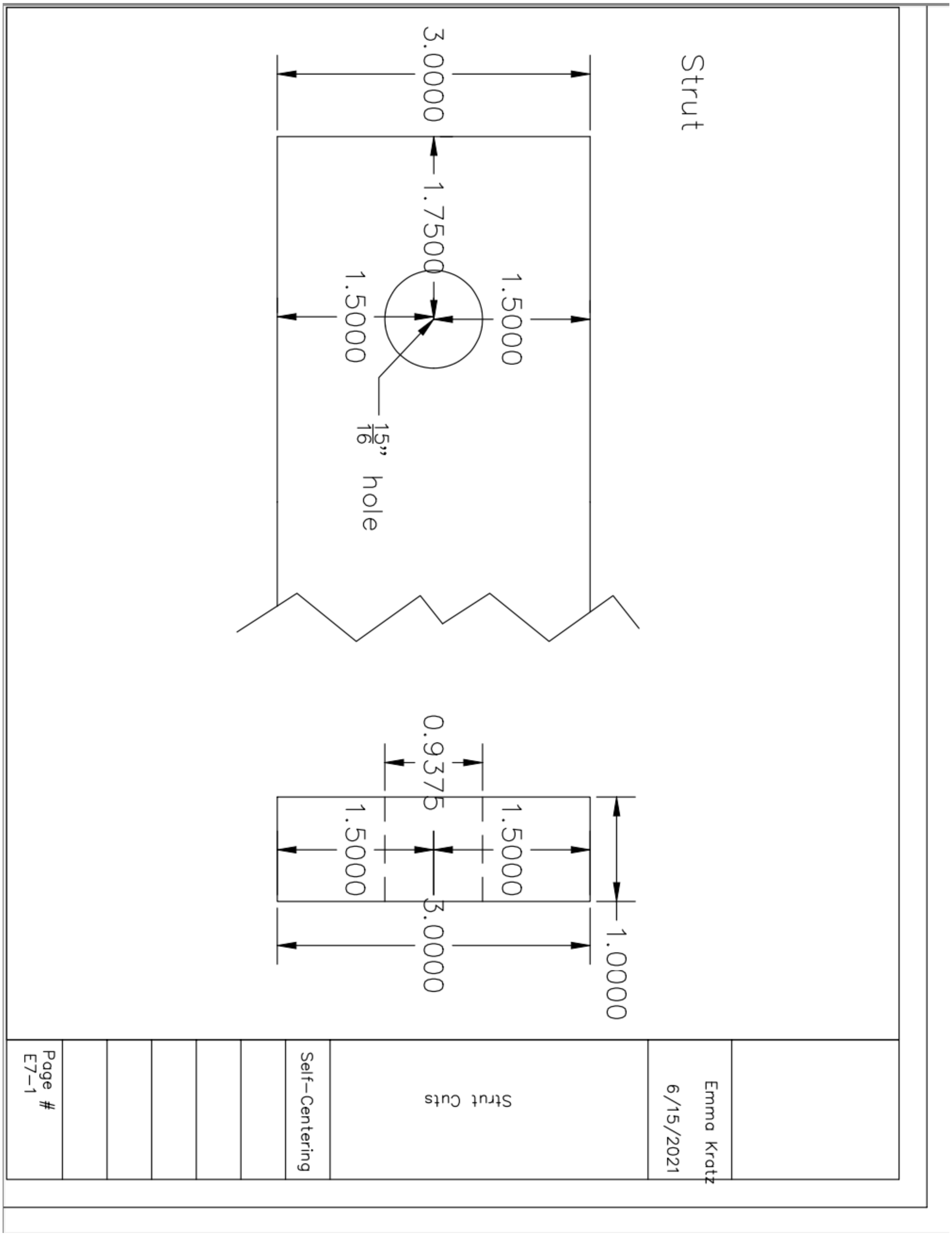
Seat Conenctions
Self-Centering
Page # E6-2



Strut
3.0000
1.7500
1.5000
1.5000
15/16" hole
0.9375
1.5000
1.5000
3.0000
1.0000
Page #
E7-1
Self-Centering
Strut Cuts
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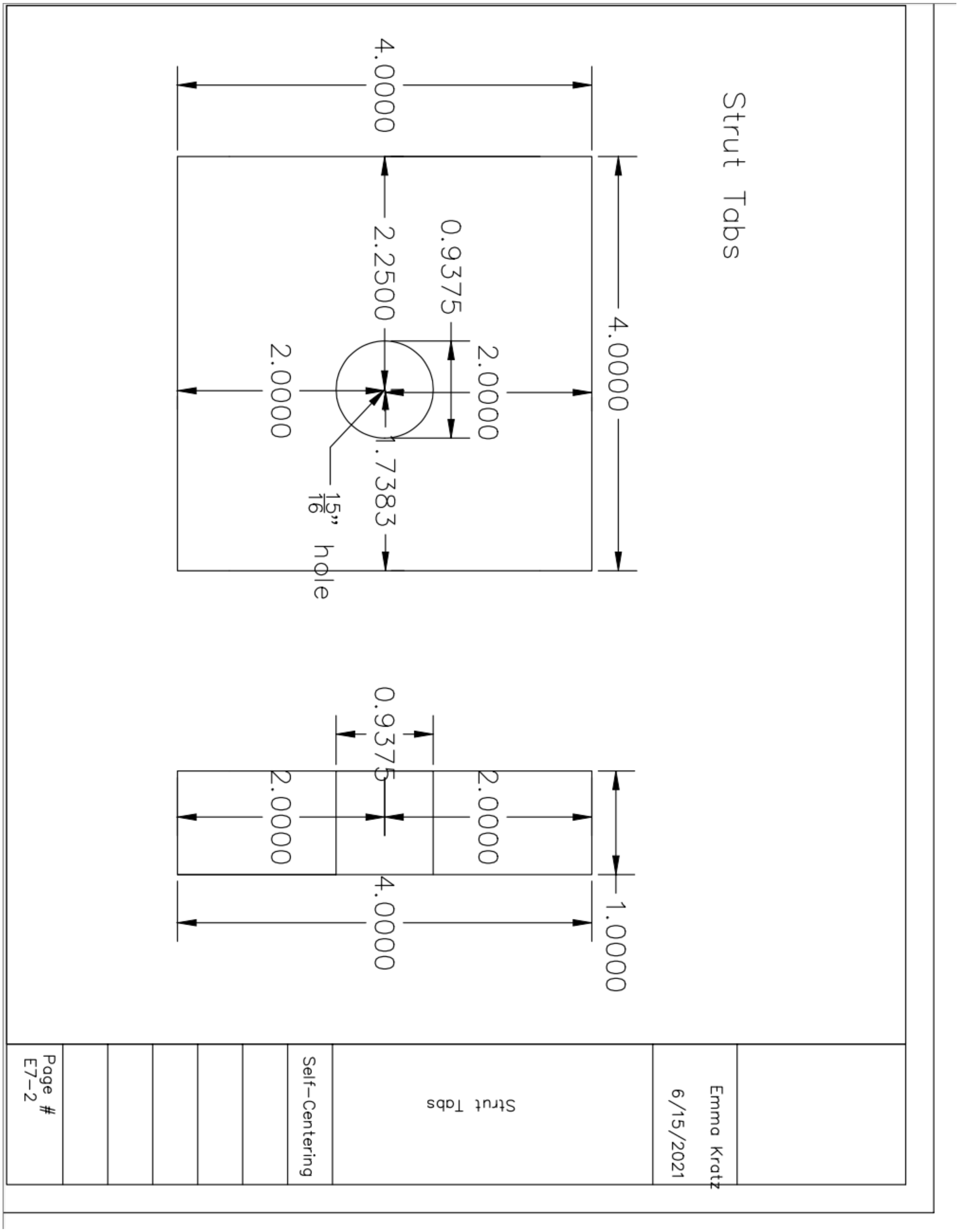
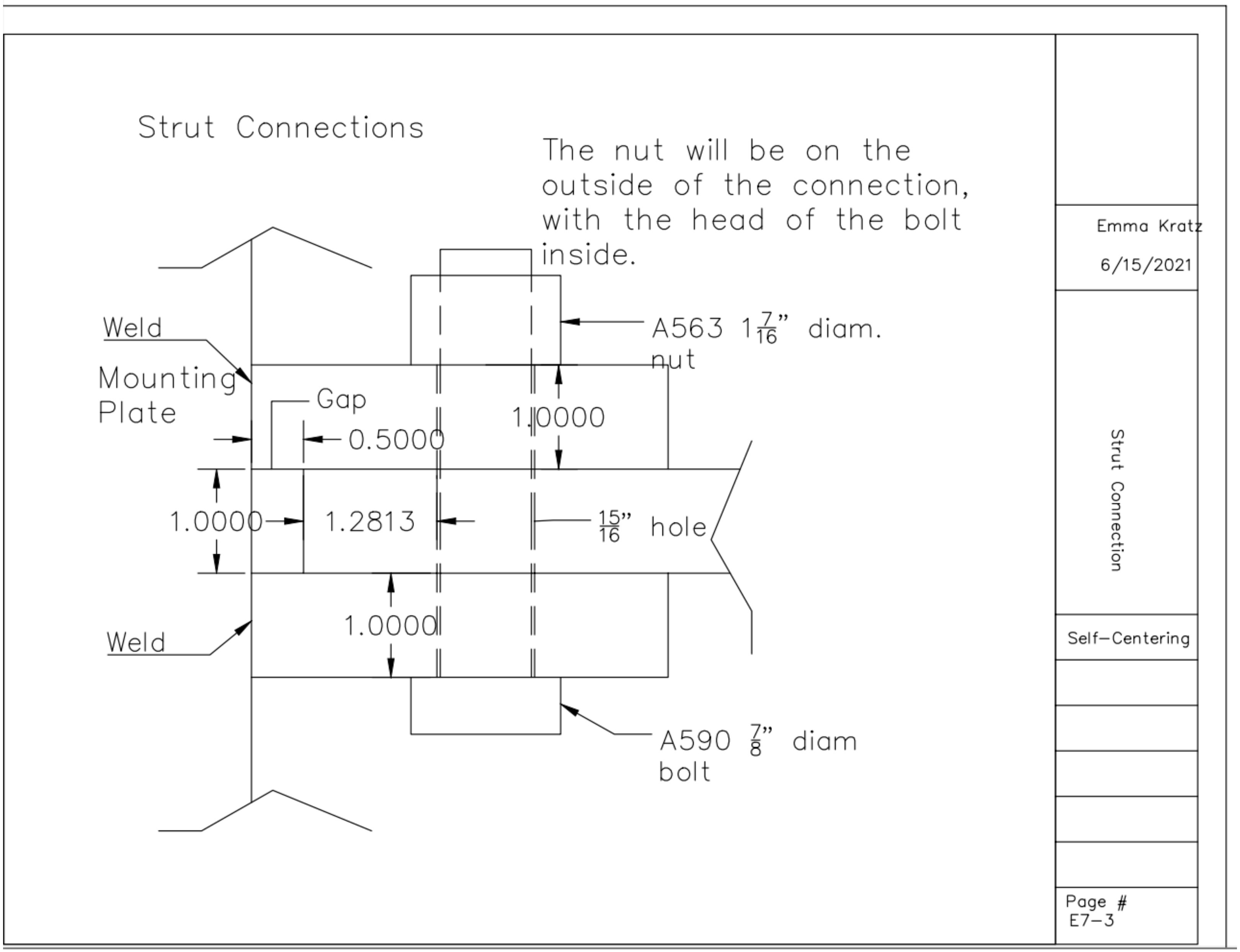
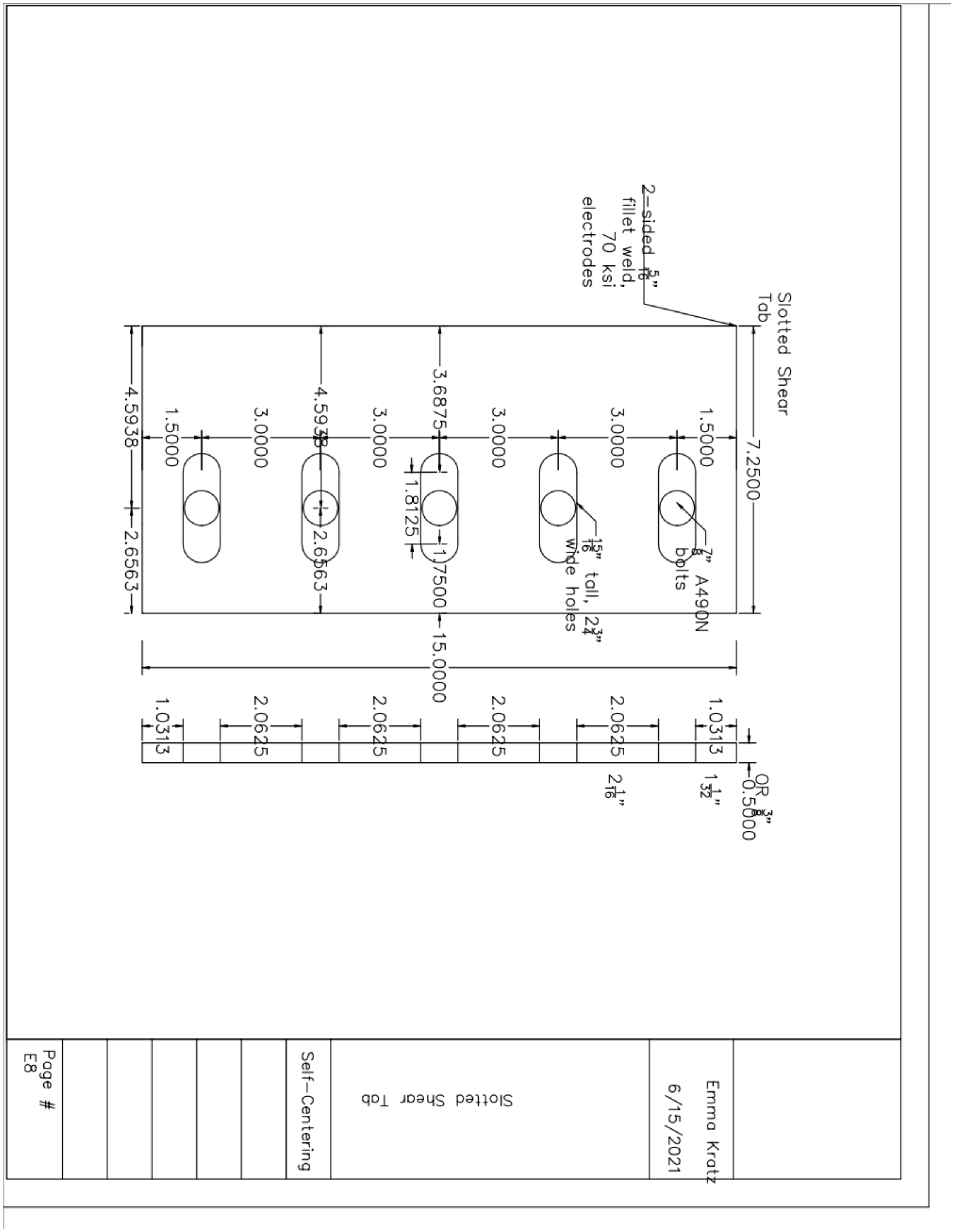
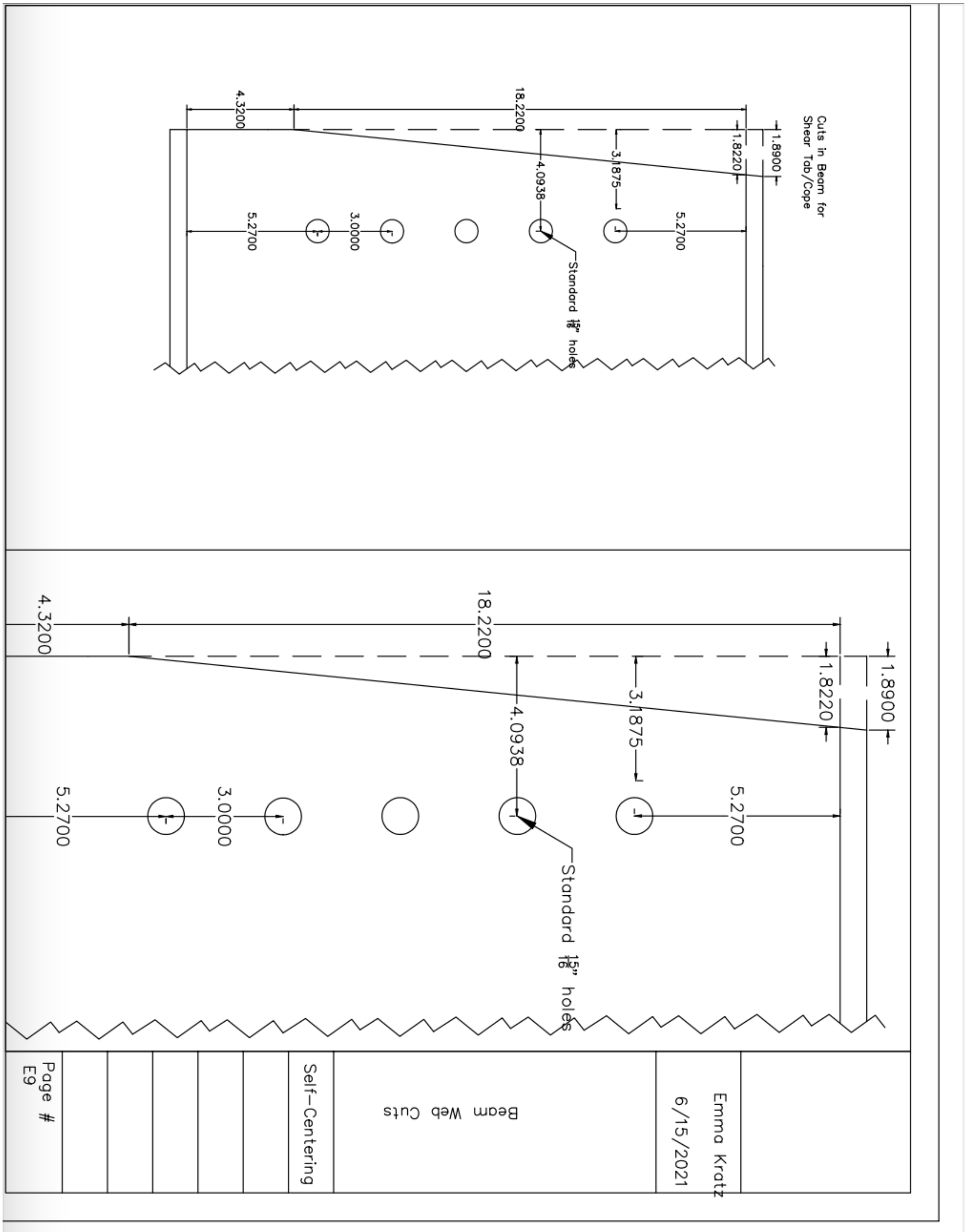

Strut Tabs
4.0000
4.0000
0.9375
2.2500
2.0000
2.0000
1.7383
15/16" hole
0.9375
2.0000
2.0000
4.0000
1.0000
Emma Kratz
6/15/2021
Strut Tabs
Self-Centering
Page #
E7-2


Strut Connections
The nut will be on the
outside of the connection,
with the head of the bolt
inside.
Weld
Mounting
Plate
Gap
0.5000
1.0000
1.0000
1.2813
1.0000
15/16" hole
A563 1 7/16" diam.
nut
Weld
A590 7/8" diam
bolt
Emma Kratz
6/15/2021
Strut Connection
Self–Centering
Page #
E7–3


Slotted Shear Tab
2-sided 5/16" fillet weld, 70 ksi electrodes
7/8" A490N bolts
15/16" tall, 2 3/4" wide holes
7.2500
1.5000
3.0000
3.0000
3.0000
3.0000
1.5000
3.6875
4.5938
4.5938
2.6563
2.6563
1.8125
1.7500
15.0000
1.0313
2.0625
2.0625
2.0625
2.0625
1.0313
1 1/32"
2 1/16"
0.5000
OR 3/8"
Emma Kratz
6/15/2021
Slotted Shear Tab
Self-Centering
Page #
E8



Cuts in Beam for Shear Tab/Cope
4.3200
18.2200
1.8900
1.8220
3.1875
4.0938
5.2700
3.0000
5.2700
Standard 15/16" holes
4.3200
18.2200
1.8900
1.8220
3.1875
4.0938
5.2700
3.0000
5.2700
Standard 15/16" holes
Emma Kratz
6/15/2021
Beam Web Cuts
Self-Centering
Page #
E9

APPENDIX B: MATERIALS LIST

a. Columns: (2) W30x191 A992 13-ft tall
b. Beam: (1) W24x76 A992 12-ft long
c. Struts: (2) PL1x3x12’-0” A572 Gr. 50
d. Post tension strands: (8) 0.5 in. dia. 270 ksi low-relaxation PT strands, ~25-30 ft long
e. Concrete: 2 cubic yards of 4 ksi lightweight concrete
f. Headed Studs: (11) 5/8” diameter HAS studs, 5-3/16” long
g. Metal Deck: 11’-1” of 3-inch, 18-gage deck
h. Shear Tabs: (2) PL0.5x7.25x15 A572 Gr. 50 (Or PL3/8x7.25x15 A572 Gr, 50)
i. PT Conduits: (4) 1” outer diameter, 12/16 inner diameter, 11’-1” long
j. Seat Angles: (2) L6x9x1x0’-8” (9” OSL) A36
k. Strut Tabs: (8) PL1x4x4 A572 Gr. 50
l. Fuse Plates: (4) PL3/8x3x36 A36
m. End Plates: (2) PL1x5x6 A572 Gr. 50
n. Stiffeners: (4) PL1x1.5x6 A572 Gr. 50
o. Plastic Covers/Sleeves: Needed for struts in concrete
p. PT Anchors: (8)
q. Beam mounting plates: (2) PL1x15x3’-6” A572 Gr. 50; (2) PL1x15x6
r. Bolts: Various sizes
s. Cross-laminated wooden floor: Use pre-existing blocks in lab