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Heterogeneous Thermal Effects on Structural-Grade Steel

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Heterogeneous Thermal Effects on Structural-Grade Steel

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Department of Civil Engineering

Honors Research Project

Submitted to

The Honors College

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ABSTRACT

The AISC Steel Construction Manual covers structural steel design while at atmospheric and elevated temperatures. The manual does not, though, cover what happens to the steel after it has cooled from elevated temperatures. To fill in this knowledge gap, A36 steel was studied with respect to three main criteria: time, temperature, and cooling. Time was sub-divided into a standard burn (17-20min) and a prolonged burn (90min). Temperature was sub-divided into an average burn (600-800^{o}F) and an extreme burn (>1200^{o}F). To reach such temperatures, a forge was constructed and used during the burning process. Cooling was sub-divided into standard (air cooling) and rapid (water quenching) cooling. All possible combinations of time, temperature, and cooling were made in order to test all possible effects. No mechanical loading was used during any of the burns in order to only test the heterogeneous thermal effects. The prescribed burn combinations were performed on Charpy impact samples, compression slugs, and tensile coupons. The samples were then destructively tested in order to determine the principal stresses and the ductility of the samples after the burns. After testing, it was determined that while the standard burn is not ideal for the health of the structure, no immediate effects should be seen. For extreme burns though, depending on the length of time of the burn and the rate of the cooling, two main thermal effects will be almost immediately noticeable. Under rapid cooling conditions, brittle-strengthening will most likely be present; the degree of which depends on the duration of the exposure to the heat source. Without rapid cooling conditions, when the steel was exposed to the heat source for a long period of time, annealing will most likely be exhibited by the steel. Without rapid cooling conditions, when the steel was exposed to the heat source for a short period of time, no immediate effects should be seen. For seismic design, any adverse thermal effects could potentially be detrimental to the safety/stability of the structure. That is why it is recommended that after any fire event, the steel elements of the structure be inspected and retrofitted/replaced if it has been determined that brittle-strengthening or annealing has occurred. For structures not under immediate seismic threat, the urgency of the retrofit/replacement of the elements after inspection should be based on which thermal effect would most likely have occurred. Brittle-strengthening should be handled immediately, while annealing can be handled at a later, more convenient, time.

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SPECIAL THANKS

Special thanks to Dave McVaney. Without Dave this project would have never gotten off the ground. From his advice on the design of the samples, to him allowing us to use the machinery in his lab for our testing, or with his bubbly personality encouraging us to go further than we ever thought we could, none of this would have been possible without him. Thank you, Dave, for everything that you have done for us, you are a true friend.

INTRODUCTION

The AISC Steel Design Manual is thorough with respect to the design of steel members at normal, atmospheric temperatures and while at elevated temperatures. The elevated temperature section, Appendix 4: Structural Design for Fire Conditions, covers the "degradation in mechanical properties of materials at elevated temperatures that cause [a] progressive decrease in [the] strength and stiffness of structural components and systems" (Steel Construction Manual, 2013). Unfortunately, this section lacks information on what happens to the different grades of structural steel after being subjected to elevated temperatures. The purpose of this research project is to partially fill in the information gap on this subject. To do this, the grade of steel that will be focused on will be A36 steel. To fully test the steel, an array of different heating/cooling conditions and different testing methods will be studied using each sample in order to thoroughly examine how the steel reacts under principal stress conditions. The following pages detail how each burn and test was conducted and the resulting data that came out of this research project.

MATERIAL AND SUPPLIES

Forge: A forge was developed, built and used to subject the steel samples to elevated temperatures.

Forge Materials. The following materials were used in the construction of the forge:

-50lb bag of Play Sand
-Bag of Plaster of Paris
-Clean supply of water
-6 gallon steel can
-5 quart plastic bucket
-Two U-bolts
-Two 1-1/4"x10" steel pipe
-1-1/4" steel coupler
-1-1/4" PVC female adapter
-1-1/4" PVC pipe
-1-1/4" PVC regulator valve

Forge Equipment. The following tools were used in the construction and operation of the forge:

-1-3/4" bi-metal hole saw
-Pair of locking tongs
-11" needle nose pliers
-Multiple bags of charcoal
-High temperature thermometer
-Bucket of water
-Assorted safety equipment

Test Samples. All of the samples used in this report were made out of A36 steel. The following materials were used as the tests samples in this report:

-3/4" dia x 1" long Compression Slug

-3/8"x3/8"x2 1/8" Charpy Impact Sample

-Tensile Coupon that is 8" long overall with a 3" long narrowed section in the middle that is ½" wide and ¼" thickness

*See Appendix D for more detailed dimensions of the tensile coupon and images of the manufacture of the samples.

Testing Equipment. The following machines were used in the testing of the samples:

-Tinius Olsen Charpy Impact Hammer

-Baldwin, Warner & Swasey Press

-Instron, Satec Series Press

CONSTRUCTION OF THE FORGE

Design of the Forge. Please see Appendix A for final design drawings of the forge.

Mix Design. The mix to be used in the construction of a forge is as follows:

-21 cups play sand

-21 cups Plaster of Paris

-15 cups of water

The above mixture creates one batch of fire concrete. With fire concrete being a special mix of concrete that is resistant to extreme temperatures.

Construction of the Forge. In order to construct a forge, the materials listed in the Materials and Supplies: Forge Materials section that apply to the forge must be collected. First measure out the dry components of the mixture and place them into the can that will make the outside shell of the forge. Then begin to add the water to the dry mix, and stir until the mix is a consistent paste. For the forge that was built in this report, two batches of fire concrete were necessary to fill the can. The number of batches needed to fill a can will vary due to different can sizes. NOTE: the mix begins to set almost immediately after mixing. After the bucket is filled roughly 2/3 full of fire concrete, the 5-quart bucket must be pushed into the mix to create a cavity where the fuel source will burn. To keep the bucket in place more easily, the bucket can be filled with water to cancel out the buoyancy of the bucket in the fire concrete. The fire concrete now must sit for approximately 30 minutes in order to set.

After letting the fire concrete set for 30 minutes, the concrete should be hardened enough to work with but still soft enough to make tooling easier. First, empty the water from the plastic bucket inside the forge. Next, using the hole saw drill bit, begin to cut horizontally into the side of the can. Once through the metal, fire concrete, and plastic bucket, drill a downward sloped hole where the horizontal hole was drilled. Using the horizontal hole as a guide, continue to drill until the bit has pushed into the main cavity of the forge. The end result should be a downward hole that sits approximately one inch above the bottom of the forge's cavity. At this time, make sure to check if the steel pipe used for the air supply tube fits tightly into the drilled hole, yet is still easily removed without too much force. If the tube does not fit, re-drill as needed. Next, using a set of pliers, grip the rim of the plastic bucket and begin to twist the bucket into itself in order to pull the bucket out of the forge. NOTE: use care not to hit the sides of the forge too hard, since the fire concrete is still soft. Once the bucket is removed, the forge must then be allowed to cure for at least 24 hours before performing the first burn.

The next phase of constructing the forge is casting the lid. The lid will use the same mix as the forge, but at a reduced batch size. Once again, measure and add the dry components of the mix to the mold that will be used for the lid. The mold can be a plastic bucket, but for the forge that was built for this report, the lid of the can was used instead. Once the dry mix components are measured, add the water to the dry mix and stir until the mix is a consistent paste. For the lid that was built in this report, 1/3 of a batch was used to make the lid. This may vary from design to design due to different sizes of lid molds. NOTE: the mix begins to set almost immediately after mixing. Once the fire concrete is in place in the mold, place the U-bolts deep enough into the mixture in order to keep them in place during use. The fire concrete must sit for approximately 30 minutes for it to cure to a workable strength. Next, using pliers, pull the mold off the lid. After the lid is removed from the mold, use the drill bit that was used to make the air supply hole and drill a vent hole in the middle of the lid. This will allow fumes to escape from the forge while retaining most of the heat inside the forge. Finally, allow the lid to cure for at least 24 hours before performing the first burn.

Images of the construction of the forge that was used in this report are included in Appendix B.

Test Burning the Forge. After waiting at least 24 hours after initially building the forge, the first burn can be performed. This burn is meant to be a relatively light burn in order to remove any remaining moisture in the fire concrete. The forge must be placed in an area that creates minimal risk to any structures, personal property, or personal harm to anyone. First place the air supply tube into the forge. It is recommended that a support block be placed under the tube in order to minimize stress on the side of the forge. A blower system must then be placed in a manner that allows the blower to force air down the air supply tube. Once the air supply systems are in place, the fuel can be added. The fuel used in this report was charcoal due to cost constraints. Once the fuel is in place, carefully ignite the fuel and turn on the air supply once the users are at a safe distance in order to prevent a flare up from the added air flow from the blower. Make sure to set the blower system at the lowest possible setting in order to prevent the fire from getting too hot. Once again this is meant to be a light burn in order to cook out any remaining moisture left in the fire concrete. After the fire is steadily burning, carefully place the lid on the forge to allow the lid to cook too. This preliminary burn should last for approximately one hour.

Once the burn is completed and the fuel source has been exhausted, allow the forge to sit and air cool until it has returned to a safe temperature at which the users can handle it without fear of burning themselves. After the forge is safe to handle once again, clean out the ashes (if any) and place the forge in a safe, dry place for storage until needed for further burns.

Images of the testing of the forge that was used in this report are included in Appendix B.

After the first official burn, it was determined that the blower used pumped too much air into the forge even on the lowest setting. It was determined that a PVC pipe with a regulator valve should be added to better control the air flow for this study.

BURNING PROCEDURES

Burn Criteria. The following burn criteria will be used in order to generalize the conditions a structure may endure during a fire event:

Time. Two categories for time will be used during the controlled burns. The first category will be called a Standard Burn, which will be based off the average 911 Emergency response time of 7-10 minutes plus an additional 10 minutes to account for a delayed response in reporting the fire. This totals to a Standard Burn being 17-20 minutes long. The second category will be called a Prolonged Burn which will be based on an out of control fire that has to burn itself out. For the sake of time and integrity of the forge, the prolonged burn will be limited to a 90 minute burn time.

Temperature. Two categories for temperature will be used during the controlled burns. The first category will be called an Average Burn and will have a temperature ranging from 600-800^{o}F. This will represent a standard wood fire or house fire. The second category will be called an Extreme Burn and will have a temperature greater than 1,200^{o}F. This will represent a more extreme fire such as a chemical fire.

Cooling. Two categories for cooling will be used after the burns have been completed. The first category will be called Standard Cooling and will consist of allowing the test samples to air cool until the samples are at room temperature. This will represent when the steel is allowed to naturally air cool in the outside atmosphere. The second category will be called Rapid Cooling and will consist of placing the test samples in an ice bath or blasting with a high pressure hose until the samples are at room temperature. This will represent when the steel is cooled by a fire hoses or outside weather conditions that would result in such a cooling condition.

Note. The samples are not placed under any mechanical loading during any of the burns or cooling procedures in order to only test the effects of the thermal changes.

Preparing the Forge. In order to prepare the forge for burning the samples, the pipe and blower must first be set in their respective places. After that, the forge must be filled with charcoal and a small amount of lighter fluid is to be added in order to light the charcoal. Once the fire is lit, the blower must be turned on at its lowest setting in order to supply air to the charcoal. Once the blower is on, the regulator valve must be adjusted appropriately in order to maintain a constant air flow to the charcoal, but not enough to overheat the forge. Using a high temperature thermometer, adjust the air flow with the valve until the thermometer reads the desired temperature within the forge.

Burn Combinations. Once the forge has been prepped, the following burn combinations will be performed on each type of sample within the forge:

-Standard Burn, Average Burn, Standard Cooling (SAS)

-Standard Burn, Average Burn, Rapid Cooling (SAR)

-Standard Burn, Extreme Burn, Standard Cooling (SES)

-Standard Burn, Extreme Burn, Rapid Cooling (SER)

-Prolonged Burn, Average Burn, Standard Cooling (PAS)

-Prolonged Burn, Average Burn, Rapid Cooling (PAR)

-Prolonged Burn, Extreme Burn, Standard Cooling (PES)

-Prolonged Burn, Extreme Burn, Rapid Cooling (PER)

Burning the Samples. Once the forge is at the designated temperature, the samples for that specific temperature must be placed into the forge. The samples should be placed under a layer of charcoal in order to evenly heat the samples. During the burn, the temperature of the forge must be constantly monitored with a high temperature thermometer and the air flow valve must be adjusted accordingly to maintain a constant temperature. Once the sample has been burned for its designated burn time, the sample is to be removed from the forge with tongs. The samples are then allowed to cool based on their designated cooling condition. If the sample calls for rapid cooling, then the sample is to be placed in a bucket of water until it is at a safe temperature to handle. If the sample calls for standard cooling, the sample is to be placed on a brick until it is at a safe temperature to handle.

Documenting the Samples. After the samples have been pulled out of the fire and have cooled, each sample is placed in an individual envelope and labeled with its burn combination.

TESTING PROCEDURES

Charpy Impact Samples. The Charpy impact samples, after they have been burned and cooled, are to be destructively tested using a Tinius Olsen Charpy impact hammer or similar type of machine. During the testing, the impact hammer is to be raised to its apex and the sample is to be placed in the sample seat. Then the hammer is to be released and swung into the sample. The hammer must not be allowed to swing more than once in order to prevent the hammer from skewing the data. The data is to be read from the hammer and recorded for further analysis.

Compression Slugs. The compression slug samples, after they have been burned and cooled, are to be destructively tested using a Baldwin, Warner & Swasey Press or a similar type of press. Before the sample is tested, a piece of sacrificial metal must be placed above and below the sample in order to prevent damage to the machine during testing. The sample is to then be loaded by the machine at a rate of approximately 100 lb/s. The sample will be tested until the sample fails or it compresses to half of its initial length. The load placed on the sample and the deflection of the sample, using a dial gauge, are to be recorded for further analysis.

Tensile Coupon. The tensile coupon samples, after they have been burned, are to be destructively tested using an Instron, Satec Series Press or a similar type of press. The samples are to be placed in the machine's clamps and then pulled apart at a rate of 100 lb/s until the sample ruptures. The load placed on the sample and the deflection of the sample, measured by the testing machine, are to be recorded for further analysis.

RESULTS/DATA

Sample Images. Images of the samples before and after burning and testing are included in Appendix C.

Charpy Impact Sample Data. The following is the data collected pertaining to the Charpy impact samples tested.

Name*	Burn Time (min)	Burn Temp (^{o}F)	Cooling Time (min)	Energy Absorbed (ft-lb)
Base	-	-	-	160
SAS	20	700	30	165
SAR	20	700	5	154
SES	20	1300	30	146
SER	20	1300	5	10
PAS	90	700	30	166
PAR	90	700	5	190
PES	90	1300	30	170
PER	90	1300	5	29.5

*For unabbreviated names, please see Burning Procedures: Burn Combinations.

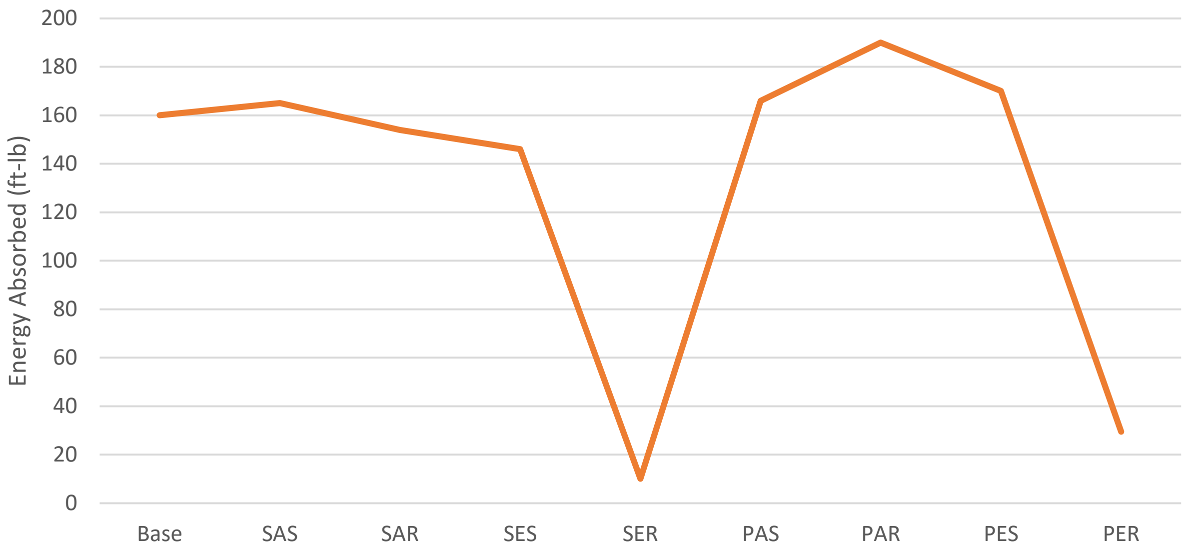
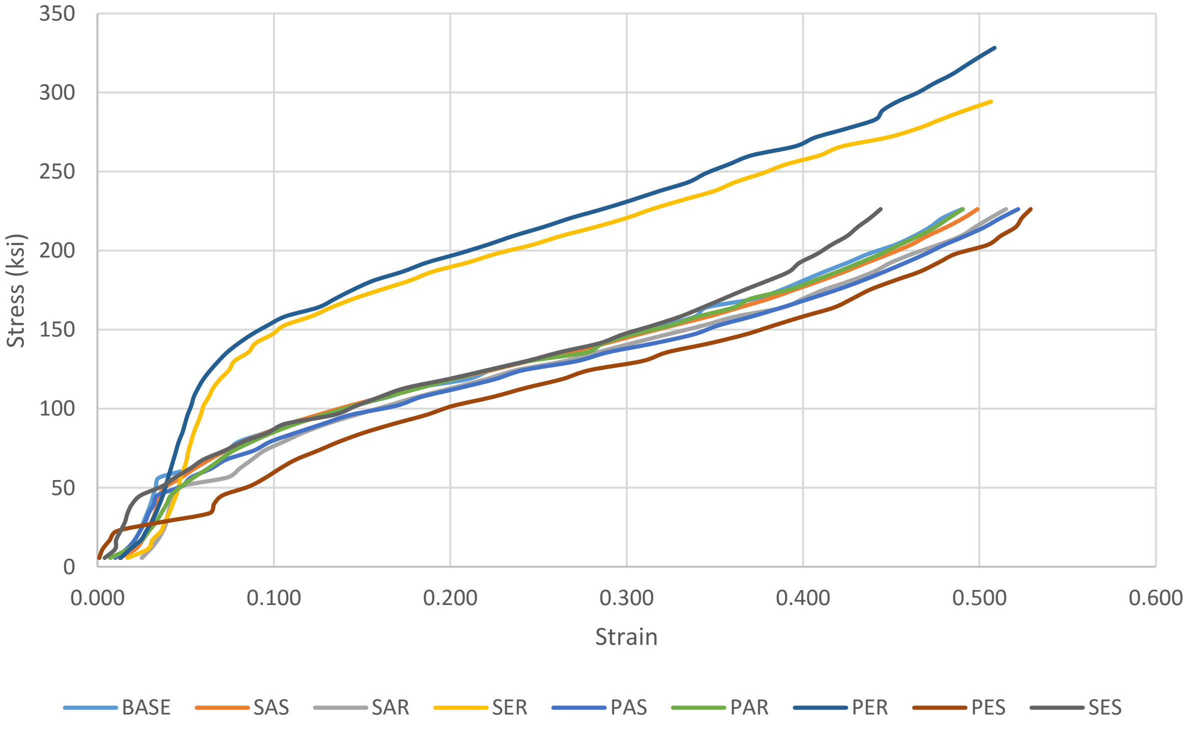


Figure 1. Charpy Impact Sample Comparison.

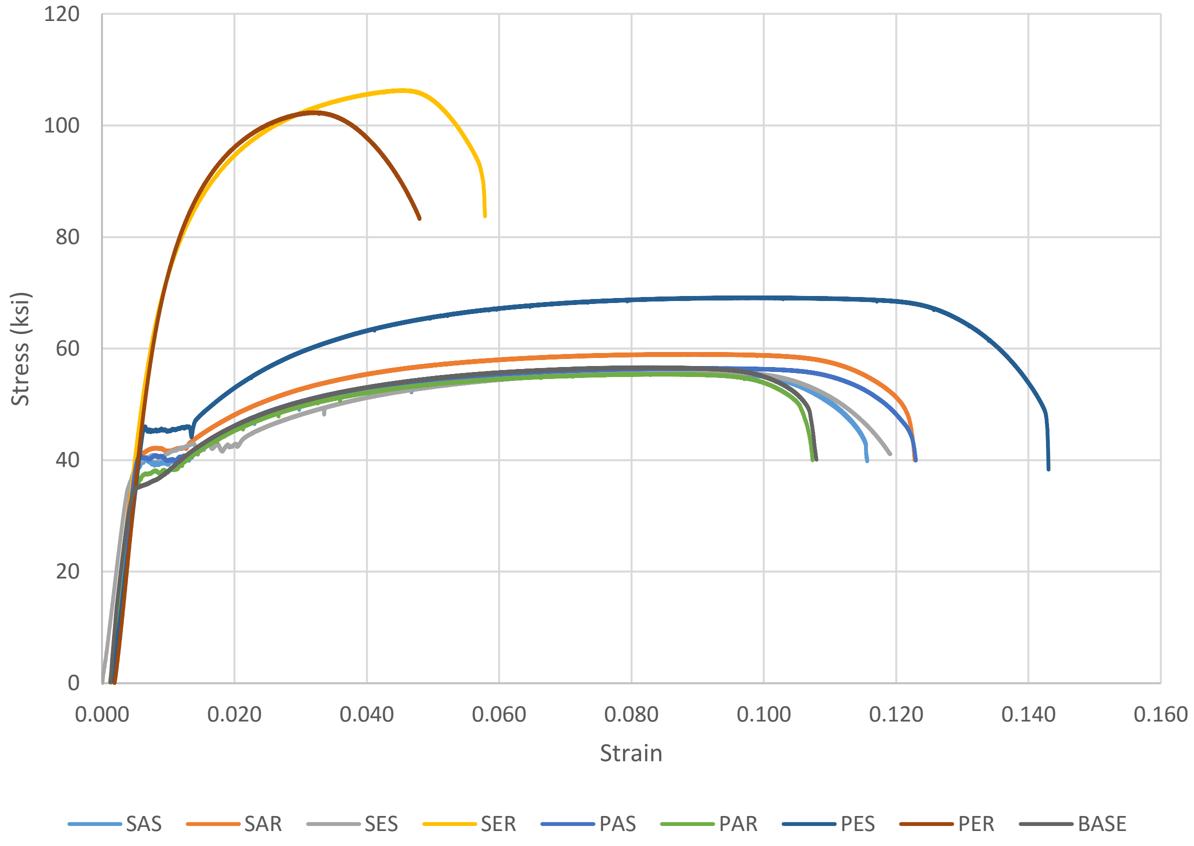
Compression Slug Sample Data. The following is the data collected pertaining to the compression slug samples tested.



*The initial strain seen in the samples is likely caused by the sacrificial steel compressing before the sample itself begins to compress.

Figure 2. Compression Slug Comparison.

Tensile Coupon Sample Data. The following is the data collected pertaining to the tensile coupon samples tested.



*The initial strain seen in the samples is caused by the slack in the machine being taken up and measured by the testing machine.

Figure 3. Tensile Coupon Comparison.

DISCUSSION

From the data above, it can be determined that the process of extreme heating and rapid cooling causes a brittle-strengthening effect in the samples exposed to these conditions (PER and SER). From the Tensile Coupon and Compression Slug Comparisons, it can be seen that both the PER and SER samples have a dramatic increase in strength over all of the other samples tested. Both samples yielded at nearly double the strength of all the other samples. These two samples, at the cost of increasing their strength, become very brittle though, and do not show the typical strain hardening seen in most of the other samples. Examples of the samples' brittleness can be seen in Figures C5, C9, C16, C18, C25, and C27 in Appendix C. All of these images display brittle fracturing of each of the samples. It is important to note that other samples, as seen in Figures C12 and C13, show brittle fracturing as well, though, those samples are not necessarily as brittle as the PER and/or SER samples. This is confirmed when compared to the energy absorbed by the Charpy impact samples. Each of the Charpy impact samples tested absorbed 5 to 20 times the amount of energy absorbed by the PER and/or the SER samples. Finally, an important factor that cannot be over looked is the length of time the samples were exposed to the heat source. In the Tensile Coupon Comparison graph, it can be seen that the PER sample reaches a lower ultimate strength and a lower strain at rupture than the SER sample. It can be concluded that with longer heat exposure, the brittleness becomes more severe, with the strength beginning to decrease as well. This leads to the possibility of optimizing the strength and brittleness of the steel by changing the duration of exposure to the heat source.

In the PES sample, an annealing effect can be seen. Annealing is the process of heating steel and allowing it to slowly cool, thereby relieving internal stresses and toughening the steel. This is evident in Figure 3, with the PES sample having an increased yield strength, ultimate strength, and ductility. All of these benefits are gained without losing the typical tensile stress-strain profile, and the sample still exhibiting strain hardening. This process occurred due to the fact that the PES sample was exposed to a high enough temperature to allow the steel to initially soften, allowed to sit at temperature long enough to be heated throughout the sample, and was allowed to cool at a slow/even rate.

For the samples exposed to the standard temperature burns, only minimal changes to the strength and ductility occurred, regardless of the length of time of the burn or the rate of cooling. Therefore, it can be concluded that a burn of 800^o or less will result in no significant changes in the mechanical properties of the steel.

For the samples exposed to the extreme temperatures, the length of time of the burn and the rate of cooling can alter the properties of the steel depending on the combination used. Steels exposed to extreme temperatures and rapidly cooled will show brittle-strengthening, the degree of which depends on how long the steel was exposed to the extreme temperatures. If the steel is exposed to extreme temperatures and is allowed to slowly cool, the steel will either anneal if it is exposed for a longer period of time or will show little to no changes if it was exposed for a shorter period of time.

With this knowledge, the next step in the engineering process is to incorporate the knowledge into the design and maintenance of new and old structures.

Firefighting Implications. Since during a fire it is impossible to determine if the structure is under standard or extreme burn conditions, it is highly recommended to avoid spraying the steel components of the structure with water during and/or after the fire event. This is to prevent any negative heat treatments to the steel, such as brittle-strengthening as discussed earlier. In order to facilitate this recommendation, firefighters must be partially educated on these thermal effects and trained on how to avoid intentional rapid cooling of the steel structure. Unfortunately, though, while running into an inferno, most firefighters are unlikely to think of anything else other than putting the fire out and keeping as many people alive as possible. That is why the responsibility falls on the engineer, and the design/maintenance of the structure must account for expected rapid cooling.

Design/Analysis Implications. The brittle-strengthening effect has the potential to threaten any structure that has been built in any seismic region. For seismic design, in a seismic event, the structure is supposed to have specific elements exhibit ductile deformation. By doing so, the specific member that yielded absorbs energy in the process of failing. This allows the structure to act as a shock absorber and dissipate the energy, thereby avoiding (in theory) collapse of the structure. As stated in the AASHTO LRFD Seismic Analysis and Design of Bridges Reference Manual, "If one link of the chain is ductile and the tensile strength of that link is less than the strength of the other links, which may even be brittle, the chain will exhibit ductile behavior based on the behavior of the one ductile link" (Buckle et al., 2011). Unfortunately, the brittle-strengthening effect could cause the "link" that is supposed to fail to increase in strength and become brittle if it were exposed to the same/similar conditions of the PER or SER samples. This would then cause the "chain" to fail at a "link" that was not originally intended to fail and potentially cause the structure to collapse. Even the annealing effect, as seen in the PES sample, could pose a threat to this system since it increases the strength of the steel. One could argue that the ductile nature of the effect would allow the structure to deform even further and thereby absorb even more energy, but only if it was still the weakest "link" in the system. To counter these issues, once it has been determined that a fire event could create the same/similar conditions of the PER, SER, or PES samples in the structure, the structure should be thoroughly inspected. If it is determined that any key element(s) of the structure have been compromised by the fire event, the element(s) should be retrofitted or replaced.

The brittle-strengthening effect and the annealing effect pose a threat to the structural rating inspection/analysis as well. During routine maintenance inspections, engineers typically inspect and document the damage/fatigue exhibited on the structure. This includes possible elongation of the steel members. Unfortunately, the brittle-strengthening effect causes the steel to become brittle and will not give engineers as much warning of possible failure like steels that show elongation with strain hardening. Once again, an argument could be made for the benefits of the annealing effect in the steel, but the uncertain nature of fire makes it an unnecessary gamble. On the rating analysis side of the inspection, the steel strength must be known in order to accurately rate the structure's load-carrying capacity. The analysis will also typically reveal which member would be the first to fail in an overloading case. This allows the inspectors to watch specific members in order to better inspect and maintain the structure. The change in strength, though, from the two main thermal effects could cause the analysis to give false readings if an incorrect strength of the material is entered after a fire event, thereby leading to a false load rating and possible misdirection as to which member may fail first in an overloading case. In order to prevent this misdirection, samples should be taken at appropriate locations for further analysis of the materials strength. If it is then determined that the member has been compromised, the engineer should consider a possible retrofit or replacement of the member in question. The urgency of the retrofit/replacement of the member would be based on which thermal effect would most likely be present from the fire event. If brittle-strengthening was determined to occur, the member should be replaced as soon as possible. If annealing was determined to occur, the member should be replaced, but not as urgently, since it would still maintain the warning signs of yielding with strain hardening.

CONCLUSIONS

Overall Results. While the standard burn is not ideal for the health of the structure, no immediate effects should be seen. For extreme burns though, depending on the length of time of the burn and the rate of the cooling, two main thermal effects will be almost immediately noticeable. If rapid cooling occurred, brittle-strengthening will most likely be present, the degree of which depends of the length of time of the exposure to the heat source. If standard cooling occurred and the steel was exposed to the heat source for a long period of time, annealing will most likely be seen in the steel. If standard cooling occurred and the steel was exposed to the heat source for a short period of time, no immediate effects should be seen.

Design Recommendations. For seismic design, any adverse thermal effects could potentially be detrimental to the safety/stability of the structure. That is why it is recommended that after any fire event, the steel elements of the structure be inspected and retrofitted/replaced if it has been determined that brittle-strengthening or annealing has occurred. For structures not under immediate seismic threat, the urgency of the retrofit/replacement of the elements after inspection should be based on which thermal effect would most likely have occurred. Brittle-strengthening should be handled immediately, while annealing could be handled at a later, more convenient time.

Future Testing/Research. The next step in this research would be to determine the peak temperature the different thermal effects require to show a significant change in the steel's mechanical properties. In addition to testing the temperature, the length of time required to see a significant annealing effect in the steel should be tested as well. Finally, different grades of steel, such as A992, should be tested to see if the same principles that apply to the A36 steel apply more universally.

WORKS CITED

Steel Construction Manual (14th Ed.). (2013). American Institute of Steel Construction.

Buckle, I., Kavazanjian, E., Marsh M. (2011). LRFD Seismic Bridge Analysis and Design of Transportation Geotechnical Features and Structural Foundations: Reference Manual (NHI Course No. 130093 and 130093A). Washington, D.C.: U.S. Dept. of Transportation, Federal Highway Administration.

APPENDICES

Appendix A. Final design drawings for the forge:

Note: All drawings are not to scale.

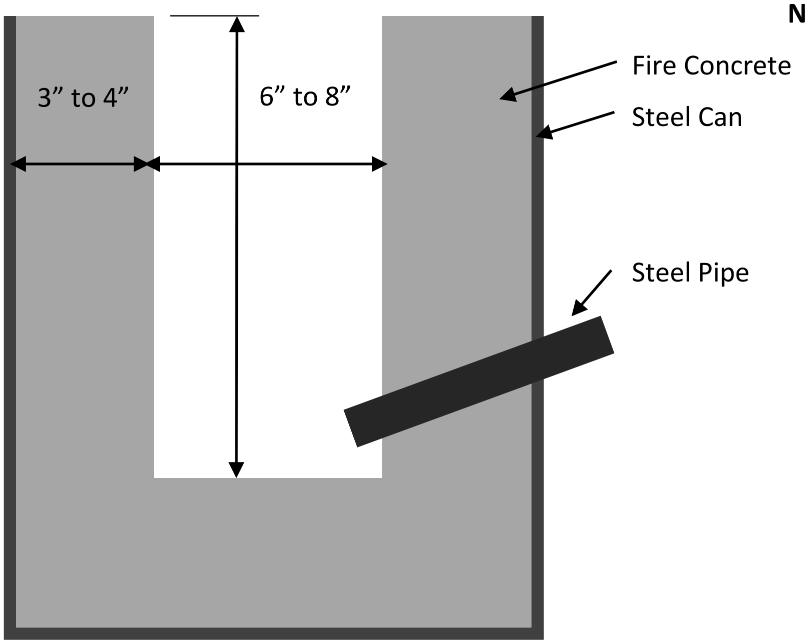


Figure A1. Cross-section of the forge.

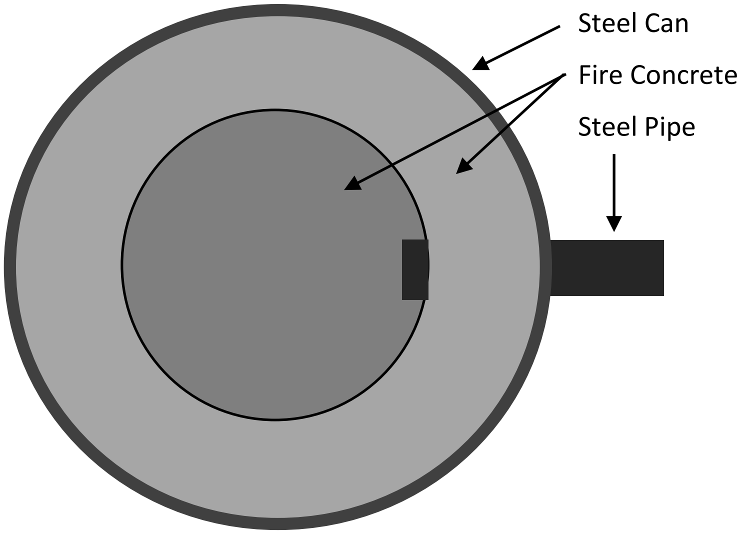


Figure A2. Top view of the forge.

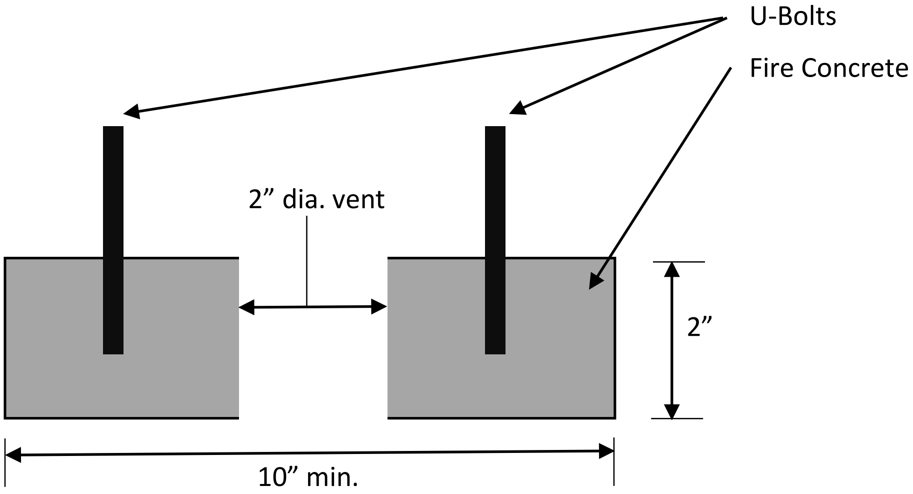


Figure A3. Cross-section of lid.

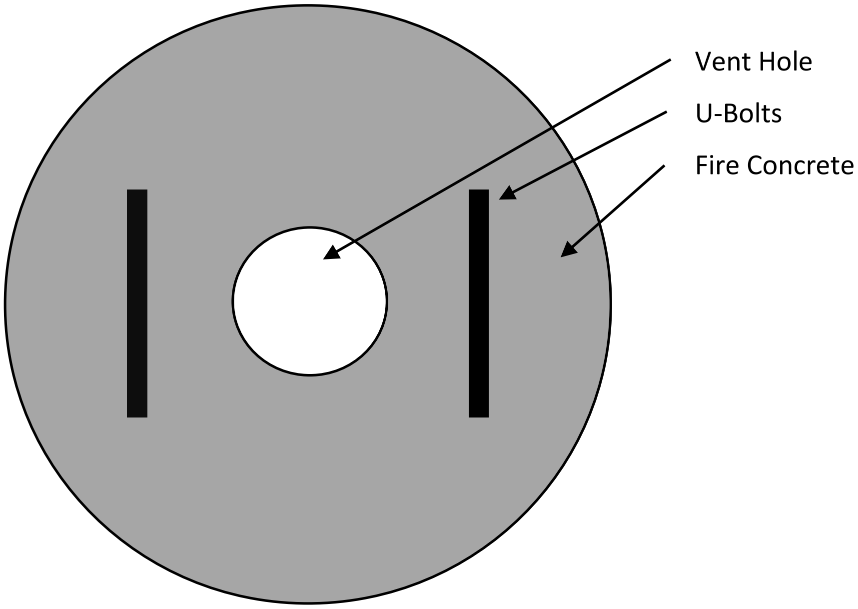


Figure A4. Top view of lid.

Appendix B. Photo log of the construction and test burn of the forge:

Figure B1. The forge after the mix has been poured into the 6 gallon steel can and the 5 quart plastic bucket has been put in place and filled with water to create the main cavity in the forge.

Figure B2. The forge after the fire concrete has cured for 30 minutes and the air supply hole has been drilled and the plastic bucket has been removed.

Figure B3. The forge with the steel air supply tube supported by a wood block checking the seal of the pipe to the forge walls.

Figure B4. The lid of the forge with the vent hole drilled in the middle and the two U-Bolts on either side of the vent to accommodate the removal of the lid during operation. Unfortunately, due to operator error, the lid shown in this image cracked in half and was later discarded.

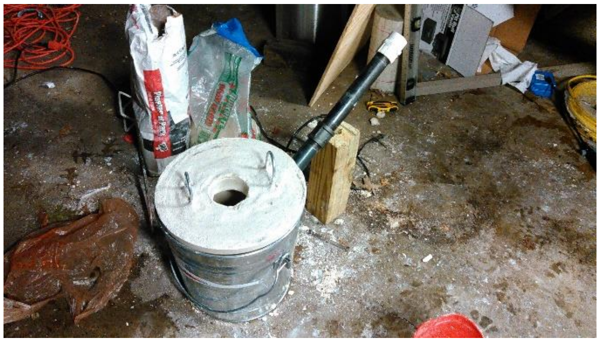


Figure B5. The forge with the lid and air supply tube. This is the final configuration of the forge.

Figure B6. An overall view of the forge with a blower fan during the first test burn.

Figure B7. The inside of the forge after the first test burn.

Appendix C. Photo log of the test samples after burns and/or after destructive testing:

Charpy Impact Samples.

Figure C1. Charpy Impact Base sample after destructive testing. The sample did not completely break, both sides are still connected. Very ductile break.

Figure C2. Charpy Impact SAS sample after destructive testing. Ductile break with both sides separating.

Figure C3. Charpy Impact SAR sample after destructive testing. Ductile break with both sides separating.

Figure C4. Charpy Impact SES sample after destructive testing. Ductile break with both sides separating.

Figure C5. Charpy Impact SER sample after destructive testing. Nearly a perfect shear break. Shows signs of extreme brittleness.

Figure C6. Charpy Impact PAS sample after destructive testing. Ductile break with both sides separating.

Figure C7. Charpy Impact PAR sample after destructive testing. The sample did not completely break, both sides are still connected. Very ductile break.

Figure C8. Charpy Impact PES sample after destructive testing. Ductile break with both sides separating.

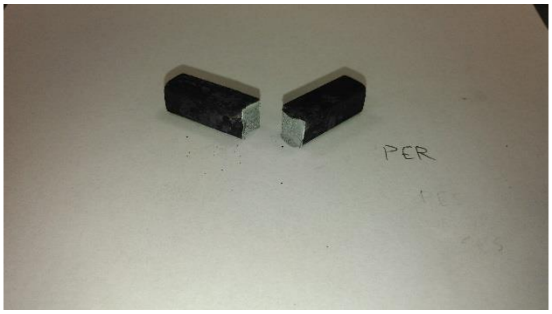


Figure C9. Charpy Impact PER sample after destructive testing. Nearly a perfect shear break. Shows signs of extreme brittleness.

Compression Slug Samples.

Figure C10. Compression Slug Base sample after destructive testing.

Figure C11. Compression Slug SAS sample after destructive testing. A few minor hairline cracks forming on the perimeter of the sample

Figure C12. Compression Slug SAR sample after destructive testing. Note the fracture beginning to propagate on the one side.

Figure C13. Compression Slug PAS sample after destructive testing. Note the fracture beginning to propagate on the one side. A hairline fracture is beginning to propagate to the left of the main fracture as well.

Figure C14. Compression Slug PAR sample after destructive testing. Two hairline fractures were beginning to propagate on the front face of the sample.

Figure C15. Compression Slug SES sample after destructive testing. Multiple hairline fractures began to propagate on the sides of the sample.

Figure C16. Compression Slug SER sample after destructive testing. Note the large fracture on the front face of the sample. Smaller fractures began to develop on the other sides of the sample as well.

Figure C17. Compression Slug PES sample after destructive testing. Very ductile. No noticeable cracks on the exterior surface of the sample.

Figure C18. Compression Slug PER sample after destructive testing. Note the two large, brittle fractures on the front face of the sample. Another large, brittle fracture developed on the back face of the sample as well.

Tensile Coupon Samples.

Figure C19. Tension Coupon Base sample after destructive testing.

Figure C20. Tension Coupon SAS sample after destructive testing.

Figure C21. Tension Coupon SAR sample after destructive testing.

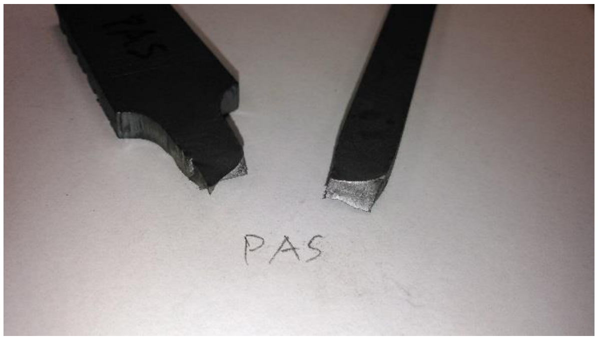


Figure C22. Tension Coupon PAS sample after destructive testing.

Figure C23. Tension Coupon PAR sample after destructive testing.

Figure C24. Tension Coupon SES sample after destructive testing.

Figure C25. Tension Coupon SER sample after destructive testing.

Figure C26. Tension Coupon PES sample after destructive testing.

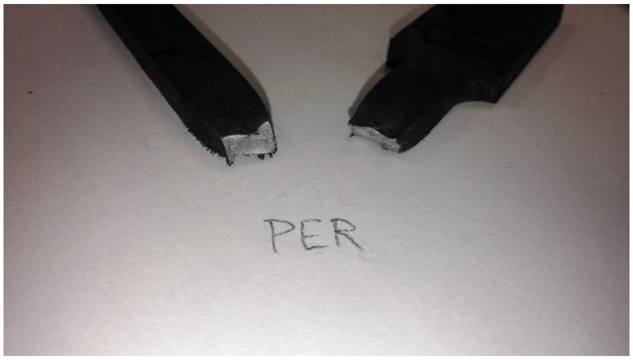


Figure C27. Tension Coupon PER sample after destructive testing.

Appendix D. Design and manufacturing of the samples.

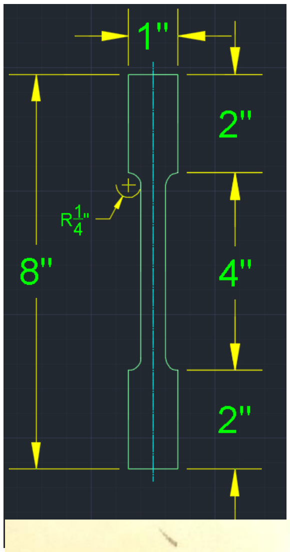


Figure D1. The final dimensions used on the tensile coupon for manufacturing and testing (thickness of ¼" used).

Figure D2. The tensile coupons being laser cut.

Figure D3. The charpy impact samples being cut.

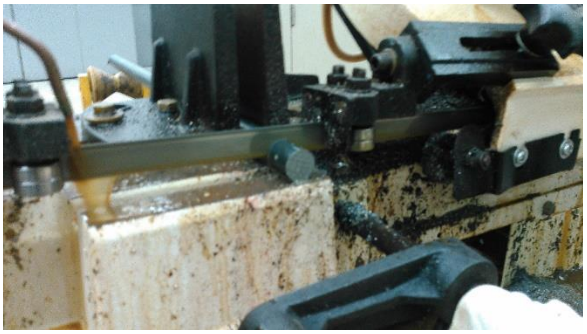


Figure D4. The compression slug samples being cut.