NOTE: I wrote the article in the fall of 2003 with the intention of editing and revising it at a future date. This was never done. If you have any questions or need clarification of specific points please contact me. paul@ferrocement.net I do plan to add photos in the future.

Fabric/Ferrocement Vault

The following paper describes an experimental, vault-type structure.

In the summer of 2003 a small project was undertaken to study the feasibility of using Fiberglas fabric combined with ferrocement to construct a vault shaped structure.

Required materials:
4 - 20' sections of 1" diameter, schedule 40 PVC pipe
Wire mesh sufficient to cover the framework
Fiberglas fabric sufficient to cover the framework

Footing preparation was begun by digging a three-sided trench in the ground. This trench forms a U shape with the back part of the building corresponding to the bottom of the U and the open, front end of the building corresponding to the top of the U. The dimensions of the trenches I used are 6" wide x 6"deep.

The two parallel trenches [the sides of the U] are 9', 6" long and the trench at the back of the building [the bottom of the U] is 8' long.

While the dimensions I chose were arrived at because they suited my need for a shelter for a trailer mounted air compressor, the materials and methods used can be scaled up for larger projects.

Now that you have a U shaped trench in the ground you need something to support the PVC framework. Using #3 rebar, cut 6 pieces 18" long. Move to the corner of one of the trenches and locate a point in the middle of the trench and 3" from the end of the trench. Drive a piece of rebar into the ground at this point leaving approximately 8" of rebar sticking above the bottom of the trench. Repeat the procedure in the other 3 corners. These corner rebar pins provide an easy method for erecting the PVC arches

Drive a piece of rebar into the ground midway between the corners. Again leave approximately 8" of the rebar sticking up.

Building the initial framework will require 4 pieces 20' long of 1", schedule 40 PVC pipe. Place 1 piece of PVC pipe over one of the corner rebar pins. Bend the length of PVC into an arch and place the other end of the pipe over the rebar pin in the corner that is directly across from the rebar pin that you started with. Do the same with two more pieces of the PVC pipe so that you end up with 3 parallel PVC arches. Take the 4th piece

of PVC pipe and hold it up to the center top of the arches so that it can act as a ridgepole. Be sure the ridgepole is mounted on the inside of the three arches. You can secure the ridgepole with wire or with plastic wire tires commonly used in the automotive industry. The ridgepole does need to be cut to length so that it does not extend beyond the two end arches.

Now that the PVC framework has been erected we will begin covering it with wire mesh.

Cut some 6x6x10x10 mesh, also called remesh in the concrete industry. Cut this 18”wide and as long as necessary to run the length of the side. You will most likely need to cut two pieces of this and overlap them in the middle. The 6x6 mesh is inserted into the trench on the outside of the PVC. Wire tie this mesh to the PVC being certain that the bottom of the 6x6 is 1” above the bottom of the trench and extending past the ends of the arches by 2”. If you used more than 1 piece of 6x6 wire tie the pieces of 6x6 to each other as well as to the PVC. Repeat the procedure for the other side of the building.

Now cut 4 piece of #3 or #4 rebar to the 2”longer than the length of your building. Place two pieces of rebar in the trench and so that they extend 1” beyond the end arches. Wire tie the first piece at the bottom of the 6x6 and wire the second one so that it is 2”-3” above the first. Both pieces of rebar should now be in the trench, running parallel to each other with about 2”-3” between the two. Repeat the procedure for the other side of the building. These two pieces of rebar will help the shallow footer act as a beam.

Cut two more piece of rebar for the trench that joins the two side trenches [the bottom of the U] Wire tie these pieces at the same height as the other pieces of rebar in the side trenches by overlapping the ends of the rebar. Tie them to each other as well as to the PVC.

The wire mesh used in this test is galvanized, welded wire fencing with rectangular openings 1,1/4”x 2,1/2”. The diameter of the wire is approximately 14gauge. When this mesh is unrolled it will still be in somewhat curved shape and since we are building a curved, vaulted structure it will serve our purposes nicely.

Since our pieces of PVC pipe are 20’ in length we know we need a 20’ long section of the wire mesh. The roll of fencing is 5’ wide and the length of the building is 9’ so two pieces of fencing material are cut to cover the framework. One piece of fencing is pulled over the arch and wired into place. Allow the fencing to go down into the trench to the level of the 6x6 being certain that you allow the fencing to extend beyond the two end arches by about 2” keeping it in line with the 6x6 you added previously, and wire it to the 6x6 in a couple of places. More wire ties will be added later but for now we want this length of fencing to be only lightly secured.

Pull the fencing up and over the framework and lightly secure it at the bottom with a couple of wire ties. At this point you will have one length of fencing unrolled and draped over the framework extending beyond the end arch by about 2 “ and in the other direction extending beyond the center arch by a few inches.

Go to side you started with and put more wire ties through the 6x6 and length of fencing also put 2 or 3 ties through the fencing, securing it to the middle and end PVC arches. Continue working up from the trench with wire ties tying the fence material to the PVC arches at 8" intervals. It is important during this stage to be certain that the fence material is held in tension by hand as more ties are added. If this is not done the mesh armature will not be as stable as it could be.

*Note:
It is virtually impossible to end up with a 'perfect' armature. Just be certain that it is as tight and straight as possible.]

When the first piece of fencing has been tied to your satisfaction do the second piece in the same way. You will notice that the two lengths of fencing overlap in the middle. Be certain that some ties are used in this section to tie the two lengths of fencing to each other. This overlapped area also gives double reinforcement in the center of the vault structure.

Now you need to decide how you want to close in one end of the vault. If you have dug your U footer with a straight line between the sides of the U your end will be straight or rectilinear. If you have dug this part of the footer in a curved line [as in the illustration of the U that I am using here] your end wall will be curved. The curved end wall will provide more strength to the closed end of the vault than a straight wall would but it will also require some fancy cutting and fitting of mesh to attain the resulting compound curve shape. Either shape will be strong enough, it's really just a matter of preference.

Cut a panel or panels of fencing to the shape required and tie this to the end of the vault to create a wall. Be certain that the mesh panels are 2"-3" larger than actual size. After wire tying this mesh panel or panels at 8" intervals to the PVC arch, bend the ends around so that they overlap the mesh on the sides of the vault. Tie the overlapped area at 8" intervals. At this point you will notice that the mesh structure or armature has become rigid and exhibits some nice structural qualities.

To further strengthen the open end of the vault, attach a piece of ¼" reinforcing steel to the outside of the wire mesh. This material comes in 20' lengths. Begin at the bottom of the 6x6. Wire the ¼" rod and 6x6 together continuing up and all the way around the arch finishing at the bottom of the other side from where you began. I tied the 1'4" rod so that it stands off about ½" from the wire mesh. This stand off allows the edge or lip of the open end to be thickened with extra mortar.

Attach a length of ¼" rod about 6" up from the bottom of the end wall. Attach another length about 4' up from the bottom. These pieces of reinforcement run horizontally and give added strength to the end wall.

If you have chosen a curved end wall use#3 or #4 rebar instead of ¼" rod. Bend the rebar to conform to the curve of the wall and tie it in place, spacing the ties 8"apart. The rebar

is needed to provide additional strength to resist the weight of the mortar when it is applied. If this is not done the wall will deform and create a different shape when the mortar is applied.

The Fiberglas fabric that I used in the next stage is distributed by Sto, a manufacturer and supplier of synthetic stucco supplies. The roll is 3' wide and 150' long. Dryvit is another company that handles this type of material as well as other synthetic stucco companies. Whatever your source for this material, be certain that it is designed and manufactured for use with cementitious products. This is done to insure minimal reactivity between the Fiberglas and Portland cement.

Cut a length of the Fiberglas cloth a little longer than your building so that it extends to the end of the wire mesh at the open end of the vault and leaves a few inches to extend around and overlap the closed end of the vault. Insert this length into the trench a couple of inches and tie it to the edge of the mesh at the open end of the building. Pull the other end of the length of cloth toward the back end of the vault attaching it along the bottom as you go. Go back to the open end of the vault and pull the fabric up tying it to the mesh as you move along. When you are finished you will have a 3' high section of fabric attached to one side of the vault.

Add another length of cloth, overlapping the first by 3" and tying as you move along. Add a third length of cloth in the same manner as the previous one.

You now have 3 lengths of Fiberglas cloth extending 9' up the vault. This will actually be 6" or so less than 9' because of the overlapped areas.

Go to the other side of the vault and repeat the previous steps.

There is a section at the top of the vault that has not been covered. Cut another length of material and tie it to the top. Except for the open end the vault structure is now covered with cloth. You will notice that since you began at the bottom of the vault on both sides and overlapped the fabric on the way up, the fabric is applied in a manner similar to shingles.

Cover the end wall with fabric beginning at the bottom and working up using the same procedures that you used on the sides.

The Fiberglas cloth should be attached to the wire mesh beneath it on a 6"-8" grid. This is to prevent the cloth from undue sagging when the mortar is applied.

*Note:
There are some tools that may help you tie wire mesh faster than just with a pair of pliers. One such tool is a P7 hog ring pliers available from Stanley. Harbor Freight offers similar pliers. These tools are fed by a magazine that holds a number of ring type staples. The ring is about 3/8" diameter when it has been squeezed together. Although you will still need to use manual methods for tying wire mesh to the PVC poles and rebar, these tools

may help you save time when attaching the Fiberglas cloth. If you are attaching the cloth using wire, precut a number of pieces of wire and bend them into bobby pin shapes. Push one end through from one side of the structure and twist the ends together from the other side securing the cloth to the wire fencing material.

You are now ready to begin pouring the footer.

I used the same mixture for the footer as I did for the rest of the vault. In this way there is no discontinuity in the material.

The formula I used is 2 parts mason's sand to 1 part Portland cement. A target water content of .4 parts was chosen to keep the finished structure waterproof. Acrylic latex admix was used to get the proper flowability while maintaining the .4 ratio of water. This formula is measured by weight – not by volume.

Different buckets can be filled with sand, cement and water while on a scale until the proper proportion is achieved. Using a permanent magic marker draw a line at the level on each bucket, also label the buckets as sand, cement and water to prevent any mix up. You now have buckets clearly marked that can be used as volume measurements to speed up the batching process.

Before pouring the footer you will want to soak the trench with water a few times. This will help to ensure that moisture is not rapidly pulled from the mortar into the ground. Moisture leaching into the ground will weaken the cure of the footer.

Mix a batch or batches of mortar of sufficient quantity to fill the trenches and form the footer. Pour the footer to the desired height. I poured mine so that the top is slightly above ground level.

The footer should be misted a few times with water during the first day of curing to allow a slower and stronger cure. If you can cover the footer with plastic, wet gunny sacks or other material to help hold the moisture in, so much the better.

Method #1

After 1 day of curing you are ready to apply mortar to the vault. This mortar can be applied by hand or by spraying with the Tirolessa stucco sprayer. The following instruction applies to the Tirolessa sprayer.

Mix a batch of mortar using the same ratios as you did for the footer mix.

Fill your sprayer and begin spraying at the bottom of the structure. Hold the sprayer about 6"-8" away from the structure when you spray. Be sure to cover the joint well where the footer joins the wall. To minimize the amount of sag in the fabric and wire spray upward for a distance of 2 feet. Continue this until you have a 2 foot high strip of mortar applied to one side of the structure.

Continue this around the back and the other side of the structure until you have a 2’ high strip of mortar all the way around the base of the structure.

Note: In the test structure I sprayed mortar non-stop until the entire building was covered with mortar. This method lead to a slight collapse at the open end of the structure. This warpage of the PVC framework and slight collapse is covered in more detail later on in this paper. After the slight failure of the PVC I straightened things up and anchored the top end of the arch to a trailer that was about 10’ away. This stabilized the top of the PVC arch and when more mortar was added there was no movement in the arch.

After spraying the 2’ strip allow the sprayed mortar to take an initial set for 12-24 hours. Normal procedures of curing should be followed to be certain that the sprayed mortar has time to properly cure before more mortar is sprayed.

After the initial set has taken place you are ready to spray the next section. Be sure the existing mortar is clean and free from debris to provide a good surface for the next section to bond to. You may wish to use a little neat cement or acrylic or other type of bonder for this step.

Spray the next section of mortar around the building again spraying up about 2’ or so from the existing section so that when you are done you have a second 2’ section of mortar. Follow the same curing procedures that you did for the first section.

*Note: Be certain that when you are curing each layer that you continue the curing process on all previous layers.

Continue adding sections of mortar in 2’ increments until the structure is completely covered.

After the structure is completely covered you will move to the interior and spray it with mortar so the bond between the fencing wire inside the structure and the fabric/mortar layer outside the structure is complete. Spraying the interior is not done in 2’ sections but should be continuously sprayed until the entire inside of the structure is covered.

Continue curing the structure.

After 12-24 hours you can if you wish spray a final layer of mortar over the entire structure. For added strength you may wish to include some fibers in this layer.

Method #2

Devise additional bracing for the structure.

It is my conclusion that 2 additional sections of PVC pipe can be included in the set up of the initial forms. In this method you would have 5 arches spaced at 2'-2,1/2' intervals instead of the 3 arches I used.

Another scheme for additional reinforcement is to use 3 PVC arches but to include stringers or braces between the 3 arches to prevent any movement of the arches in relation to each other.

Yet a third possibility would be to construct bracing in the form of the letter T. These braces would be about 7'-9' tall with the top of the T being just long enough to easily fit between the PVC arches or about 4'-5' depending on the size of your building. These T braces would be inserted at an angle so that the bottom end would be close to one side of the armature while the cross brace on the other end of the T would rest between two of the PVC arches on the other side coming to rest about three quarters of the way up the arch.

Using any of these three alternate methods of bracing would allow the spraying of the exterior of the entire structure at one time leaving only one more day of spraying, that being the inside of the arch.

Alternate Methods of Building.

I like using the Fiberglas fabric for a couple of reasons. The fabric is designed to be used with cementitious materials and also the Fiberglass provides significant reinforcement. In the method I used the fabric is on the outside of the building. This is done to prevent excess sagging of the fabric as mortar is applied.

An alternate method would use a layer of wire mesh applied to the PVC framework followed by a layer of Fiberglas cloth as illustrated earlier. This initial layer of wire mesh could be fencing, chicken wire or whatever is handy.

Instead of applying mortar at this stage put another layer of wire mesh reinforcement or even two layers of mesh on the outside of the fabric. Apply mortar either by spraying or by hand and cure.

After the structure has cured the internal PVC arches and internal layer of wire mesh could be removed or you may opt to leave the internal framework and plaster the inside of the structure.

Partial Collapse

Earlier I made reference to a slight collapse of the structure as the final section of mortar was sprayed. This slight collapse that took place occurred in the following manner:

Mortar had been sprayed over the entire structure with the exception of perhaps 1 square yard at the top of the open end of the structure. As the final piece of that final square yard was being sprayed the top of the PVC arch began to roll inward and towards the rear of the structure at a very slow speed.

This rolling inward of the PVC arch lead to some deformation of the mesh in that area which in turn decreased the tension on the top of the second arch. Please note that at this point here was over 1,000 pounds of mortar on the armature!

As the tension decreased on the top of the second arch it also rolled slightly towards the rear of the structure. The deformation of the second arch was probably half as much as the deformation of the first arch.

At no point was I concerned about the entire structure failing and although finding it unsettling to watch this occurrence it was interesting to see this happen in slow motion taking about 1-2 minutes to occur.

The one thing that I failed to do was to secure the outside of the first arch in some manner. After some temporary bracing was pushed into place I used cut two lengths of twine and tied them to the top of the arch with one being about 18" from the apex on one side and the other the same distance on the other side of the apex.

These pieces of twine were then tied off to a trailer that was about 10' away although they could just as easily have been be tied to a couple of stakes in the ground. Spraying mortar recommenced the following day. When spraying was finished there had been no movement or deformation of the PVC arches.

Variations

As an experiment do the following: After the mesh/fabric armature has been assembled tie some cord from one side of the ribs to the other side to keep tension on the PVC ribs. Lift the armature out of the trenches and set it on a piece of level ground.

Take a piece of cord and tie one of the end ribs a little tighter so that the distance between the bottom legs of the PVC rib are about 1 foot closer than the middle and other end. Note how the shape of the structure changes. Cut or untie that cord until the distance between the legs of the rib are the same as the other ribs.

Take a piece of cord and tie it so the legs of the middle rib about 1" closer together than the two end ribs. Again, note how the shape of the structure changes.

Untie any cords from the middle rib so that it is not under tension. Pull apart the bottom legs of the middle rib so that it spreads about 1' wider than the ends. Again, note the shape of the structure. This alteration leads to a hyperbolic parabaloid shape that has a great deal of strength and stability and is especially suited to thin-shell structures.

By now you are becoming aware that this simple method of forming an armature can be adjusted to yield many different variations of the standard Quonset or vault type structure.

Conclusions

This method can be used to produce larger structures by scaling up the materials involved.

Individual vaults can be easily joined together to produce different configurations and floor plans.

By adjusting the distance between the legs of a rib or ribs, this forming method can produce variations of a typical vault structure. These adjustments can be made for aesthetic reasons or to arrive at different structural shapes.

Additional ceiling height can be gained by mounting the armature on top of knee walls of the desired height followed by traditional ferrocement finishing techniques.