

FABRIC FORMWORK MODELS

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INTRODUCTION

This web-based chapter is a free resource for anyone interested in fabric formwork models and construction. It is made as a companion to *The Fabric Formwork Book* which contains far more information on the general subject and on full-scale construction techniques in particular. References made here to chapters, pages, and illustrations in *The Fabric Formwork Book* are given in blue typeface. References to figures in this chapter are given in red typeface. While this chapter can be used as a stand-alone resource, a full understanding of the subject will require reference to the larger book.

The two authors of this chapter worked for many years at the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba in Winnipeg Canada, where many of modeling and formwork techniques were developed.

This Chapter begins with a general discussion of physical parametric models, and ends with specific instruction and advice on making such models for flexibly-formed cast constructions.

We have tried to be as thorough as possible in this chapter, though this thoroughness may have the effect of making the subject seem complex, with many should’s, shouldn’ts, and dont’s. The larger truth, however, is that these moulds are actually quite forgiving. Both successes and failures hold valuable information, knowledge, and pleasures. It is really only close control and fine details that require much practice or knowledge to get right. Whether the things you make turn out the way you intended or not, we think that the inevitable strangeness, beauty, and ugliness of the results, will provide their own rewards. Enjoy!



The Physical Model as an Analog Parametric System

Small physical test models of fabric formworks are the best way to explore and learn the ways and means of flexible molds. At present, there are no digital models that can duplicate the ease and power of physical models in this regard. All of the formwork designs and construction methods we have developed were first explored through small analog working-models as a preparation for full-scale construction.

The materials and construction details for these kinds of models are chosen because their physical behavior is as close as possible to that of their full-scale equivalents. In short, they are designed and built as physical analogies, which is to say, as analogs.

These are true parametric models -- a change in any one of the parameters in play, size, stiffness, pre-tensioning, connection strategy, etc., will affect all other parameters to produce the final result.

There is a long tradition of using physical parametric models to invent, solve, and prove novel designs and construction methods. These include 20th century, pre-computer examples such as Antoni Gaudi's hanging chain funicular model of the Colonia Guell church¹, Frei Otto's soap bubble models and small fabric models of tension membrane structures², and Heinz Isler's



Figure 1 Analog construction models as small as 1:10 can be directly scaled up to full-scale constructions, with no intermediate steps

funicular models of thin-shell compression vaults³.

These are not just models for making miniature objects that represent larger things. Instead they are models of action and reaction that *behave*, in many respects, like their full-scale equivalents. In other words, "model" is used here as both verb and noun. This is an important point to keep in mind, particularly if you

are used to making models as miniature 3-D pictures of things. These are actual constructions, in action, in a miniature world of construction, material, and force.

Over the years we have learned that anything that can be built in a good analog model can be built at full scale. Models as small as 1:10 can be used to work out and develop strategies that



Figure 2 A "library" of fabric-formed plaster models

can be directly applied to full-scale concrete construction (Figures 1 and 9).

The tradition of designing and problem solving using physical parametric models has recently been transferred to the realm of digital parametric modeling. As digital models have rapidly become faster and more powerful, they have replaced physical models in many aspects of design and

design research. They may yet do so in the realm of flexible moulds as well, but the complexity of flexible systems makes computational models difficult to work with. At present, there is plenty of room for both kinds of parametrics in flexible formwork design. As such, their relative strengths and weaknesses should be well understood.

Digital vs. Physical Parametric Models

A good parametric model, whether physical or digital, will behave as an analogy (analog) of full-scale construction, providing predictions of full-scale events. To be clear, the difference is not between "digital" or "analog", but rather between the kinds of analogies used. One uses analogous materials made

of matter and the other uses analogous virtual materials, made of quantified geometric and mechanical properties. These two analogical realms have their own strengths and weaknesses.

Physical parametric models are rich in qualitative information, but poor in quantitative information. Conversely, digital parametric models are rich in quantitative information but poor in qualitative information. So, the strengths of one, compliment the weaknesses of the other.

In a physical working-model, you can actually feel the forces in play and immediately see the physical and formal results of actions in the material world. This allows a designer’s hands to think and offer up ideas (the hands of a maker are, after all, organs of thought). It also allows the materials to offer up ideas that the maker/designer would never dream of through purely abstract thinking, drawing, or imagination. The deep “intelligence” of the material world provides a treasure trove of idea-laden events (usually through mistakes) to anyone willing to get their hands dirty.

Digital models work in the speed or their computation, in a 3-D virtual reality (VR). Physical models work in real time and in actual reality, what we like to call AR. In terms of ideas, thinking, and feedback, AR far out-performs VR; the processing speed is astound-



Figure 3 Forces can be directly felt in physical models, but not easily measured

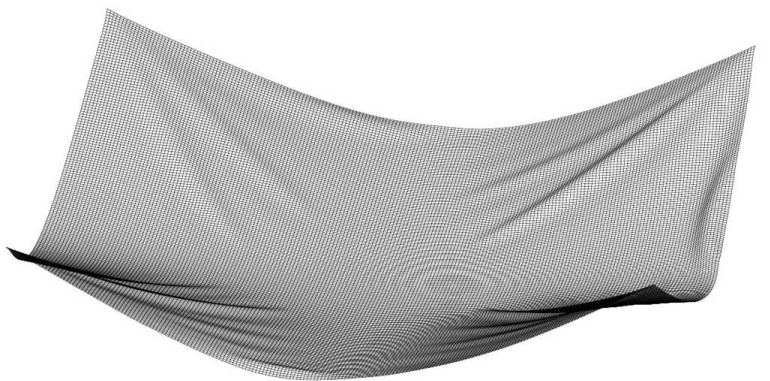


Figure 4 Similar textile behavior modeled physically (top) and digitally (bottom, by Dr. Chris Williams, Bath University, UK)

ing, the resolution is perfect, and the systems never crash. For example, when you move the location of a pull-point in a physical model, you immediately see and feel the differences it makes (**Figure 3**); knowledge is gained much faster and more easily than arranging for the same kind of change in a computational model (**Figure 4**). With close attention to physical events, intuitive knowledge can be rapidly developed.

But despite this speed and high qualitative resolution, it is very difficult to get quantitative information out of a physical model. How do you query a working fabric membrane about the force distribution in its weave? Not so easy to do. Also, physical models are subject to unavoidable scaling factors that proportionally distort the magnitude of the forces at work (see below), making the extraction of accurate quantitative information even more complex. A digital parametric model, on the other hand, is *made of quantities*, so a virtual fabric membrane knows the force distribution in its skin before it knows its shape. Furthermore, a digital parametric model does not suffer from the scalar distortions of physical models (see scaling factors, below); it always acts, analogically, at “full size” depending on the size assigned to the model.

Another important difference between physical and digital models is the question of construction sequence. The construction sequence used to build a digital parametric model bears no relation to the construction sequence of the physical thing it represents. For example, a virtual construction is created by assigning points, lines, planes, and other quantities in a virtual space. This sequence of events is entirely disconnected from that needed to produce a physical construction out of real materials. In general, the act of assembling a virtual model does not help you think through the sequence of assembly for the physical thing it represents.

A physical model, on the other hand, is a natural tool for thinking through physical construction sequences. In a casting process this aid-to-thought is particularly important as the sequence of assembly and disassembly is key; a mould not only needs to be built, but more importantly *un-built* (de-moulded) during the process of casting. This crucial part of the construction process is entirely invisible in a digital model which gives information on the geometry of the final form, but no information on the sequence of events involved in its creation or its removal from a mould. A physical mould model requires you to go through all the steps of actual construction and de-moulding before you can obtain the casting (Figure 5).



Figure 5 A physical model also tests the ability to de-mould a casting. This is information that is not directly available from a digital model

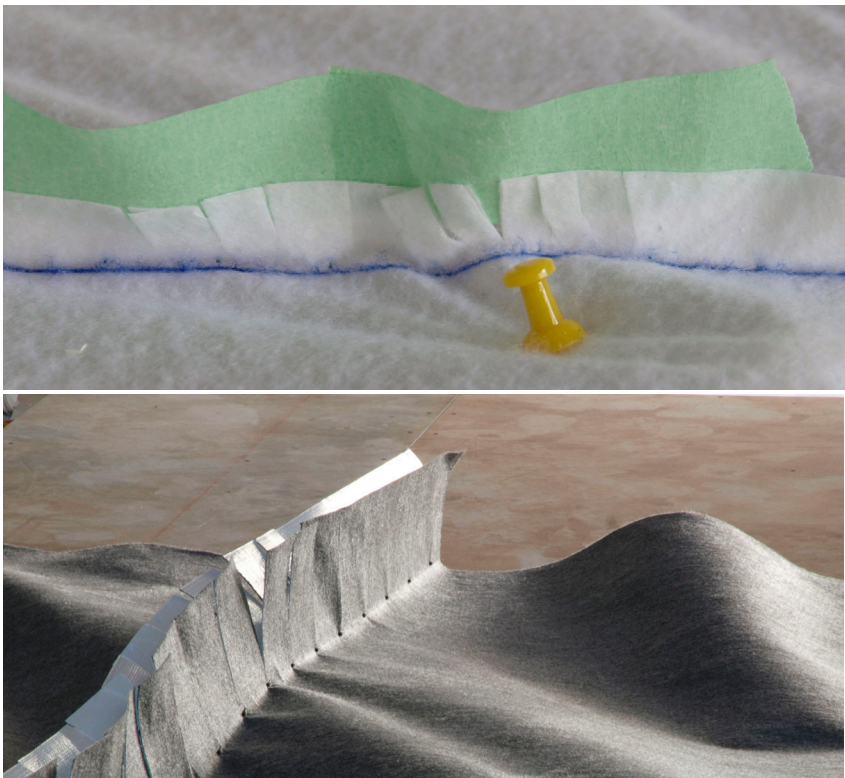


Figure 6 A physical model (top) allows construction details and joints to be invented and detailed in principle, before being applied to a full-scale mould (bottom)

This is key because it is quite common for crucial details in the de-moulding sequence to be overlooked by a mould designer/builder. A physical model will always let you know, in no uncertain terms, about such lapses in design by not allowing the cast to leave the mould.

Physical models are also the best place to work out construction problems and ideas for tricky connections and other details of a mould. Figure 6 gives an example of how a model was used to invent the full-scale joint discussed in Chapter 6, Figures 6.33 and 6.23, p. 84, and seen in context in Chapter 11, Figures 11.31 and 11.32, p. 216-17.

MAKING WORKING MODELS

A modest degree of preparation is required to make working-models of flexible moulds, but once the space, tools, and materials have been assembled, you will have a true laboratory for exploration and invention. We use the word “laboratory” to mean a separate space in which a large number of mistakes can be made in a short period of time. Such a space allows non-punitive mistakes – you can try anything you want without paying a high price for your failures. Most importantly, every failure contains both valuable lessons and, potentially, new ideas. The trick is, even in your disappointment, to pay close attention to the



Figure 7 Ronnie Araya’s apartment-sized model shop



Figure 8 Some of the more expansive kit at the CAST Laboratory dedicated to fabric formwork models

gifts hidden in mistakes. This small adjustment in frame-of-mind, though perhaps difficult to accomplish, is an invaluable tool for discovery and learning. It also makes your “failures” less painful, and at times even pleasurable.

Choosing a Model Size

At CAST we made many models at 1:10 (almost our default scale -- See [Figure 1](#) and [Figure 9](#)), and often scaled up to 1:5. Occasionally our models were as large as 1:2. Some ideas and solutions can be found, and fairly well developed, in sketch models with no assigned scale whatsoever. Such scale-less sketches of formwork ideas allow themselves to be imagined at various scales, and for various applications, making them more open-ended as tools of thought and imagination. In all cases, the actions that occur in a good model will be the same actions that occur at full-scale, whatever size that may be.

Choosing the size of a model is key. There are a number of factors at play in this decision. Perhaps the most fundamental factor may simply be the size of your workspace. At CAST we had lots of space but a full model shop can even be made in a small apartment ([Figures 7, 8](#)).

Even small models can sufficiently inform much larger constructions, so a limited workspace need not stand

in your way. The larger the model's size, the higher the resolution of the results, but larger models obviously require more space, material, money, and generally more time to construct. Smaller models generally require less investment, though sometimes they may be more difficult to build, for example when the connections become smaller than your fingertips. For this reason, scales smaller than 1:10 may be more maddening than helpful.

The smaller the model, the less palpable the forces will be. A “read” on the forces at work, through fingertips and muscles, gets clearer as the size of the model gets larger, and diminishes rapidly as models get smaller.

Scaling Factors

A scale model, as a miniature, holds the same linear proportions as the larger thing it represents. But other aspects of the model, besides linear dimensions, do not scale so simply. As an example of this, consider a 1:10 model of a 4 meter tall, cylindrical, column. The model, at 1:10 scale, is one tenth the height, and its diameter also shrinks to 1/10th. But the area of the model's surface, or any of its cross-sectional areas, shrink by a factor of 100. This is because all areas are multiples of two linear dimensions (length x width), with each linear dimension being ten

times larger or smaller (i.e. 10^2). The difference in volume is even more extreme because volume multiplies three linear dimensions (10^3). in our example the two volumes varies by a factor of 1,000! Other physical aspects will scale according to their own laws -- some linearly and some geometrically.

A digital model is quite different in this regard because it is not a miniature of anything and has no assigned scale (although it may appear so on your computer screen). It is, instead, a virtual full-size thing. You can assign different sizes to it, but it will never be a miniature.

Physical models, however, are trapped in scale and all the natural scaling factors that go with miniaturization. These various scaling factors make comparisons between a miniature physical working-model and its full-scale equivalent somewhat complex.

These factors also affect the qualitative information you can get from your models as well. For example, the tension in a pressurized formwork membrane in a 1:5 model will be 1/125th of the full-scale tension (pressure scales linearly, but the skin tension relies on the area of fabric, which squares) (See the Text Box at the beginning of [Chapter 8, p. 137](#)). A 1/125 reduction in tension makes for a very light force, but this is still possible to feel with your fingers. Cut

the dimensions just in half to a 1:10 model and the tension in the fabric is reduced to 1/1000th of the full-scale version -- vanishingly small in comparison.

But relax. It is best not to worry too much about these inherent complexities in your physical models. It is entirely sufficient to understand that they are there, and to get a feel for which ones are more dramatically affected by scale changes than others. Physical models are not terribly useful when it comes to gauging magnitudes anyway, so don't sweat it. Instead, get used to thinking in terms of *actions and events* when working with physical models. These remain palpable, to one degree or another, and are of the same kind as those that will occur in full-scale moulds. Your models will reveal much about what will happen in the actual construction and how it all works. These actions will teach you how to design various kinds of forms according to how you handle the flexible membrane and its supports. This is what is most important. Magnitudes can always be calculated (or digitally modeled) separately.

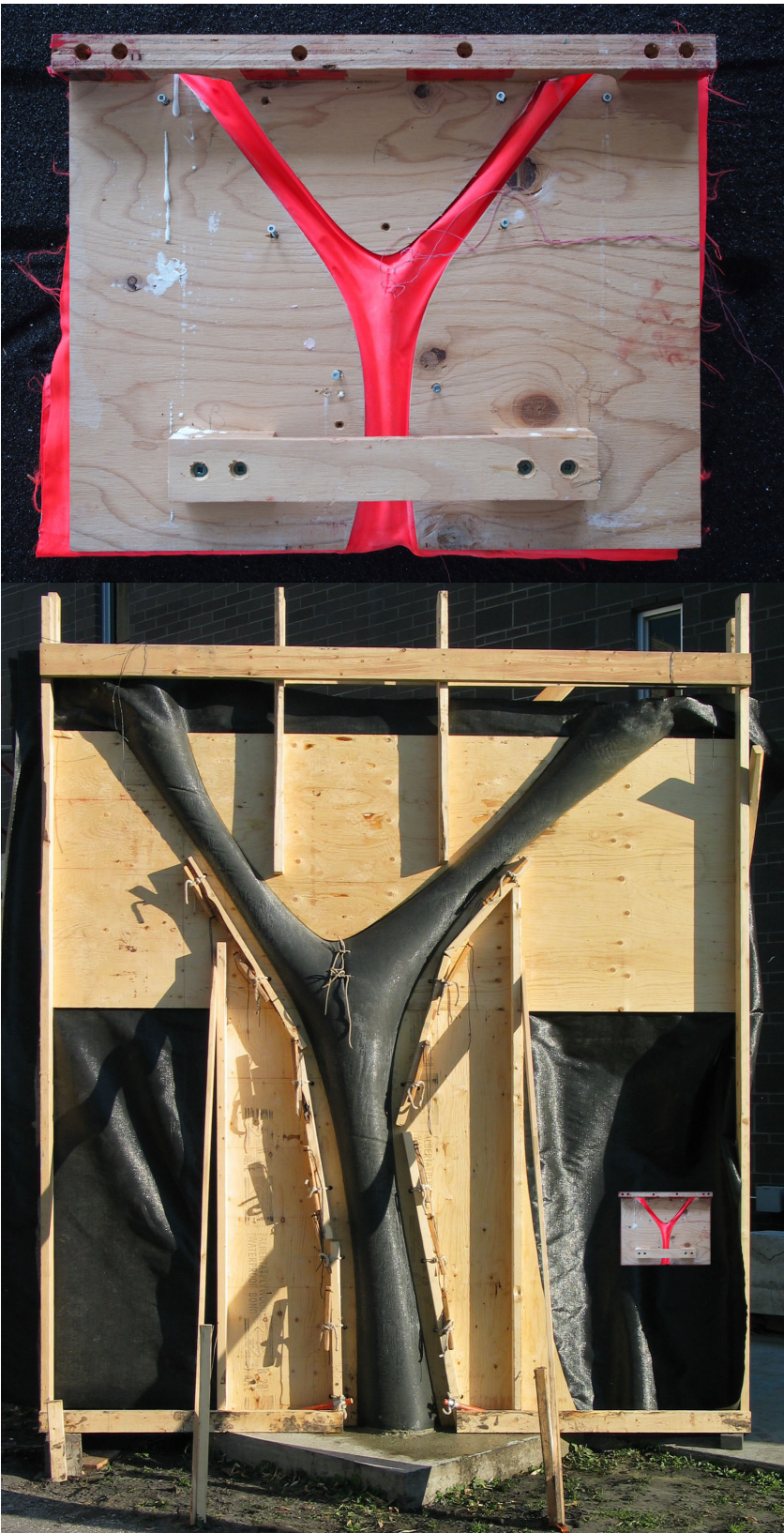


Figure 9 The 1:10 model formwork (top, and shown to scale in the inset at bottom) was used to design and construct the full-scale mould (bottom). See also, [Figure 1](#)

MODEL FABRICS
AND HANDLING

Fabric formwork models should be constructed with very light fabrics. This is because model fabrics will tend to be proportionally stiffer than full-scale formwork fabrics. If a heavy fabric is used to make a small model, its own stiff resistance will unduly influence the final casting as it will tend to resist a free deflection of the membrane in tension. The lighter the fabric used in your model the better.

At CAST we were never able to figure out a way of definitively calculating the relative fabric stiffness of our model fabrics compared to that of full-scale formwork fabrics. However, simple empirical comparisons can be used to gauge the relative scales of fabric stiffness. **Figure 10** shows one method of comparison: the lower fabric is a full-scale fabric - in this case a heavy, industrial, coated, woven, polyethylene fabric. The upper fabric is a light non-woven plastic. Both fabric sheets make similar (though not perfectly identical) buckled patterns, but at different scales. The stiffer fabric naturally makes larger sized buckles than the lighter one. By measuring the linear difference in size between the buckles of the two fabrics, a model scale equivalent can be inferred.



Figure 10 Empirically finding the scale difference between a model fabric (top) and its full-scale equivalent (bottom)

Fabric Internal Structure
and Deformation

The internal structure of the full-scale and model fabrics should also be taken into account. For example, a woven (warp and weft) fabric behaves differently than a knitted fabric, which is different again from a sheet of plastic film, or a sheet of rubber. If you plan to use an uncoated woven fabric for your full-scale mould, it is wise to choose a (much lighter) woven, uncoated, fabric for your model [for different textile types and structures see [Chapter 4, Textiles pp. 52-60](#)].

The relative, scaled, stiffness of a model formwork fabric matters most when making models of relaxed, non-pressurized, moulds – for example where push-buckle wrinkles are formed [see [Chapter 11, pp. 205-19](#)]. When pressures are relatively small, the fabric’s stiffness plays a more dominant role in the final shape the cast.

Preferred Model Fabrics

That said, finding the best model fabric will always be a more or less doubtful enterprise because fabrics available for sale in small quantities are not reliably sourced. Retail fabric stores typically stock end-lots of commercial runs, which change over time with the market and fashion. In the end, you can only use what is available to you, and if you find a really good modeling fabric it may be impossible to find again for later casts.

Generally speaking, synthetic fabrics such as nylon, polyesters, or acrylics, will de-mould more easily than natural fabrics such as cotton, but cotton may be available in more flexible, lighter weights. Certain synthetic materials, including some nylons and polyesters, are more sensitive to the heat generated by setting plaster (sometimes causing strange wrinkles to appear). Trial and error is the only practical method of choosing your model fabric. But again, don’t worry – with so many variables beyond your control, close will be good enough. Your model will still speak to you, even if it does so with an accent.

Small Scale Handling of Fabric

One of the most important adjustments you will have to make when you are building model formworks will be working at miniature dimensions. At 1:10, for example, a millimeter represents a full centimeter (1/16th in. represents 5/8th in.). If your full-scale construction tolerance is 1 cm, then you need to make your 1:10 model within a 1 mm construction tolerance. Very fine, almost infinitesimal adjustments with your fingertips will have real dimensional consequences in such a model. For designs that demand dimensional control, fanatic accuracy is a virtue at this scale.

Using model fabrics with small gridded patterns in the weave (as found in light “rip-stop” nylon for example) can be helpful in keeping track of fabric lengths and gauging symmetry. Figure 11 shows a detail from a 1:10 beam model with dimensional notations drawn on the grid of such a fabric (by counting squares). This is the same model formwork seen in Figures 10.22, p. 185 and 10.26, p. 187.

A reference grid can also be drawn onto the flat surface of plain fabrics before making your model. You don’t need to do this but in plain, non-gridded fabrics it will be very helpful in gauging both dimensions and symmetry. Note that if the drawn markings are placed towards the inside of the mould,

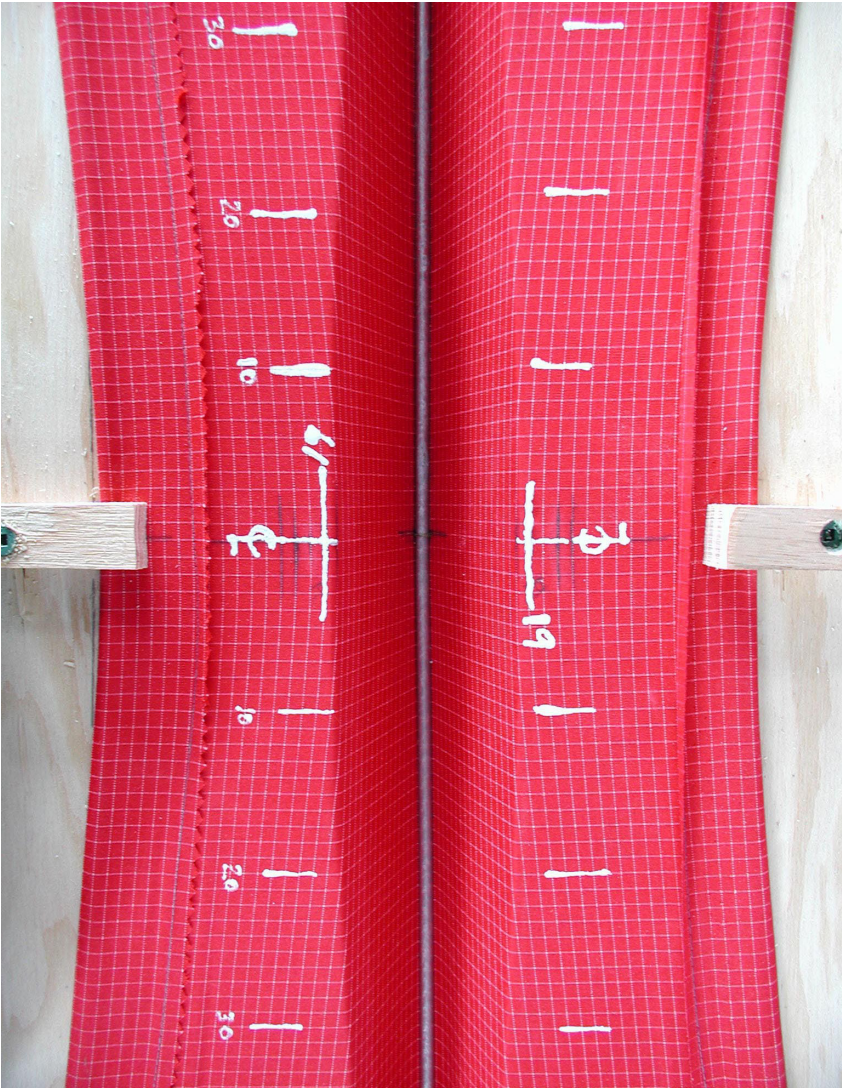


Figure 11 Reference marks on a gridded fabric help gauge symmetry and dimensions in a small-scale mould

they will likely be transferred to the surface of the cast (a kind of tattoo). An example of this can be seen by looking closely at Figure 6.47 on p. 95.

The force you use in pre-tensioning should also be scaled down. This is harder to gauge, as there are no measurements for the forces generated by your fingertips. In general, you will find that the forces you can produce with your fingers

and hands in a model will be greater than those you can produce at full-scale with your full body strength. The general rule is: be gentle with your models. If you are pulling with all the strength in your fingers in a small-scale model, you are modeling a very high full-scale tension force that can only be produced with some mechanical advantage, for example a block and tackle, or hydraulics.



Figure 12 Model fabric attached directly to a soft pine frame edge using map pins placed in the side of the frame

SMALL SCALE MOULD RIGS

Effectively modeling the rig that holds a fabric membrane requires some careful consideration. A literal miniaturization of the various techniques listed in Chapter 6, Connections, may not be appropriate in a scaled model construction. For example, a connection that requires a screwed pressure plate at full-scale as seen, for example, in Figure 6.41, p. 93, may be modeled most effectively by simply using just a map pin. A wrapped ball connection for a pull point [Figure 6.48, p. 96] may best be modeled with a thread stitched through a point in the fabric, and so forth. Likewise, the frame construction for a full-scale bulge-wall mould [for example Figure 9.17c, p. 168] may simply be modeled

using a single piece of plywood [Figure 9.13, p. 166]. In other words, a working model does not need to be a slavish and complex miniature of the full-scale rig, but rather an appropriate translation that provides the same actions as the full-scale rig.

Modeling Scaffolding and Connections

Plywood and soft pine are excellent choices for model scaffold constructions. MDF (medium density fiber board) or other particle boards are not recommended as they can swell or lose their integrity when exposed to water, and because pins are much harder to use with these materials.

The best way to directly attach a model fabric to its frame

is by using map pins, such as those seen in Figures 12 and 19. Don’t use staples, as these are difficult to remove and adjust. Map pins hold well and allow you to quickly and accurately adjust or remove your connections.

Pins are best placed not on the top of a frame, but on the side or bottom, where they are away from casting surfaces (Figure 12). This also provides some friction and stress distribution for the fabric as it takes a “turn” around the frame edge.



Figure 13 Braided twine (bottom) is far superior to twisted trine (top), as it does not easily fray apart when cut

Modeling Rope

String or twine perfectly models rope. You can use the same knots and rope tricks as in full scale construction (see [Chapters 6 and 7](#)). Although nearly any kind of twine can be used, some kinds are much easier to work with than others. Braided twine is far superior to twisted twine not only for its handling and knot-holding ability, but because it will not fray easily when cut (**Figure 13**). Nylon or polyester is far superior to polypropylene or natural fiber twine.

It can be very useful to prepare a piece of string by pulling it across a chunk of bee's wax. This will make the string

stiffer and slightly tacky, making miniature knot-tying much easier. Methods of attaching string to fabric include sewing (using a large upholstery needle) and the wrapped ball method described in [Figure 6.48, p. 96](#) and seen here in [Figures 14 and 15](#).

Two excellent methods for anchoring a string to a scaffolding frame are also shown in [Figures 14 and 15](#). The basic idea is to securely attach the string in a way that allows quick and easy readjustment, removal and reuse.

Figure 14 shows a soft pine wood frame which has been given a guide notch to hold the string at a specific location

(the guide is optional). The string is turned two or three times around the shank of a map pin to belay the string, and it is held (or "tailed") by inserting it into a "jam cleat" formed by a simple slice cut in the soft pine. This provides a very strong and secure anchor that can be rapidly undone or readjusted.

Figure 15 shows another method of securing a thicker string or twine using two map pins. Here the string is wound around the shanks of the pins in a figure-eight pattern. This method works particularly well if the string has been coated in bee's wax.

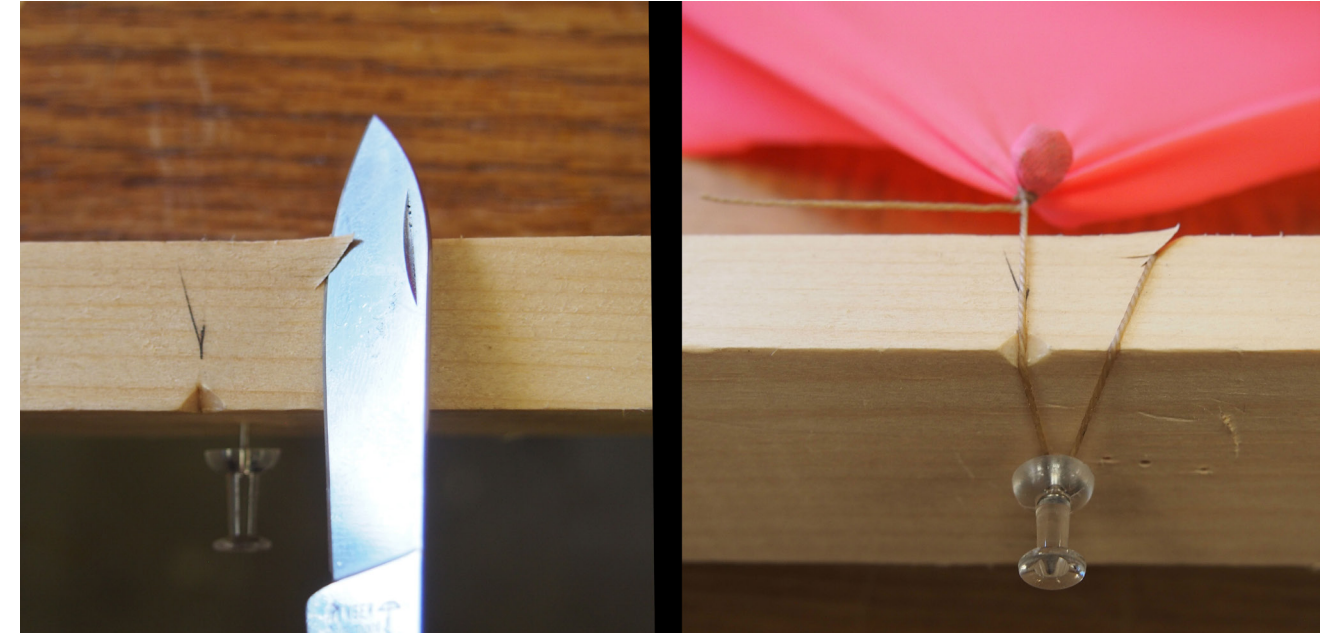


Figure 14 Attachment to a scaffolding frame using a notched guide and "jam cleat" detail, both configured by simple knife cuts in the wooden frame

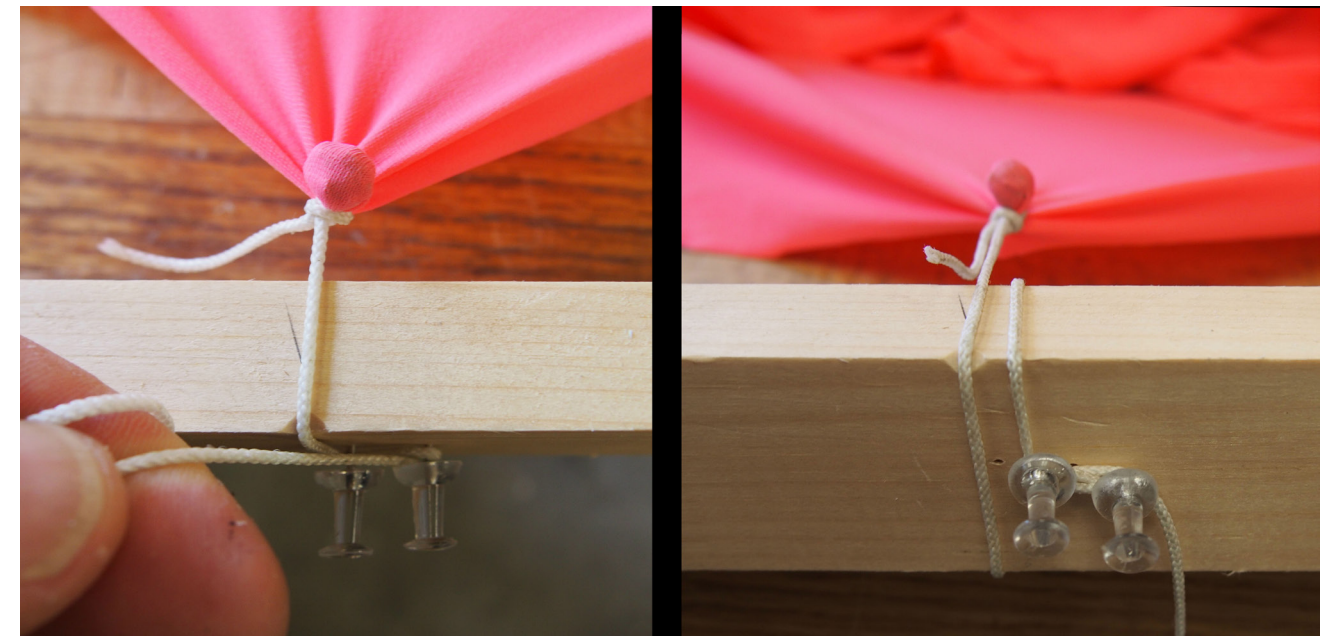


Figure 15 Attachment to a scaffolding frame using a notched guide and a figure eight cleat provided by a pair of map pins

Tape

It is very useful to have different kinds of tape on hand for making models. Tape is useful for holding down a model fabric while it is being drawn on for cutting, marking, or measuring, or as a temporary fabric-to frame connection -- like an extra hand holding things in place before making a final connection.

Double-sided tape is perfect for modeling a full-scale, closely stapled edge connection like the one shown in [Figure 6.31, p. 88](#).

A waterproof plastic tape should be applied to the sides of any wood pieces in contact with wet plaster to prevent the cast from adhering to exposed wood. For large production runs, waterproofing may be done by painting or clear-coating the wood surface, but when a limited number of casts is expected it is much easier and faster to simply cover exposed wood surfaces with plastic tape. A roll of common plastic packing tape works well for this. Several examples of taped edge-frames can be seen in the book. For example, [Figure 11.21, p. 208](#), or [Figure 11.29b p. 215](#) where a heavy red plastic tape is used.

The adhesion of hardened plaster to uncoated wood surfaces not only makes de-moulding difficult, it can cause fatal damage to a cast. This is particularly true of thin



Figure 16 Plastic tape used to shield frame edge from wet plaster and to cover and protect screw head



Figure 17 Digging hardened plaster out of a screw head: cover your screws (!) to avoid this difficult and time consuming labor

panels or shells. Such thin castings may crack as they shrink if they remain held by their surrounding edge frames. A plastic tape-covered surface allows the plaster to easily pull away from the edges as it shrinks (more on plaster shrinkage below).

Tape is also used for attaching paper masking or for covering screws heads so these things don't get covered and filled with plaster by accident during a pour ([Figure 17](#)). [Figure 16](#) shows a plastic tape used for this purpose.



Figure 18 Water test for a 1:10 model of a curved open trough mould

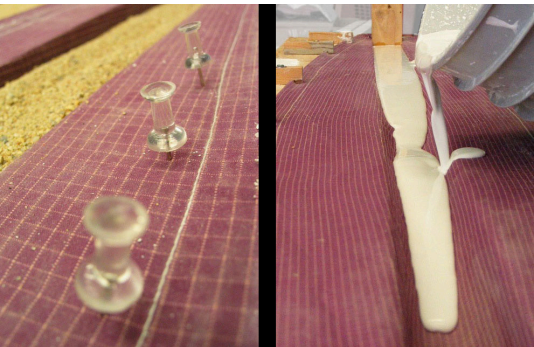


Figure 19 Sand test and adjustment using map pins (left), prior to filling with plaster (right)



Figure 20 Spirit level used to level an open pan mould

MOULD PREPARATION

Mould-making and casting is 99% preparation and 1% actual casting production. We cannot stress strongly enough the virtues of being completely prepared before you actually use your moulds for casting. Here are some tips about that:

Sand Tests and Water Tests

Filling a mould with dry sand, or water, will give you a rough approximation of the casting's final shape, while allowing you to play with or adjust the mould while it is, at least partially, pressurized ([Figures 18 - 19](#)). Sand is easier to use, but the "pressure" is less than ideal. Water provides actual fluid pressures, though not as great as what the wet plaster will produce. A water test is messier and more complicated, so we recommend starting with a sand test. This gives you a very rough sketch of the casting, and allows you to play with the mould at your leisure. It is a really interesting thing to do and is a great learning tool. You can follow up the sand test directly with plaster, or move on to a water test for a higher resolution sketch.

A Level Mould

When a fresh, liquid, plaster mix is poured into a mold, its surface will naturally find a horizontal level. An out-of-level mould can ruin a cast, particularly in thin, horizontal, casts such as panels. Before mixing and pouring plaster in your mold, make sure that the surface where your mold is placed, is properly leveled. A flat piece of plywood placed beneath your mould can be easily brought to level using small wood wedges. If you do not have a proper spirit level ([Figure 20](#)), a pan of water can be used to find a true horizontal position.

Volume Calculations

The volume of plaster needed to fill a prismatic mould (ex. cylinders, rectangular solids) can be easily calculated, but the volume of more complex or amorphous fabric moulds are not so easily calculated. You can make geometric approximations or, if you have done a sand or water test, you can simply measure the volume of sand or water used in the mould to gauge the approximate volume of plaster needed. In every case, however, you should always mix a bit more plaster than

you think you will need. If you mixed just enough, you mixed too little. Running out of plaster before the mould is filled is an unhappy event and may ruin your cast.

PLASTER - THE MATERIAL

Plaster as a Model for Concrete

Plaster is an excellent material to model concrete for two reasons: it is more fluid than concrete, rendering a more realistic pressure on a small model mould (see Scaling Factors above), and it hardens much faster than Portland cement, speeding up the production cycle for your mould tests.

However, the more fluid nature of plaster requires more water-tight connections in a mould than would be required in full-scale concrete formwork. For example, the jointless connections described in [Chapter 6, p. 73 and pp. 102-104](#), only work because concrete is not really a fluid, but more like a plastic rock-filled glop that will not flow through small openings (the stiffness of concrete’s plasticity is measured in terms of its “slump” as described in [Chapter 5, p. 67](#)). Formwork for a plaster column model needs a more or less watertight connection at its base and edges. As such, the connection details for a plaster model may be more difficult to make than those of its full-scale equivalent.



Figure 21 Fine glass beads, typically used for sand blasting, make an excellent fine aggregate for thickening a plaster mix

When it is called for, however, it is possible to make plaster behave in a less fluid manner, and more like concrete, by mixing in a fine aggregate to thicken the wet plaster. This can be done when you want to avoid making unrealistic and time consuming waterproof joints -- for example at the bottom of a column mould (see [p. 103](#)). But be aware that the thicker plaster will produce lower, and therefore less realistic pressures in your model formwork and will also weaken the hardened plaster.

Fine sand can be used to thicken plaster, but the salts inevitably found in sand will tend to speed up the chemistry of the gypsum plaster to the point where it may be difficult to mix and place the plaster before it sets. We have found

that adding fine glass beads to the mix -- the kind used as abrasives in “sand blasting” ([Figure 21](#)) -- does an excellent job and will not speed up the set time of plaster. Glass beads are commonly used as a blasting abrasive for stripping paint in auto body shops and can be easily sourced from suppliers to that trade. We have found that a mix ratio of approximately 1:1 glass beads to plaster powder, by volume, works well to stiffen plaster to a concrete-like thickness, but you will need to find your own proportions by trial and error.

The Right Type of Plaster

Plaster, which is made from Gypsum, comes in several different types. Choosing the right type is crucial. For



Figure 22 Plaster powder -- just add water

model-making purposes the important differences are, in order of importance: faster or slower set times, and higher or lower strengths. Unfortunately, it is difficult to offer instructions on which plaster to buy because different manufacturers use different names and recipes for their products, and availability differs from place to place.

“Plaster of Paris” is a commonly used term that generally refers to a fast setting gypsum plaster. *Fast setting plasters are not recommended.* A faster set time makes both mixing and casting much more difficult as your plaster is more liable to set up before the job is finished. In North America, the names “Molding Plaster” and “Dental Plaster” both refer to fast setting prod-

ucts. Avoid them. An example of a good slower setting plaster is “Statuary #1” (a designation used exclusively by the North American manufacturer Georgia Pacific).

Avoid buying your plaster from arts and crafts stores. They generally sell “Plaster of Paris” in small, relatively expensive containers. You can source less expensive, larger quantities of plaster from suppliers serving the drywall (sheetrock) or masonry trades. They will typically sell 20 kg or 25 kg (50 lb.) bags, and they may offer a choice of plaster types to choose from. At CAST we preferred a relatively slow-setting, high strength plaster for our models. Georgia Pacific’s “Densite” product, and U.S. Gypsum’s (USG) “Hydrocal” plasters are two examples.

Higher strength plasters are slightly more expensive, but when you are working with small or thin castings, or when aggregates such as glass beads are added (see above) the extra strength is great to have.

In the end, your choice may simply be limited to what’s available in your area. Be aware that even when a range of types is available your local supplier may not know much about different set times. You can check with the manufacturer (through a tech-support line), but the only way to know for sure if your plaster has a workable set time is to try it out. If the product gives you enough time to mix and place the plaster, then all is well.

Plaster, like concrete, does not harden by “drying”. It hardens by a chemical reaction with the mix water, called hydration. Temperature affects all chemical reactions, so you can slow down the set time by using very cold water, or by working in colder ambient temperatures (but always above freezing). Conversely, hot water, or higher ambient temperatures, will speed up set times.

Shrinkage

Like concrete, plaster will generate heat while it is hardening (called “heat of hydration”). The temperature of your cast can get quite high, particularly when its mass is

large. This heat causes the solidifying cast to expand as it hardens. Shrinkage will naturally occur as the hardened plaster slowly cools down after setting. Plaster, like concrete, will also shrink after hardening as the mix water that was not consumed in the initial hydration slowly evaporates from the solidified plaster (just as a damp sponge shrinks when it dries). Both the heating/cooling and drying processes cause shrinkage, which in turn can cause internal stresses and shrinkage cracks in the final cast. This can be particularly troublesome in thin castings such as panels or shells. For this reason, thin casts will benefit greatly by having small random fibers included in the mix to help provide some tension resistance for the control of shrinkage cracks.

In plaster, the easiest way to provide random fiber reinforcing is to dissolve some high quality toilet paper into the mix water. Toilet paper, which is made of random cellulose fibers, is designed to dissolve in water. Simply add the toilet paper to the mix water until the water becomes milky in appearance. Do not use recycled paper, which has shorter fibers. Small, hair-thin glass or plastic fibers, sold for crack control in concrete mixes, may also be used in plaster.

Plaster Consistency

Different moulds and application types can require different consistencies in the plaster

mix. The consistency of wet plaster depends on 1. the proportion of water to plaster powder, 2. whether any aggregates are added to the mix, and 3. how close the plaster is to solidifying.

In a hanging sheet mould for example (see [Chapter 11](#)), or other moulds using a spray application (see below), the plaster cannot be too liquid or it will simply run off the mould sheet. Instead, an almost yogurt-like consistency is wanted. This is achieved by using proportionally less water, or by waiting until the wet plaster starts to thicken slightly.

In a pressurized mould (for example, the moulds in [Chapters 8, 9, 10, & 12](#)), or in a mould with a small fill-opening, such as a small scale column mould, a more fluid mix is wanted to ease the placement of the wet plaster. A more fluid mix also helps to produce higher fluid pressures so that the model fabrics are more realistically stressed (see scaling factors above). On the other hand, a mix that has too much water will not harden or strengthen properly. A sure sign you have added too much mix water is a cast that remains soft after it has set.

MIXING PLASTER

The single most important step in mixing and placing plaster is making sure that the mould is 100% ready (more on this below). Scrambling to fix some-

thing in your mould while you have plaster hardening in the bucket is not a happy situation and not conducive to good results. That said, you will surely have this experience more than once – particularly when you are beginning. Enjoy the excitement, but study to eliminate that kind of drama by checking and double checking your mould *before* you start mixing the plaster.

As in any chemical reaction, proper proportioning for opti-

mized strength is determined by weight, but for our purposes, proportion by volume is much easier to do and quite sufficient for our purposes.

Mixing and pouring plaster is really a multi-person job ([Figure 23](#)). If at all possible, do not work alone. Although an experienced person may be able to carry out the work alone, this is often a stressful way to work. If you can, get at least one friend or partner to assist.

Preparations Before Mixing Plaster

Each brand and type of plaster requires its own particular proportions of water to powder, so tests must be made for each new brand or type of plaster to determine the correct proportions for that particular plaster.

There are only two fundamental ingredients needed for making plaster: clean water and plaster powder.

Tool List

(Note: for spray plaster, see “Additional Tools for Spray Plaster” below.)

- Measuring containers (for measuring the correct volume proportions of the mix ingredients)
- Mixing containers (separate containers used only for the actual mixing)
- Wash-Out (Sink) Buckets (reserved exclusively for cleaning tools and hands)
- Putty knives and/or small trowels (for scraping off excess plaster or finishing the top surface of the cast -- also useful for clean-up)
- Filter mask (to protect your lungs from plaster powder)
- Eye protection (to keep plaster from splashing in your eyes while mixing and pouring.
- Floor Tarps (to protect your floor). Plaster dust from waste and cleanup is famously insidious, and can take ages to fully disappear, even after multiple moppings.

Optional Tools

(but highly recommended):

- Water Hose -- very handy for both mixing and clean-up
- Power drill with paint mixer attachment for fast, high quality, mixing (shown here, top right)
- Funnel or Grout Bag -- for guiding wet plaster into small mould openings (see [Figure 28](#)).



For most applications, aim for the consistency of heavy cream (not milk, not yogurt). Once you have established the relative volumes of plaster and water for this target consistency, adjustments can be made for lightly thicker or more fluid mixes as may be required for particular casts.

As indicated in the tool list above, you will need separate measuring containers (one for measuring water volume and one for plaster volume), and at least one separate mixing container (for the actual mixing). You will also need multiple wash-out (sink) containers (Figures 24 and 25). Each of these should be prepared and marked ahead of time. This is important because each container performs a separate task in the work. You do not want them getting mixed up and “polluting” each other.

Measuring containers
These should be labeled Water Only or Plaster Only, and marked with volume lines (for example: small mix; medium mix, large mix), so that each batch you make has the correct proportions.

Mixing containers
These should be labeled and used only for mixing. You will probably want more than one mixing container so that you always have one ready while empty ones are being cleaned out.



Figure 23 Making plaster models is best done with at least one helper

It is important to keep your mixing buckets clean. Old plaster in a mixing bucket will chemically excite a fresh batch of wet plaster, causing it to harden faster. This can cut short your working time. It is always easier to clean a mixing container while the remaining plaster is still wet. If you can't clean the bucket while the plaster is wet enough to be rinsed out, it is best to wait until it the plaster hardens, and then crack it out. Flexible rubber or plastic buckets work best for this last procedure.

Sink Buckets
You will need extra buckets for washing your mix containers, tools, and hands. NEVER WASH WET PLASTER DOWN THE DRAIN. If you do, it will eventually harden in your drain pipes and that will make you very sorry indeed that you did not heed to this warning. Unless your shop has a specially designed plaster sink, always use wash-out buckets instead or the sink. The plaster will eventually sink to the bottom of these wash-out buckets, allowing you to safely pour off the water left at the top. Later you can remove and discard the gloppy solids. You will be happy to have multiple sink-buckets so you don't run out of capacity when you need it.



Figure 24 Separate, labeled, plaster and water measuring buckets, prepared to ensure proper volume proportions for the mix



Figure 25 You can never have too many buckets! Prepare separate containers for measuring water and plaster, for mixing, and for washing up. Here we see two batches being mixed at the same time for a multi-person workshop class

The Actual Mixing

Once you have your moulds 100% prepared, and all your mixing and cleaning tools are assembled, and all your measuring containers are filled and ready, you have two options: A) a slower mix method or B) a faster method of mixing:

- A) Slower mix method (Figure 26)
- 1. Empty the measured water into a mixing bucket
 - 2. Slowly sift the measured plaster powder into the water, letting it settle gently, on its own, to the bottom of the mixing bucket.
- DO NOT START MIXING THE PLASTER YET.

At this point it is good practice to let the water + plaster sit for 1 or 2 minutes. Allowing the plaster to sit under water for a while will help make the plaster stronger and easier to mix. The chemistry (hardening) will not begin until the mix is agitated, so you have some time. Best to check over your mould one last time while the plaster is soaking to make sure you are 110% prepared (you probably won't be).

- B) Fast and Dirty method (Figures 23 and 27)
- If you are in a hurry you can start mixing as the plaster is being sifted into the water. In this case it is important to sift in the plaster powder gently and slowly to get a smooth creamy mix and avoid creating lumps.

In either case, plaster likes high-energy mixing, which actually helps make the plaster stronger. An electric drill with a paint mixer works perfectly. It helps to have your mixing bucket well proportioned to the volume you are mixing so that the mixer blades are well submerged and not pulling air into the mix. If you don't have a power mixer, you can mix the plaster by hand.

Mix time also affects plaster strength. You could mix for up to 4 or 5 minutes to improve strength, but you will simultaneously be reducing your open pour time. It's a compromise. We generally mix for no more than a minute or so, opting for slightly less strength and a longer open working time. Once the plaster has achieved a completely smooth and creamy consistency (no lumps at all), it is ready for your mould(s).



Figure 26 Slow Mix Method. Top: plaster has been sifted into the mix water and is allowed to soak. Bottom: mixing with a power drill and paint stirrer. Chemistry starts *after* the mixing begins



Figure 27 Fast mix method: plaster being mixed as it is sifted into the water



Figure 28 Funnel (top) and grout bag (bottom) used to fill moulds with small or narrow openings



Figure 29 Vibrating a freshly filled mould using a hammer

PLACING THE PLASTER

For Poured Plaster

Depending on the shape and size of your mould and the mould opening(s), you may want to have a funnel or a grout bag to help get the plaster in the mould, as shown in Figure 28. Otherwise, either pour directly from the mixing container itself or if more control is needed, transfer the wet plaster to a smaller container for pouring.

Vibration

When pouring plaster, you should vibrate the cast. Vibration helps remove any air bubbles that did not rise to the top or pass through the fabric mould wall. This can be done by hand (poking or patting the exterior of the fabric), or by tapping/banging the mould rig with a hammer (Figure 29). You can also make a vibrating table (a reciprocating saw clamped to a slightly wobbly tabletop works well) to vibrate your mould(s). Examples of full-scale vibration of fabric moulds can be seen in Figure 6.63, p. 104, and Figure 9.1, p. 156.

While one person is vibrating the mould, another person should be cleaning up before the plaster in your mix bucket or funnel takes its set.

Multiple “Lifts”

Having warned against mixing too little plaster, it is also interesting to see what happens when a flexible mould is filled in multiple “lifts” (i.e. multiple separate pours). Examples of the kind of “live edge” that is formed by a second lift in a vertical flexible mould is shown and discussed in [Chapter 6, p. 107, Figures 6.67 and 6.68](#).

Figure 30 shows a horizontal panel mould that was not entirely filled and requires a second pour to complete the casting. The top surface of the first layer of plaster has been prepared by roughing it up while it was still plastic. This provides a mechanical bond between the two layers.

Sometimes a second layer of plaster is required to back up a first thin sprayed plaster layer. This situation is illustrated in **Figure 31**.

In each case where wet plaster is poured on top of hardened plaster the set time of the wet plaster will be accelerated. This is because the dry layer below sucks water out of the wet plaster, and also because the set plaster will excite a fresh mix to a faster chemical reaction.

Screeding

A screed is a (usually) flat bar used to evenly distribute material, or scrape excess plaster (or concrete) off the top of your cast, producing a uniform, (usually) flat surface.



Figure 30 Top surface of a previous cast should be roughed up to help it bond to the new layer to be poured on top



Figure 31 A second layer of plaster being poured to back-up a thin, fragile, first layer of sprayed plaster

Setting plaster goes through several states of plasticity/hardness. Finding the right moment to screed or scrape the top of your mould takes some play and experience. It is all about timing: too liquid and the plaster will not be scraped off -- too hard and it's too late.

For Sprayed Plaster:

A thin layer of plaster can be applied to irregular surfaces, such as a hanging fabric sheet, by a spray application. This is done with a “hopper gun” (**Figures 32, 33, 36, 37**). This tool requires a source of compressed air, which is used to propel droplets of wet plaster through the nozzle of the gun. This method of placing wet plaster closely models spray concrete applications (ex. shotcrete or gunnite) and is the best way to create thin-shell plaster elements.



Figure 32 A hopper gun used for spray plaster applications



Figure 33 Curved surfaces will require you to spray plaster onto the formwork from different angles. Give yourself room to work all around the mould

Additional Tools for Spray Plaster

- Hopper gun (**Figure 32**)
- Compressed air source
- Valve to regulate this air pressure (important for controlling plaster droplet size and velocity)
- Water hose with a spray nozzle (to clean out the gun and hopper).
- A prepared space to spray: make a spray booth that protects floor and walls and surrounding spaces (more on this below).
- Mask, safety glasses, and work clothes. ALWAYS PROTECT YOUR LUNGS AND EYES

Due to the thinness of the plaster layer produced, it is a good idea to add fibers into your spray mix to control shrinkage cracks (see discussion above under the Shrinkage heading). Be careful to not add too much fiber to the mix as this can jam up the hopper gun.

Depending of the size and shape of the mold, more than one layer may be necessary to achieve a sufficient thickness and strength. This is best done when before the previous layer is still “green”, in other words, solidified but not completely dried.

Spraying plaster is a messy procedure. Don’t try to do this alone, at least not until you have mastered the workflow. Working with at least one partner or assistant will make a big difference in achieving positive results.

Workspace Preparation for Spaying
Over-spray is unavoidable, so you will need a spray booth of some kind. This can be prepared using inexpensive tarps as shown in **Figures 34** and **35**.

Also, make sure you protect any mould frames, fasteners, clamps, etc. with some kind of masking. Masking tape and paper or plastic sheets should be used to cover anything you don’t want covered in over-sprayed plaster. This important step will save you lots of time and trouble in your clean up.

Spraying undulating or complex surfaces will require spraying from a number of different angles; make sure you have access all around the mold (**Figure 33**).

The Right Consistency
The plaster mix has to have the right constancy as well. If it is too thick it will not spray. If it is too liquid it will tend to run off of the mould surface. If you find your mix too liquid you should wait until it thickens slightly -- but remember, this means that the plaster is starting to gel and set, so in this case work fast and clean up fast.



Figure 34 A spray booth made with 2x4's and a cheap poly-tarp

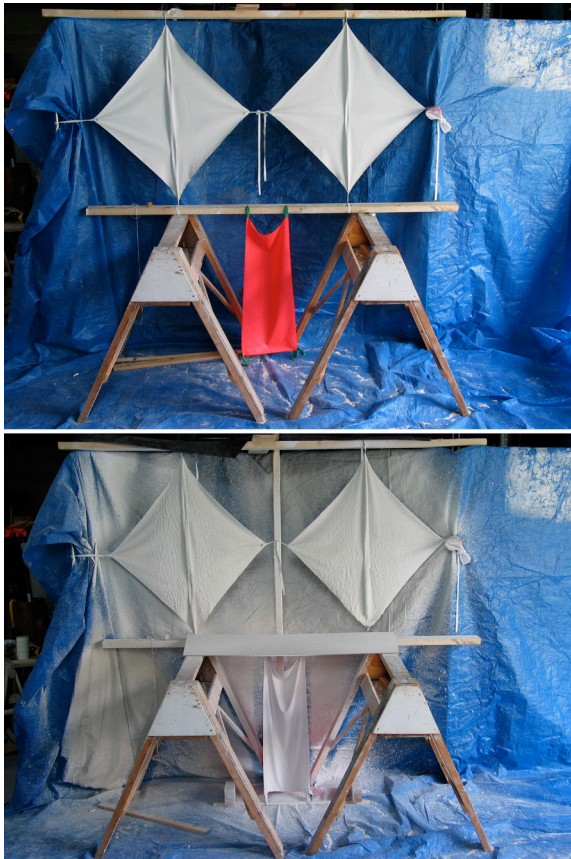


Figure 35 Be prepared for lots of over-spray -- provide a spray booth and masking



Figure 36 Overloading the hopper makes spraying more difficult. Work with a partially filled hopper, re-filling as the work progresses



Figure 37 Clean the gun earlier rather than later. If plaster is allowed to set up inside the tool it will be ruined. A water hose (with wash-out bucket) is ideal for spray-cleaning the gun

Workflow
We find it best to spray in smaller batches. This makes the gun less heavy for better handling. Have your assistant ready to re-load the hopper (**Figure 36**). Our experience is that two half-full hopper loads is about all you should expect from each mixed batch before the plaster becomes too stiff to apply. Better not to mix too much. You will probably need multiple layers anyway, so clean out the gun, mix another batch and go again.

Timing and a good workflow is key. If your first layer of plaster completely sets and dries before the next layer is applied it will create a cold-joint between the old and new plaster layers and will not bond well. Having multiple batches measured and waiting will speed up the production of sequential batches. As previously described, you will probably find that the subsequent layers set up on the mould much faster than the first layer did.

Clean the gun before the plaster sets (**Figure 37**). If that means stopping your work prematurely, then so be it. Use good pressure in your water hose when cleaning the gun, and make sure you get ALL the plaster out. No need to ruin your tool just because you were in a rush.

After each layer is sprayed, screed off the top of any edge frames with a scraper. Don’t forget to do this, or the overspray will become part of your shell and it will be extremely difficult, or impossible, to remove the excess without cracking the rest of the shell. Screeding off the over-spray on all your edge-frames is the only way to get clean, accurate, edges.

DE-MOULDING

When To De-Mould Your Cast

You may be able to remove your plaster casting in a couple of hours. A fingernail test is a good way to estimate the strength of the hardened plaster. Try pressing your fingernail into the plaster at the top of the mould: if your fingernail easily enters the plaster it's not ready yet. Give it more time to gain strength. (A fingernail test on a properly cured piece of plaster will give you the comparative gauge of a fully hardened casting.) It is good practice to leave some extra plaster from the batch lying around so you can also gauge its strength by breaking bits of it in your hands, following its progress over time.

Patience is a virtue when it comes to de-moulding. There is a great temptation to remove the mould as soon as possible. *Resist this temptation* (if you can). After all the preparatory work of making a mould and of doing the casting, it is a real pity when the results are damaged or destroyed by an impatient maker.

Stripping Fabric Moulds

If the mould fabric has not been pinched together or captured by the casting (see [Chapter 7, pp. 122-3](#)) removing the fabric is usually very easy. Care must obviously be taken with thin or delicate por-



Figure 38 Stripping fabric mould sheet from a thin, spray plaster shell



Figure 39 Direct-cast plaster mould (bottom) used to make an invert-cast thin shell (top)

tions of a casting. **Figure 39** shows a fabric mould sheet in the process of being stripped from a thin and delicate plaster shell.

Keep in mind that freshly set plaster is still very much “alive” and any dirt or stains transferred to its surface (by dirty fingers for example) will be permanently captured in the surface and cannot be cleaned off. Handle newly set plaster accordingly.

INVERTED CASTINGS

A plaster cast can be used as a mould to produce an inverted casting (**Figure 39**). This process effectively inverts the geometry of the original cast, which in the case of certain fabric-formed geometries offers very interesting structural and sculptural advantages (for direct and invert casts see [Chapter 11, p. 196](#) and for structural geometries see [Chapter 3, p. 40, Figure. 3.1](#)).

There are two fundamental tricks to making casts off of plaster moulds. The first is to assure that there are no keyed, or undercut, geometries in the mould (see [Chapter 7, p. 124](#)). The other is to prepare the surface of the plaster mould as a release surface, so that the plaster cast on top of it can be easily separated and removed.

Preparing a Plaster Mould

Exposed plaster cannot be used as a mould until it is sealed. Plaster cast against an unsealed surface will aggressively stick to it. The best way to prepare a plaster mould surface is to use *mould*

soap. Choices include buying a dedicated product such as *Douglas and Sturgess Potters Soap*, or using either *Murphey's Oil Soap*, (available as a housecleaning product, or from hardware stores in North America) or soap flakes (available everywhere including Europe and UK) mixed with water. There are many reports that *tincture of green soap* (evidently available through pharmacies) also works well, though we have never tried it.

Vaseline has been used as a sealer or release agent as well, but it is not preferred for two reasons: Vaseline more readily leaves brush or spreading marks on top of the mould, and it leaves the surface of the casting with an oily film that cannot be washed off with water. Mould soap does not present these problems.

No matter what kind of soap you use, the procedure is more or less the same: a soapy mixture is brushed onto the raw plaster surface in three separate coats, allowing the liquid to soak in between coats. That's all. Another coat of soap should be applied before each subsequent cast is made.

Potters Soap can be used directly out of the jar. Soap Flakes are mixed with water until a smooth soapy liquid is produced. Murphey's Oil Soap can be used directly or cut half-and-half with water before use.

Releasing a cast from a well prepared plaster mould is usually very easy. Sometimes, however, a shot of compressed air between cast and mould may be needed to break the vacuum between the two.

ENDNOTES

- 1 Tomlow, Jos. 1989. IL 34 The Model, 1989. Karl Kramer, Stuttgart. ISBN: 3782820347. Originally published as Issue 34 of Institut für Leichte Flächentragwerke (University of Stuttgart) 1989
- 2 Otto, F. and Rasch, B. 1996. Finding Form: Towards an Architecture of the Minimal. Stuttgart: Edition Axel Menges.
- 3 Chilton, J. 2000. The Engineer's Contribution to Contemporary Architecture: Heinz Isler. London: Thomas Telford.

and

Isler, H. 1960. “New Shapes for Shells.” Bulletin of the International Association of Shell and Spatial Structures, 8.