Supporting Information

Using "Click-e-Bricks" to Make 3D Elastomeric Structures

*Stephen A. Morin, Yanina Shevchenko, Joshua Lessing, Sen Wai Kwok, Robert F. Shepherd, Adam A. Stokes, and George M. Whitesides**

Materials

We used all materials as received unless otherwise noted. We purchased polydimethylsiloxane (PDMS, Sylgard® 184, Dow Corning Corporation®) and Ecoflex® (Shore hardness 0030, Smooth-on Inc.) two-part silicone elastomer kits from Ellsworth Adhesives and Reynolds Advanced Materials respectively. We purchased acrylonitrile butadiene styrene (ABS) cartridges for use with a Dimension Elite (manufactured by Stratasys Ltd.) three-dimensional (3D) printer from Stratasys Ltd. We purchased polyethylene tubing (I.D. 0.045", O.D. 0.062", PE 160, BD Intramedic™) and silicone tubing (I.D. 0.030", O.D. 0.065", VWR International) from VWR International LLC. We purchased the dyes hexamethylpararosaniline chloride (Crystal Violet, CAS# 548-62-9, ACS Reagent, >90% dye content), 2,4-dihydroxyazobenzene (Sudan Orange G, CAS# 2051-85-6, 85% dye content), and 7-amino-4-(trifluoromethyl)coumarin (Coumarin 151, CAS# 53518-15-3, $\geq$ 99% dye content) from Sigma-Aldrich®. We purchased polymer film diffraction grating (Item #3040267; 12" x 6", 25,400 grooves per inch) from Edmund Scientifics®. We purchased LEDs and copper wire from DigiKey®. We purchased button batteries from Radio Shack®. We purchased steel wool (Red Devil 0000, Super Fine Steel Wool) pads from McMaster-Carr®.

Experimental

Master Designs for Click-e-Bricks: We demonstrated structures that were fabricated using rectangular (Figure S1 – S3) and circular click-e-bricks designs (Figure 5, main text). The technical drawings for the master we used in the fabrication of rectangular click-e-bricks are shown in Figure S5. The master for rectangular click-e-bricks has edges that are at right angles with an array of pegs and recesses that decorate a evenly spaced rectangular lattice (we used a 6×9 array, but the master could have arrays of different sizes). The master consists of three parts—a bottom (that forms the pegs), a top (that forms the recesses), and a 'union' that holds the top and bottom in the correct orientation during molding and prevents pre-polymer from leaking out of the master.The top has small holes (not shown; they are drilled into the master post-fabrication) that we used to degas the pre-polymer prior to curing and that provide exit points for excess pre-polymer to escape from when the master is closed (by placing the top onto the bottom)..

We fabricated circular click-e-bricks using the master shown in Figure S6 and S7. We used circular arrays or pegs/recesses (Figure S6) and rings of pegs/recesses (Figure S7). Similar to the rectangular master, the circular masters required a top and bottom and a union to lock them together.

Fabrication of the Masters for Molding Click-e-Bricks: We fabricated the masters for the click-e-bricks from ABS thermoplastic using a three dimensional (3D) printer (Dimension Elite manufactured by Stratasys, Ltd.). We saved the CAD designs for the masters in the standard tessellation language (.stl) file format and loaded them into the printer for production using a specialized software package provided with the printer (CatalystEX from Stratasys, Ltd.). The masters were used as printed without further modification.

Fabrication of Click-e-Bricks Using Soft Lithography: We fabricated all of the click-e-bricks using soft lithographic molding. In general, we filled the masters (Figure S5 – S7) with a liquid pre-polymer, closed the master, and thermally cured the pre-polymer in the confines of the master leading to a solid polymer piece with topographic features inverse to those of the master.

We first prepared liquid PDMS or Ecoflex® pre-polymer following the instructions provided by the manufacturer (10:1 ratio of base to curing agent for PDMS and a 1:1 ratio of part A to part B for Ecoflex®). Next we placed the union around the bottom part of the master (each design includes a notch around the rim to accept the union) and filled the bottom with an appropriate amount of liquid pre-polymer so that the level of the polymer was even with the top of union. We then closed the master by locking the top into the union and pressing downward until it was flush with the bottom part of the master. At this point access pre-polymer (displaced by the solid features of the top part of the master) exited through the holes in the top of the master. We transferred the pre-polymer-filled masters to an oven for thermal curing at 60° C. Ecoflex® 0030 required 45 min curing while PDMS required 120 min of curing. We removed the cured click-e-bricks from the oven and released them from the master by carefully prying the top part of the master from the bottom part of the master using a blunt paint scraper for leverage. If necessary, we used a pair of fine-tipped microscopy scissors to trim the edges of the click-e-bricks clean of any imperfections. This process is equivalent for both rectangular click-e-bricks and circular click-e-bricks, only the master is different.

Fabrication of Click-e-Bricks with Heterogeneous Materials Composition: We fabricated composite click-e-bricks (e.g., those with PDMS pegs/recesses and Ecoflex® bodies, Figure S2) following the methods described for the fabrication of homogeneous click-e-bricks, except we combined pre-polymers of different elastomers during the molding process. For the example of PDMS pegs/recesses and Ecoflex® bodies we first filled the bottom of the master with PDMS pre-polymer to a level just above the peg features. We then partially cured the PDMS-filled bottom in a 60° C oven for 20 minutes. We removed the bottom from the oven and filled it with Ecoflex® pre-polymer to a level of ~ 3 mm below the top of the union and then filled it the remainder of the way with PDMS pre-polymer. We closed the master by seating the top onto the union. We placed the pre-polymer-filled master in a 60° C oven for thermal curing. After 2 hours, we removed the fully cured composite click-e-bricks and freed them from the master as described above.

To fabricate click-e-bricks with alternating PDMS and Ecoflex® sections (Figure 5f, main text, top panel), we began by fabricating homogeneous click-e-bricks as described above. Once the click-e-bricks were removed from the master we used a razor blade to cut away part of the click-e-brick in the desired shape. Later we fit a click-e-brick (or piece of a click-e-brick) that was fabricated from the desired elastomer (here, either PDMS or Ecoflex®) into the void and permanently connected it by adding Ecoflex® pre-polymer and curing the composite click-e-brick in an oven for 15 min.

Fabrication of Colored Click-e-Bricks: We fabricated colored click-e-bricks following the molding procedure described above, except we used silicone pre-polymers that we colored with visible wavelength and fluorescent dyes. We made the colored pre-polymers by first dissolving the appropriate amount of the chosen dye (crystal violet for purple click-e-bricks, sudan orange G for orange click-e-bricks, coumarin 151 for fluorescent click-e-bricks) in dichloromethane to achieve an approximate concentration of 3 mg/mL. We added this colored solution to silicone pre-polymers that had been prepared according to the manufacturer's instruction (described above) to achieve a ratio of approximately 1 mL of dye solution per 22 g of pre-polymer and mixed them thoroughly using an overhead stirrer equipped with a three-paddle propeller. We degassed this mixture in a vacuum desiccator at 65 kPa to remove most of the dichloromethane. The duration of degassing was 5 minutes for Ecoflex® and 20 minutes for PDMS pre-polymer. We then used the resulting colored pre-polymer to fabricate colored click-e-bricks.

Cutting Click-e-Bricks from a Larger "Master" Click-e-Brick: We cut smaller click-e-bricks and click-e-bricks of different shapes from larger master click-e-bricks using a razor blade or a scalpel (Figure S3). To make accurate cuts, we created a template with the desired click-e-brick shape/dimension on a piece of paper, and placed it under the master click-e-brick on a level solid surface. The polymers used made it possible to see the template through the click-e-brick. We cut along the lines of the template using a razor blade (or a scalpel). For longer, straight cuts, we used a sharp-edged paint scraper with a 4” blade.

Fabrication of Diffractive Click-e-Bricks: We first fabricated click-e-bricks of the desired size following the molding procedure described above. We then coated ~ 300 μm of liquid PDMS pre-polymer onto the polymer film diffraction grating. We placed the desired click-e-brick face onto the coating of pre-polymer and allowed the PDMS pre-polymer to fully cure at room temperature. Once cured, we carefully pealed the click-e-brick away from the polymer diffraction grating and trimmed away any excess material from the edges. This procedure successfully replicated the topographic features of the grating onto the surface of the click-e-brick.

Fabrication of Click-e-Bricks with Microfluidic Channels: We first fabricated click-e-bricks of the desired size following the molding procedure described above. We then used 1 mm biopsy punches to cut out vertical channels along the axis of the peg/recess connectors. To access the channel we introduced polyethylene tubing into either the peg or recess. We could use silicone tubing or other click-e-bricks to control the route of the fluid.

Fabrication of Click-e-Bricks with Electric Conductors, Batteries, and LEDs: To make the battery and LED click-e-bricks, first copper wire was manually wound around cylindrical forms to create wire coils. Wire coils were made with 5 mm and 4 mm inner diameters. The 5 mm coils were placed around the pegs of top mold used to fabricate the click-e-bricks (Figure S5a) and snipped at the top of the peg. The 4 mm inner diameter coils were placed inside the recesses of bottom mold used to fabricate the click-e-bricks (Figure S5b) and snipped at the top of the recess. Next the wire coils were removed from the mold to be soldered to the electrical components (either batteries or LEDs). The lighting brick was wired by soldering a set of 4 and 5 mm wire coils to the positive and negative leads of a green LED.

The power brick was wired by soldering a 4 mm coil to one of the terminals of a button cell battery and a 5 mm coil to the oppositely charged terminal of a second battery. Next silver paste was applied to the unsoldered face of each battery and these faces were subsequently stacked and mated with glue. After the electronics for the lighting and power bricks was prepared they were placed into the bottom mold (Figure S5b) used to fabricate the click-e-bricks by inserting the 4 mm coil into the recess. The mold was then filled with Sylgard® 184 and closed with the top part of the mold and cured in an oven at 80° C for at least 2 hours. After the de-molding step a scalpel blade was used to remove excess material around the wire coils embedded in the pegs and recesses of the elastomeric bricks thereby exposing the coils metal surface enabling the formation of electrical connections. The conductive click-e-bricks were fabricated by creating a steel wool fiber bundle from Red Devil 0000 Super Fine Steel Wool pads and either inserting the ends of the bundle in the recesses of the bottom of the click-e-brick mold (Figure S5b) or winding the ends around the pegs of the top part of the click-e-brick mold (Figure S5a). The mold was filled with Sylgard® 184, closed, and cured in an oven at 80° C for at least 2hrs.

"Gluing" Click-e-Bricks Together to Fabricate Permanent Structures: For prototyping purposes we could assemble, disassemble, and reassemble click-e-bricks repeatedly, enabling the exploration of many different soft structures. To fabricate permanent structures (Figure 1, main text) and structures that are air-tight, as required for pneumatic actuation (Figure 2 – 5, main text, and Figure S4), we "glued" the click-e-bricks together at their interfaces using liquid pre-polymers. First, we coated the mating peg/recesses and the edges of the click-e-bricks with liquid pre-polymer (for gluing PDMS click-e-bricks to PDMS click-e-bricks we used PDMS pre-polymer; for gluing PDMS click-e-bricks to Ecoflex® click-e-bricks we used PDMS pre-polymer; for gluing Ecoflex® click-e-bricks to Ecoflex® click-e-bricks we used Ecoflex® pre-polymer) using a syringe tipped with an 18 gauge needle. We then pressed together the pre-polymer-coated bricks. In the case of hollow, inflatable structures, we also

coated the lateral interfaces of the click-e-bricks (where there are no pegs/recesses). We then transferred the assembled click-e-bricks to an oven for thermal curing at 60° C. After 40 minutes or 15 minutes for PDMS or Ecoflex® pre-polymer glue respectively, we removed the cured assembly of click-e-bricks and let it cool to room temperature before testing. For hollow, air-tight structures, we used a needle or biopsy punch to create a small (typically 1 mm in diameter) hole to vent away air that expands inside the structure during the eleveated temperatures used during curing. If this hole was not made, the expanding air would vent through the seams between the click-e-bricks, compromising the air-tight seals. This hole could be sealed later (using pre-polymer cured at room temperature) or used to introduce a pneumatic line.

Assembly of Click-e-Brick Structures with Internal Channels: We first fabricated click-e-bricks and cut them to the desired dimensions as described above. We then used a biopsy punch or a scalpel to cut out internal sections of the click-e-brick (an example is shown in Figure 3b of the main text). Finally, we glued together stacks of the modified click-e-bricks. The registration of the cut-out sections of the click-e-bricks formed the internal channels of the final structure (Figure 3c, main text). Another example of this strategy is shown in Figure 4 of the main text.

Introduction of Pneumatic Tubes to Click-e-Brick Structures and Pneumatic Operation: We inserted a single polyethylene tube (I.D. 0.045", O.D. 0.062") through the previously cut inlet/outlet hole of the click-e-brick structure in order to inflate or deflate the structure using compressed nitrogen gas. We did not use glue to seal the tube, rather, because the whole was intentionally made smaller than the O.D. of the tube, the click-e-bricks formed a compression seal around the tube.

We actuated the structures by inflating them, using compressed air, at pressures ranging from 7 to 100 kPa above atmospheric pressure. We used both computer-controlled and manually operated solenoid valves to control gas flow in and out of the structures.

Videos (available from GMW upon request)

Video S1: Inflation fluorescent cube (2X playback).

Video S2: Inflation of a cube with PDMS on the bottom and on opposing side walls (real time playback).

Video S3: Elongating cube with alternating PDMS click-e-bricks (real time playback).

Video S4: Inflation of cross-shaped structure (real time playback).

Video S5: Inflation of prismatic structure (real time playback).

Video S6: Tentacle-like soft machine with 4 degrees of freedom (2X playback).

Video S7: Rolling soft machine (real time playback first 30s, 3X playback for the remainder).

Video S8: Inflation of cube with overhangs (2X playback).

Video S9: Inflation of cube with overhangs bridged by click-e-bricks strips (2X playback).

Video S10: Inflation of cylinder fabricated from circular click-e-bricks with helically patterned PDMS sections (2X playback).

Video S11: Light redirection using diffractive click-e-bricks (real time playback).

Video S12: Reconfigurable microfluidic network assembled from click-e-bricks (actual play time, 1m 49s condensed to 32s).

Video S13: Reconfigurable LED circuit assembled from click-e-bricks (2X playback).

Figure S1. (a) Schematic illustration of the elementary peg/recess unit of click-e-bricks. The left is a perspective view and the right a cross-sectional view. The axis of the peg/recess is represented by the vertical arrow in the perspective schematic on the left. (b) A schematic illustration of a 2×3 click-e-brick. (c) A series of images showing six possible connections between two 2×3 click-e-bricks. The scale bar in panel c is 1 cm and is shared by all images in the panel.

Figure S1.

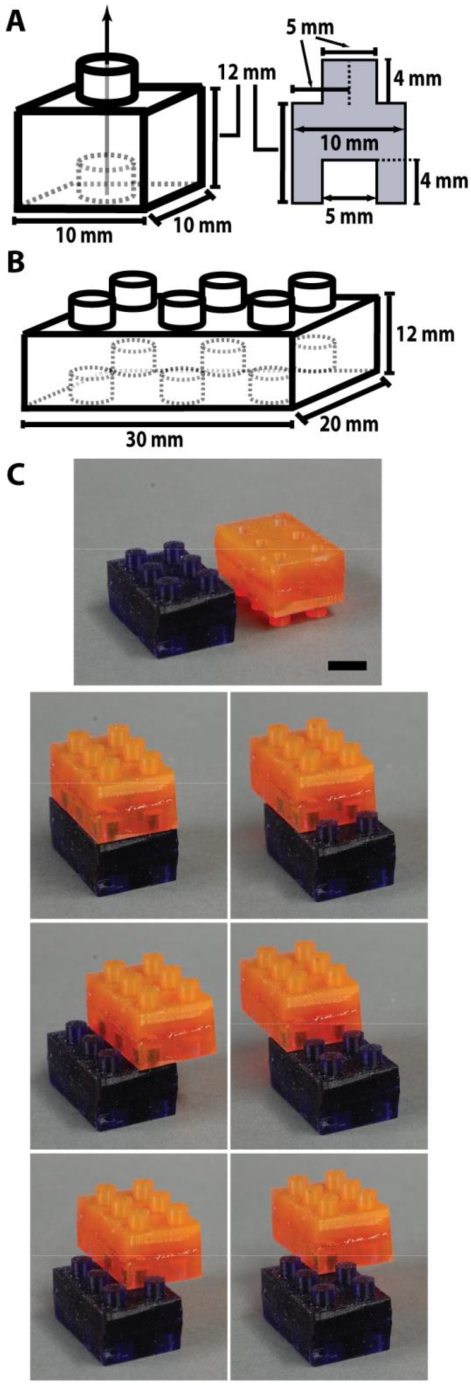

Figure S2. Photograph showing the cross-section of a composite click-e-brick. The pegs and recesses are PDMS and the body is Ecoflex®.

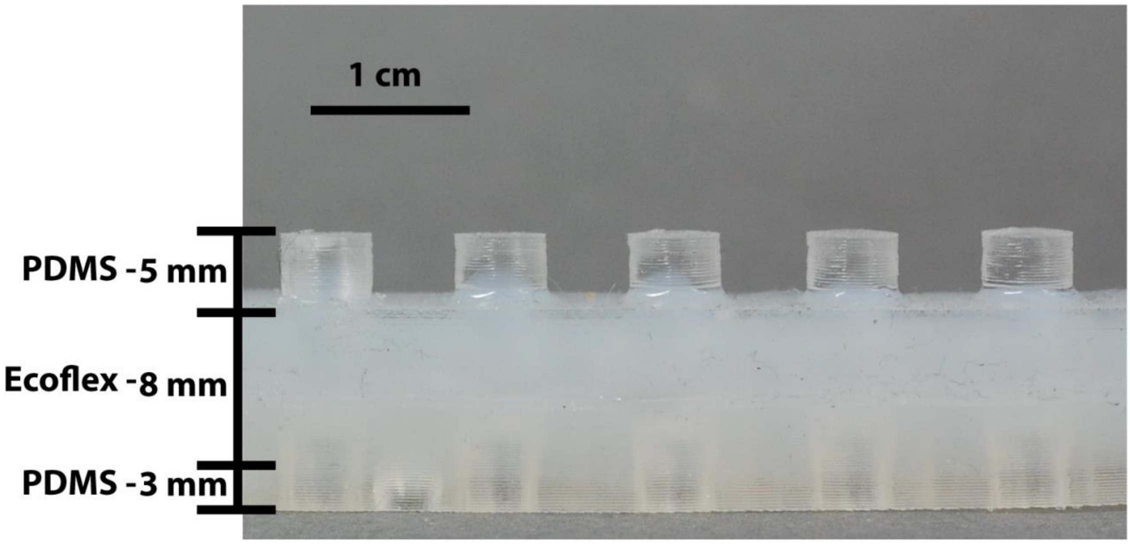

Figure S3. Examples of various click-e-bricks that were cut from the large 6×9 master click-e-brick. The array dimensions are in the upper left corner of each photograph. The scale bar is 1 cm and is shared by all the images.

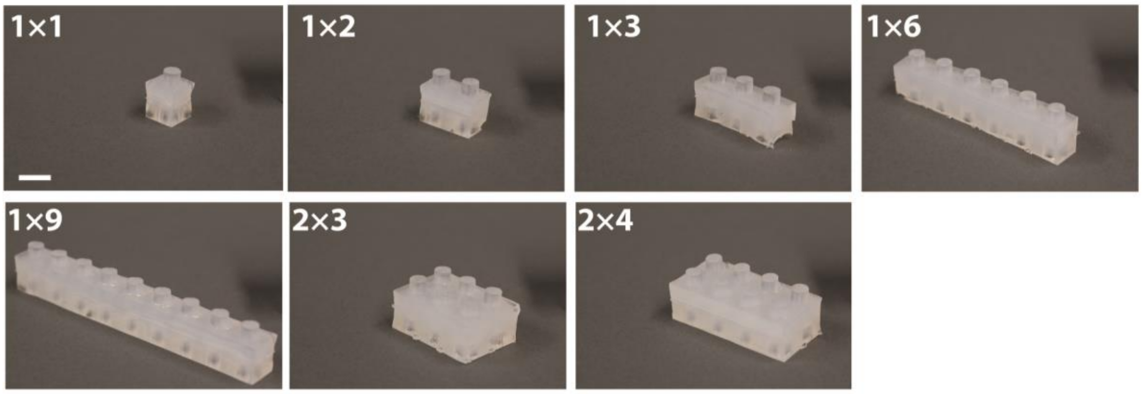

Figure S4. Assembly of click-e-brick into hollow structures and their pneumatic actuation. (a, d) Schematic illustration of the click-e-brick used to fabricate the structures shown in panels c and f. click-e-brick made of PDMS or Ecoflex® are colored gray and white respectively in the schematics. (b) Schematic illustration showing the layer-by-layer assembly of the hollow cube shown in panel c. (e) Schematic illustration showing the layer-by-layer assembly of the hollow cube shown in panel f. (c, f) Progressing downward in each column are photos of click-e-brick-based structures when no pressure or vacuum is applied (top) and when positive air pressure is applied (bottom). In all cases pressurized air was applied via a single tube routed through one of the walls of each structure, and the click-e-bricks were glued together by curing liquid PDMS or Ecoflex® pre-polymer at their interface. All scale bars are 1 cm. In panel f the red scale bar and dotted line indicate the elongation of the cube upon actuation.

Figure S4.

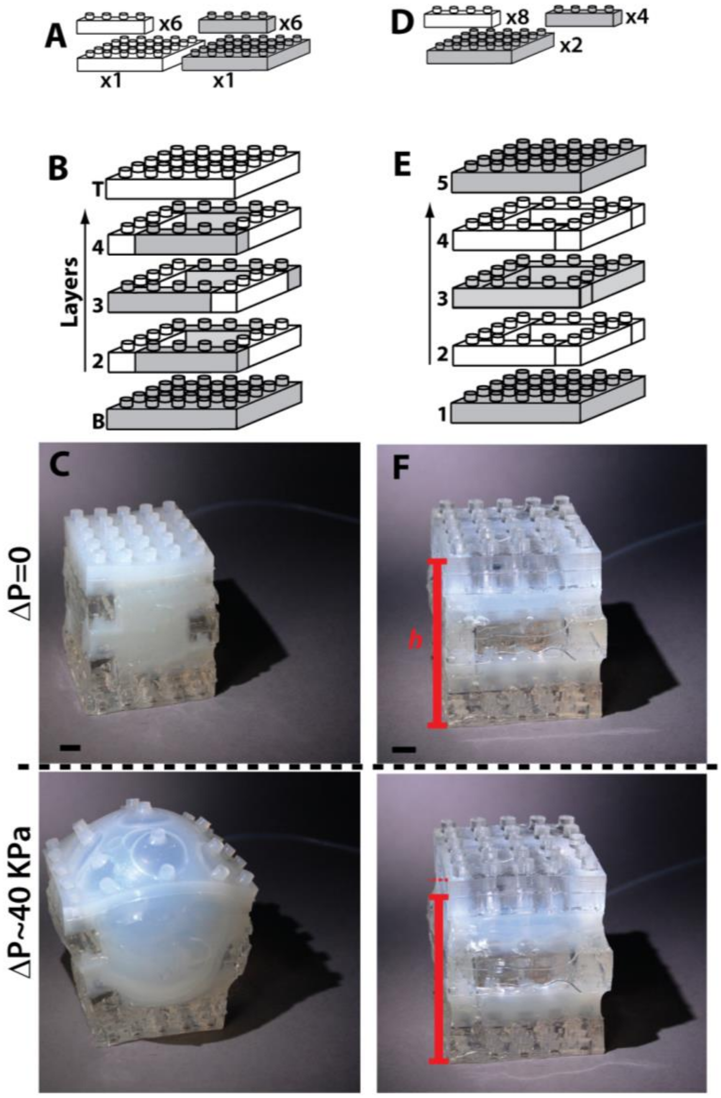

Figure S5. Technical drawings of the master used to fabricate rectangular click-e-bricks. There are three parts: (a) the top, (b) the bottom, and (c) the union that holds them together during the molding process. All dimensions are in millimeters.

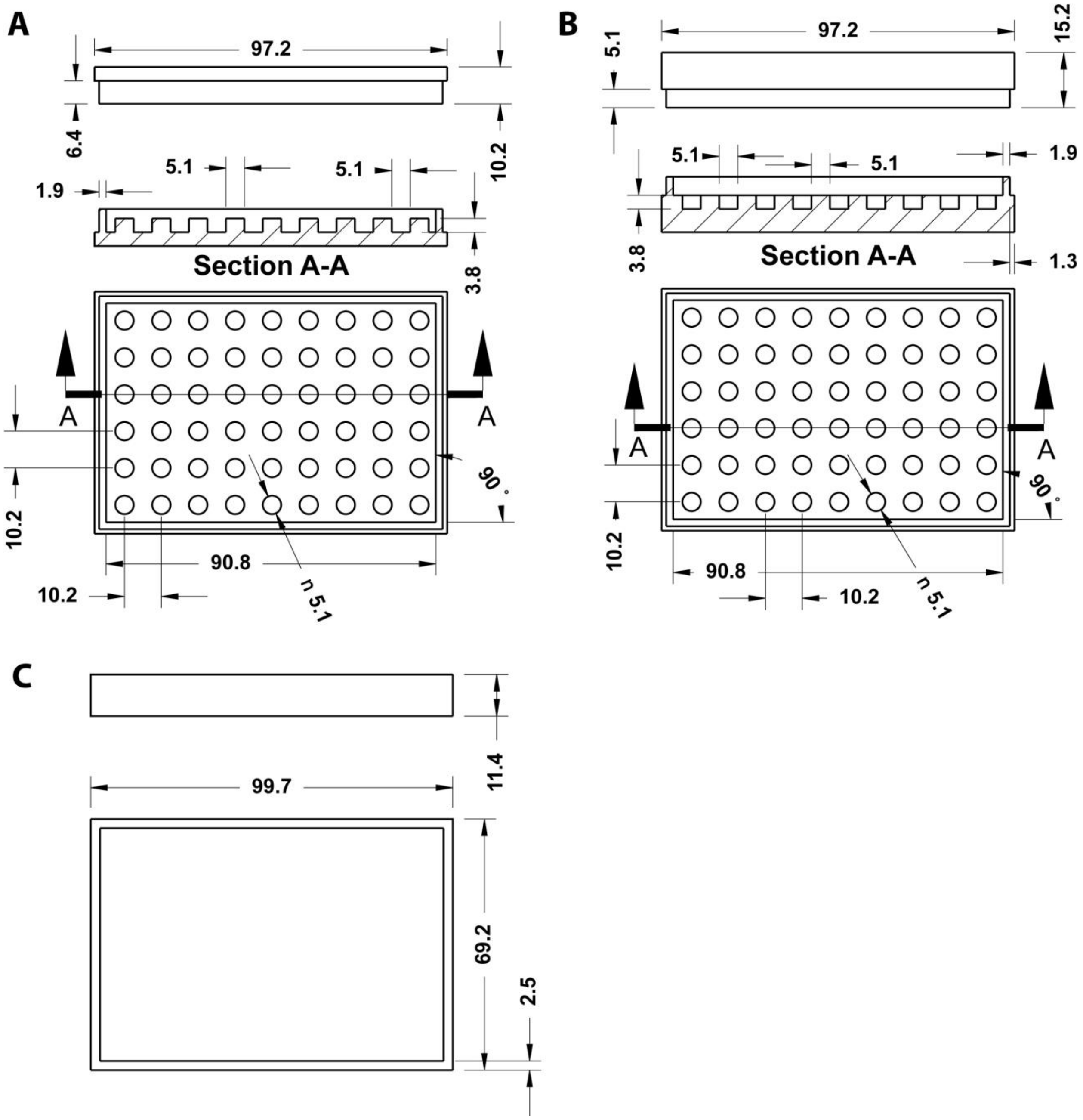

Figure S6. Technical drawings of the master used to fabricate solid-core, circular click-e-bricks. There are three parts: (a) the bottom, (c) the top, and (c) the union that holds them together during the molding process. All dimensions are in millimeters.

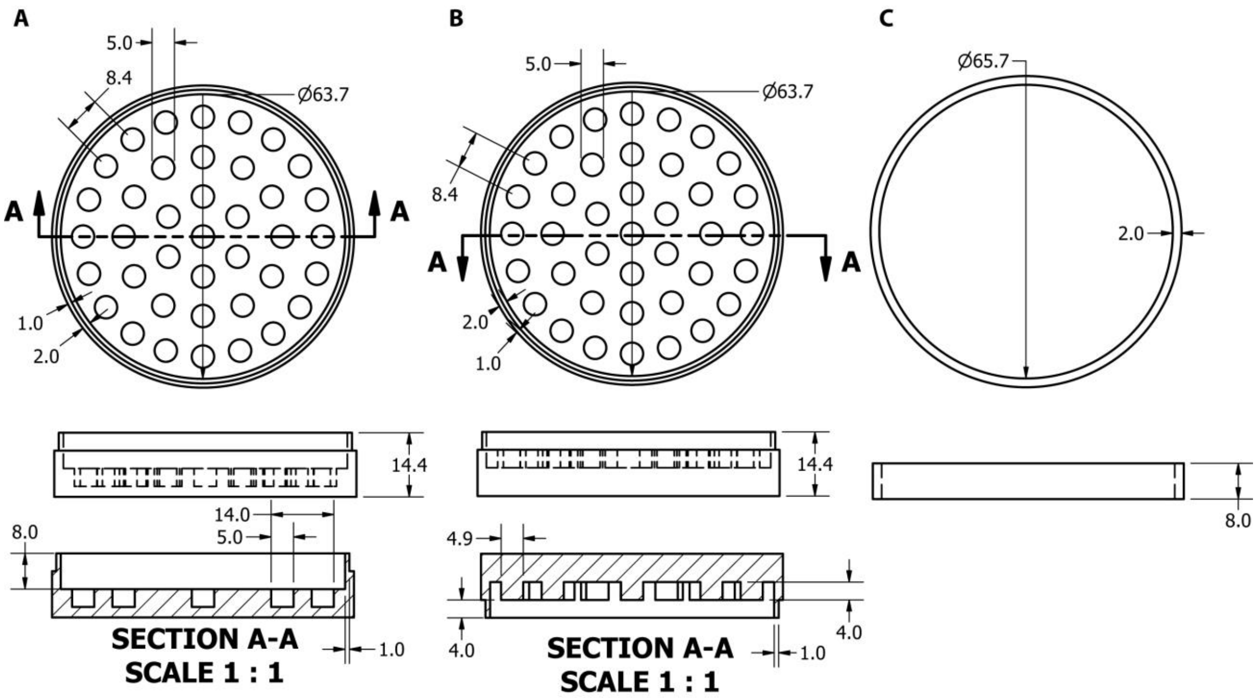

Figure S7. Technical drawings of the master used to fabricate solid-core, circular click-e-bricks. There are four parts: (a) the bottom, (b) the top, and the two unions, one for the outer radius (c) and one for the inner radius (d), that hold the top and bottom together during the molding process. All dimensions are in millimeters.