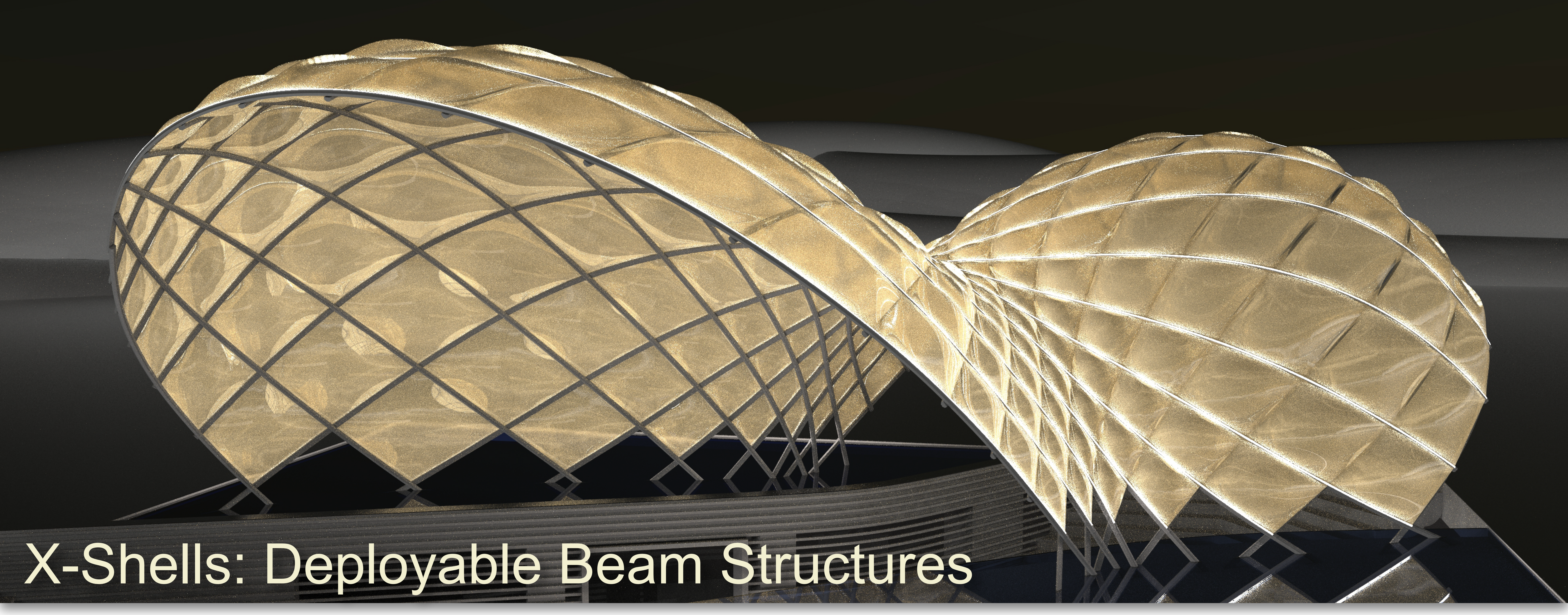
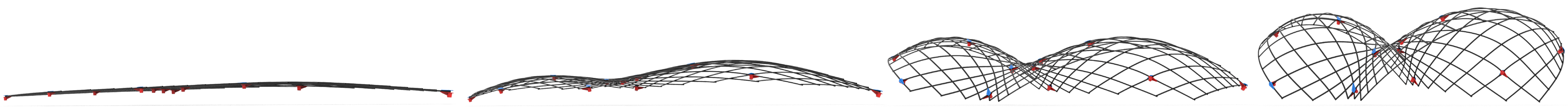
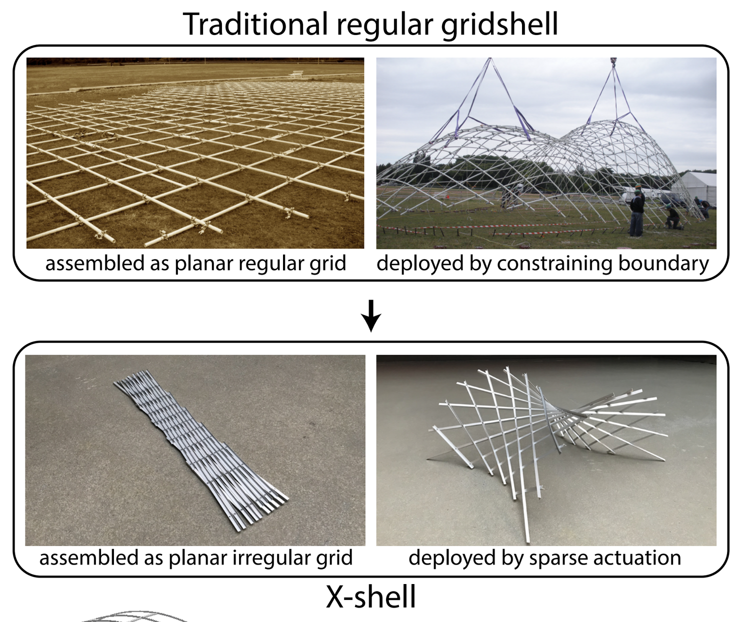
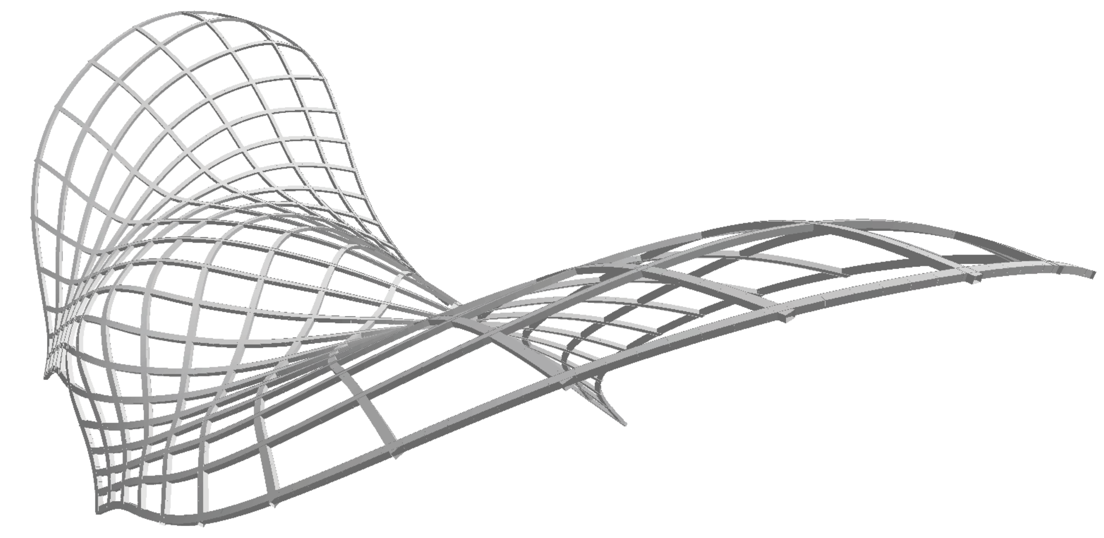


X-Shells: Deployable Beam Structures

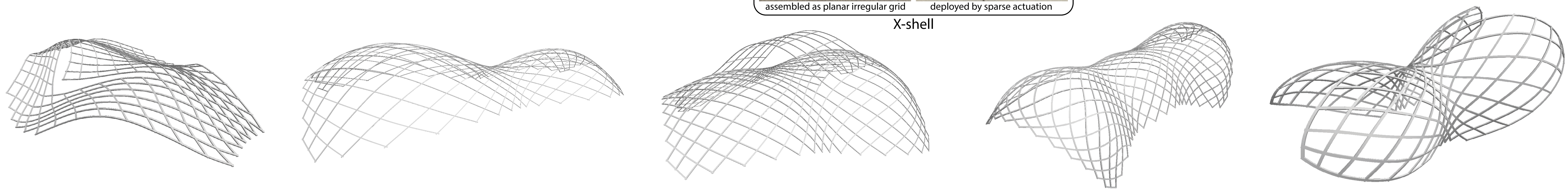






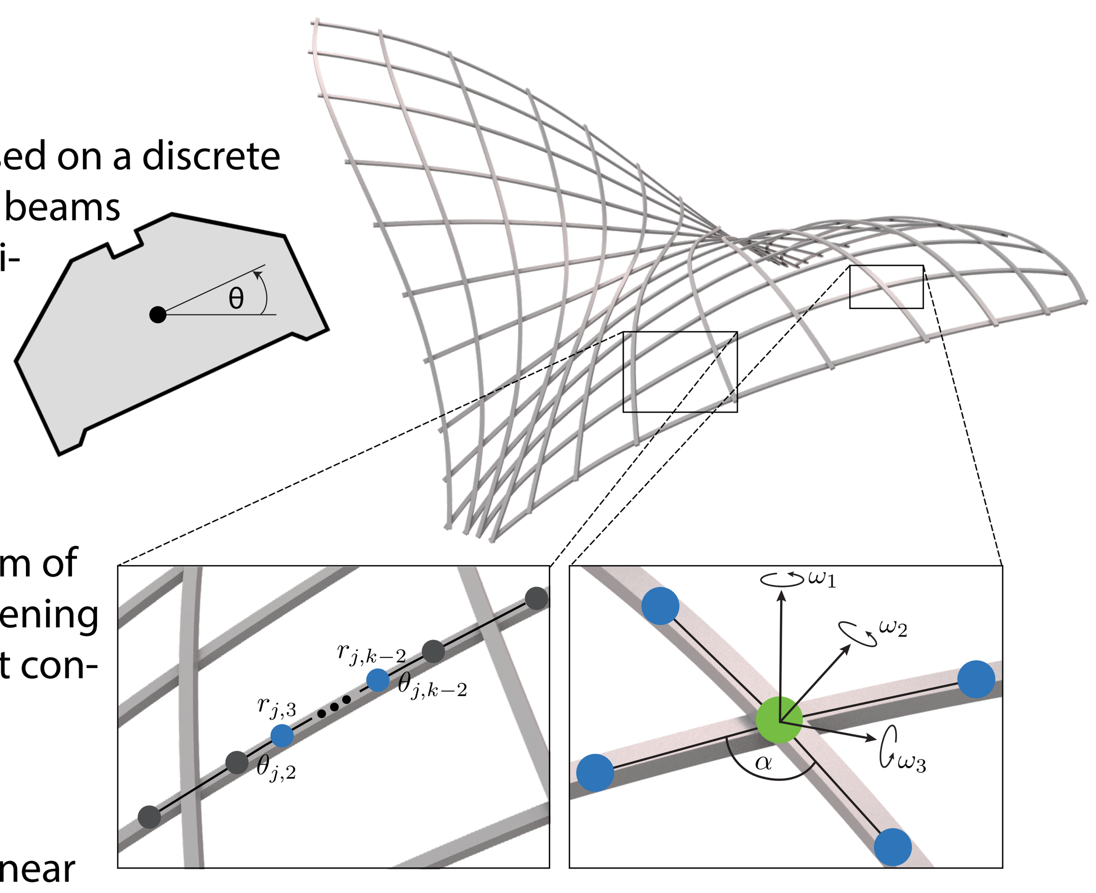
We present *X-shells*, a new class of deployable structures formed by an ensemble of elastically deforming beams coupled through rotational joints. Like traditional elastic gridshells, X-shells can be conveniently assembled in a flat configuration from standard elastic beam elements. But once assembled, they can be deployed into the desired 3D target shape simply through expansive force actuation without worrying about how to constrain the boundary.

During deployment, the coupling at the joints forces the beams to twist and buckle out of plane. Through this complex interaction of discrete joints and continuously deforming beams, interesting 3D forms emerge.



Simulation

We developed a tool for simulating X-shells based on a discrete elastic rods model, which efficiently represents beams as polygonal curves. The beam cross-section orientation at each edge of this polyline is specified by a material frame angle θ, allowing us to model beam twisting and orientation-dependent stiffness.



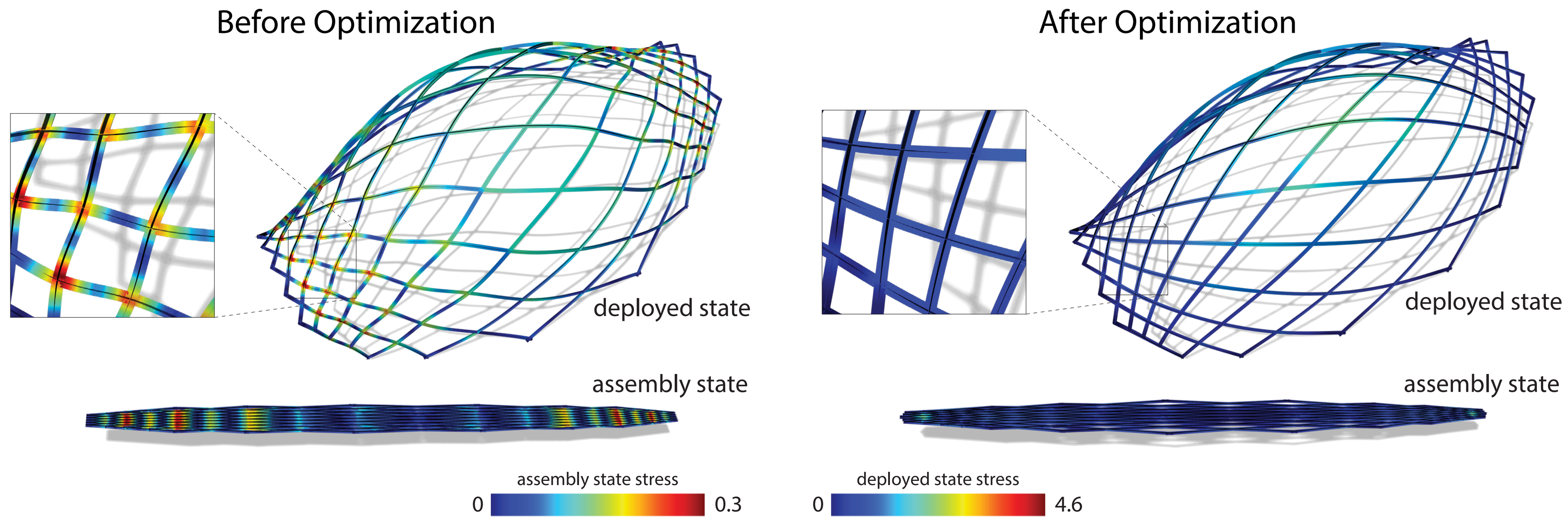
We apply constraints to bolt together each beam of the X-shell by defining an orientation ω and opening angle α for each joint (beam crossing). This joint configuration determines the vertices and material frame angle of each incident beam edge.

We compute the equilibrium by solving a nonlinear optimization problem: minimizing the elastic energy stored in the beams while constraining the joints' average opening angle. By gradually increasing this angle, we can simulate the deployment process.

Optimization

Manually adjusting an X-shell layout to fine-tune its deployed shape is extremely challenging, as small local edits can have unpredictable global effects. Also, manually created designs tend to suffer high stresses.

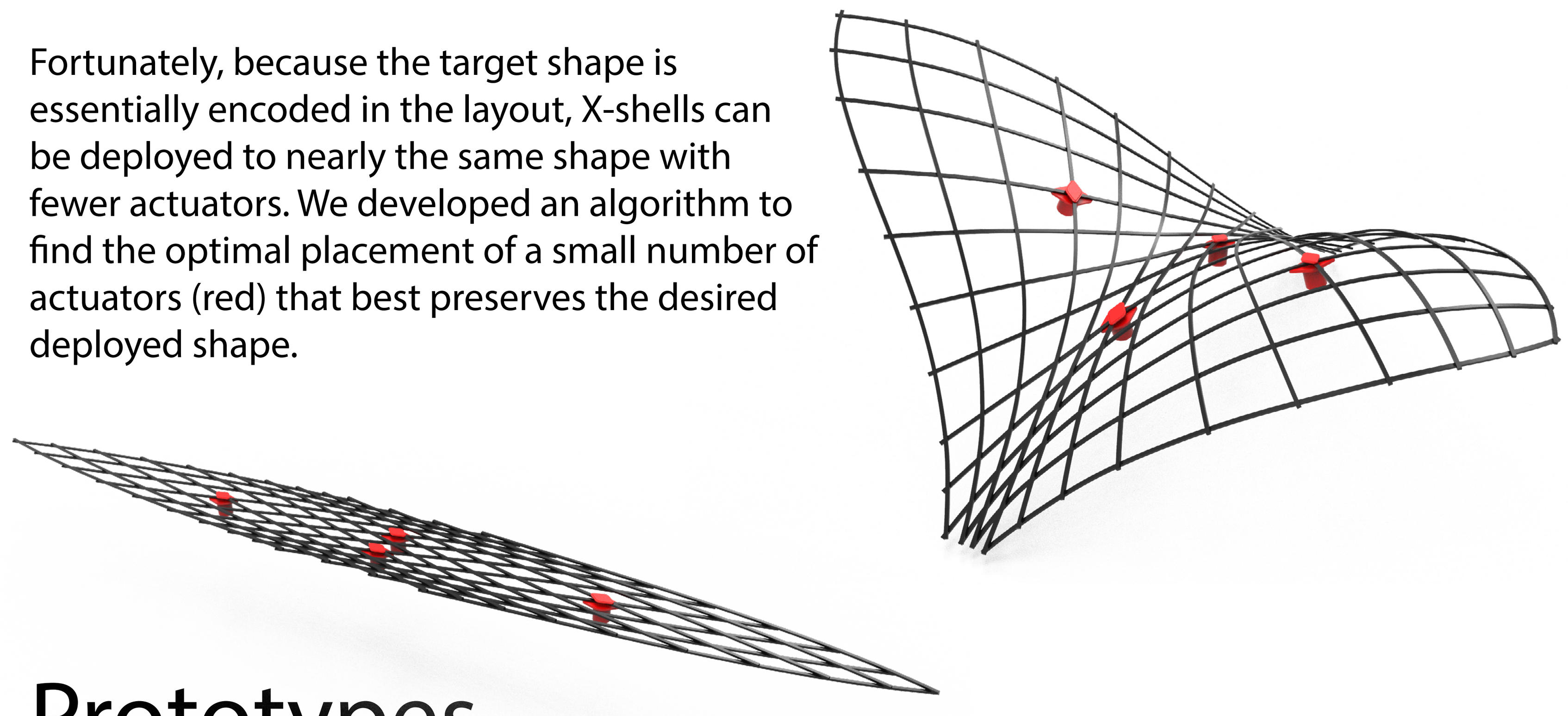
We developed an optimization algorithm to minimize stresses in the assembly and deployed states while fitting the structure to a target surface.



Actuator Sparsification

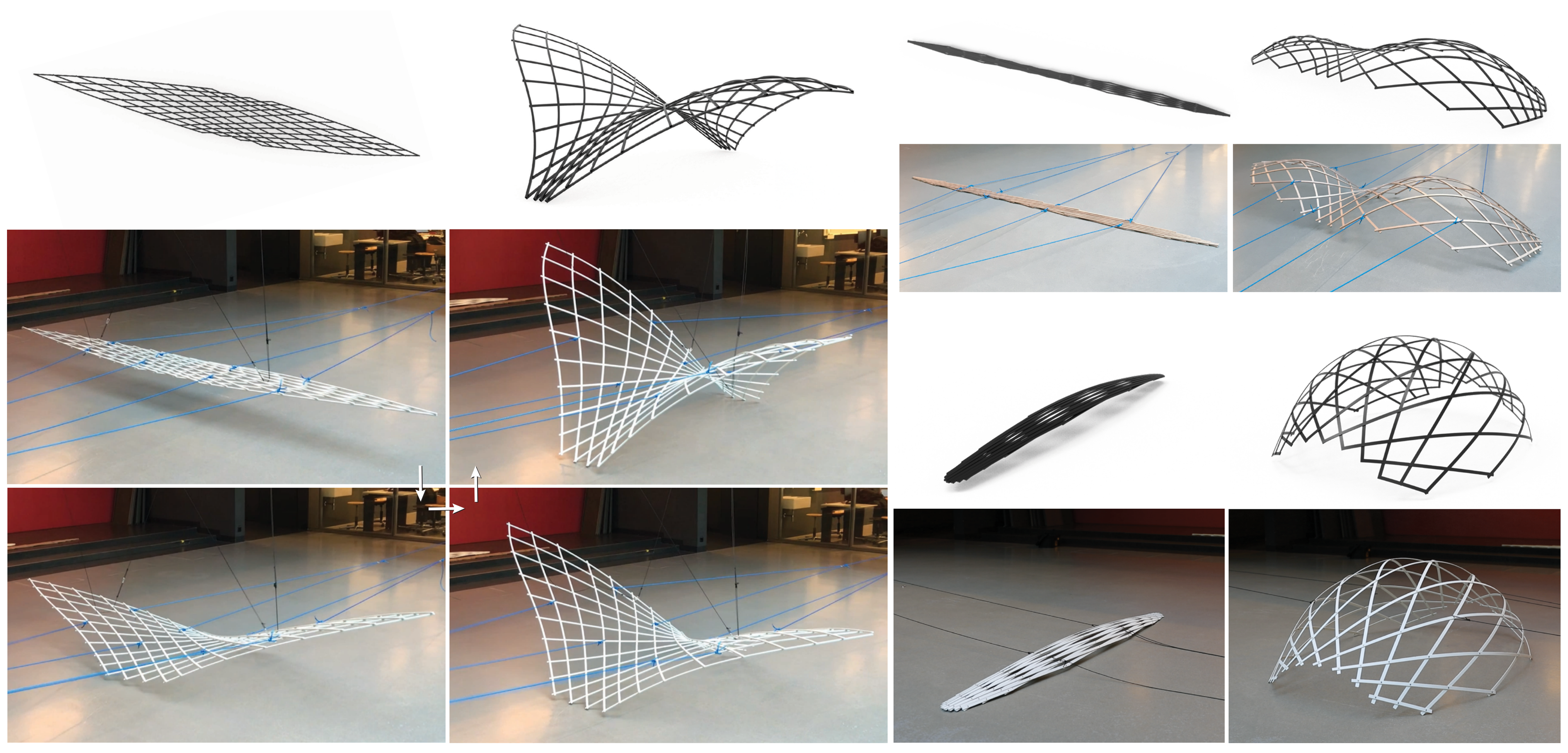
By default, our simulated deployment process opens an X-shell by applying torque on every joint. Especially for complex structures, installing torque actuators on all joints is impractical.

Fortunately, because the target shape is essentially encoded in the layout, X-shells can be deployed to nearly the same shape with fewer actuators. We developed an algorithm to find the optimal placement of a small number of actuators (red) that best preserves the desired deployed shape.



Prototypes

We built and deployed several designs created with our tools. Despite pulling the X-shells open with ropes instead of expanding with torque actuators, the physical prototypes deployed into very similar shapes to the ones predicted by our simulation:



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