Stress-Crafting - Interweaving Digital Dexterity and Manual Intelligence

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> …recent advances in electronics and computer processing found in computer numerically controlled technologies now allow us to move directly from a computer model/computer drawing to built form.[1]
> -William Massie

In discussions of parametric design and digital fabrication, terms like 'automation,' 'rationalization' and 'optimization,' with their associations of objectivity, are often applied to processes that, in their procedural and physical realities, are far messier and more subjective than advertised. While the rhetoric of parametric design tends toward valorizing increasingly streamlined processes, in practice the use of advanced digital tools often (perhaps rightly) remains embedded in more ad hoc, improvisational and open-ended approaches. Rather than perpetuating the myth of digital seamlessness in design, this paper argues for a more pragmatic and exploratory hybridity of digital and analog modes as employed for both the design and the fabrication of an experimental line of flat-pack furniture.

The *Induced-Stress Joinery Project* explores the potential for stress-activation of thin wood surface structures made by channeling the internal forces generated during assembly into useful configurations that shape three dimensional curvature, hold joints securely together, and produce structural stability –all without mechanical fasteners or adhesives. The goal of this research is to develop innovative joinery for functional and compelling furniture designs that can be easily constructed by end users. Assembly of each piece is studied in great detail to insure stability, but more importantly, to shape a rewarding choreography of manual bending and joining operations.

These projects are the result of a design process provisionally called '*stress-crafting*' that employs parametrics, digital analysis and physical modeling in hybrid ways. The core of this approach is to shape flows of forces, lines of interaction, and three-dimensional curves by iteratively adjusting the profiles of cutting patterns based on both analog and digital feedback. Internally opposing forces are organized into stable oppositions that are best described as a sort of active dynamic tension rather than as a static equilibrium. This design process is characterized by reciprocal activities of digital stress mapping, parametric variation and scaled physical prototyping that inform qualitative evaluations and advance the design exploration in cycles of adjustment, analysis and reiteration. After more fully describing the roles of digital and physical media in the process of stress-crafting, examples of its use in the design of two projects, the Clip Table

Figure 1. Clip Table (left) and Wrap Chair (right). (All images by Rob Corser)

and the *Wrap Chair* (Figure 1), will be discussed to highlight specific dynamics of this approach.

Stress-Crafting: digital discovery, physical play and parametric iteration

Although some of the forms generated for the *Induced-Stress Joinery Project* arguably could be derived through trial and error, parametric modeling and digital stress mapping using finite element analysis enables greater fluidity of exploration, while also insuring even stress distribution and structural stability. But digital design alone has proven too cumbersome and insufficiently tactile to be used exclusively. Due to the complex interaction of forces, materials and geometries involved, physically predictive digital modeling of even the simplest furniture configurations would require enormous computational resources. Instead, direct physical prototyping, using fully functional digitally fabricated scale models, has proven to be the most effective tool for quickly assessing design decisions that are then folded back into the manipulation and analysis of the digital model.

In the stress-crafting process, the importance of combining both digital and physical media cannot be overstated because each mode of evaluation gives distinct information about the evolving design that cannot be found in any single design artifact. For example, digital stress analysis can map both the flow and concentration of forces within the pattern-cut components, AND quantify the total amount of force needed to facilitate the bending. Digital analysis of a single element of the furniture design can also be used to predict the shape and curvature of that particular piece under a known set of loads. What it cannot accurately represent however (given existing or expected technology available to the architecture and design community) is the final shape of multiple bent plywood surfaces when their bending interacts as part of a complex system. Because the fitting of joints between two plywood pieces is dependant on the resulting angles of other bent surfaces where the stressed pieces interact, the degree of curvature and any potential twisting of each must be integrated within the design of both pieces simultaneously.

The best tool for observing and evaluating this complex interaction is a quick but precisely fabricated scaled prototype. Since this prototype is made of the same material as the final furniture piece (plywood), its physical behavior is highly predictive of the shape and distribution of bending in the full-size model. What the scaled prototype does NOT accurately model is the amount of force needed to assemble a full size model or the presence of potentially unsafe concentrations of stresses in particular areas that could cause localized material failure. This information is precisely what the digital stress analysis can reveal with ease. In each case the medium chosen for a particular aspect of the study incorporates a unique form of intelligence, and employs a unique mode of representation in communicating this information to the designer.

A good example of the specific contribution of digital media in this design process is the evaluation of surface stresses in a furniture project called the *Petal*

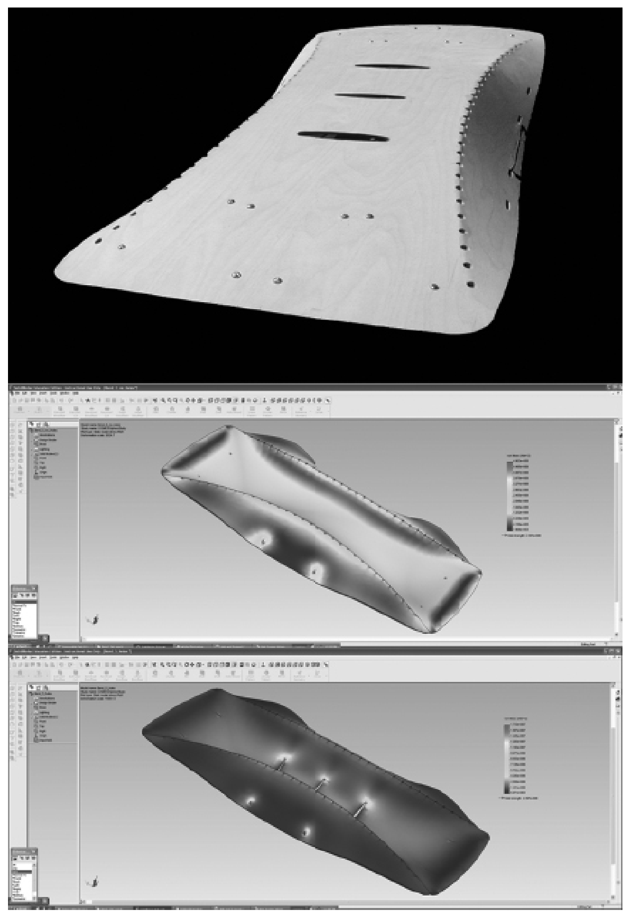

Figure 2. Petal Bench (top) with examples of digital stress analysis. No holes (middle) - Lighter tones indicate higher internal stresses. Adding holes (bottom) reduces stress and evens its distribution.

Figure 3. Wrap Chair - Scaled prototyping process (top) and detail of resulting leg joinery (bottom).

Bench (Figure 2) that was a precursor to the Induced-Stress Joinery Project. Unlike the later projects that rely only on wood-to-wood joinery, the Petal Bench employs tension cables to pull and hold a quarter inch thick piece of scored plywood into a structurally rigid and useful shape. The aspect of the design process under consideration in this example is the total amount of in-plane stress being built up in the top surface of the bench. Lowering the total stress, especially as it concentrates at the folds in the plywood, insures that the material will be less likely to crack, delaminate, or otherwise fail at this juncture. The digital design environment allowed for exploration of various methods for adjusting the magnitude and concentration of in-plane stresses. These included changing the location of stressing cable attachment points and varying the shape of the outside contour and the contours of the fold lines. What eventually emerged as the most effective strategy was a surprise. Introducing small elliptical voids was found to reduce both the total stress in the bench's top surface, and also its concentration at critical locations. (Figure 2, bottom) These holes originally were intended as visual accents to reveal the bench's subtle curvature, and as handle slots for picking up and moving the five-foot long bench. In the process of stress analysis, they were found to contribute to the structural performance of the bench as well. This important design opportunity would have remained hidden, or its significance under appreciated, without the use of digital stress analysis.

While digital modeling served well for most design development tasks in the relatively simple, single-piece Petal Bench, the centrality of scaled physical prototypes to the stress-crafting process for more complex multiple-component systems can best be illustrated by examining a selection of models made during the development of the Wrap Chair project. These models are one-eighth the size of the final chair and are made of aircraft plywood that is 1/16" thick –exactly one eighth the thickness of the half-inch plywood to be used for the final product. A laser cutter was used to quickly cut the prototypes according to the same digital patterns that, with minor adjustment, would eventually be used to fabricate the full-size chair. The Wrap Chair consists of two pieces: a roughly horizontal seat, and a vertical back that wraps around and clips onto the seat in multiple places to form the legs as well. Like all of the examples of Induced-Stress Joinery, this project began with an intuitive composition. In this case it consisted of two parts with squat overall proportions and with front legs that simply clipped onto the seat at a single location and cantilevered past it to the floor. (Figure 3, left) Manipulating this first scaled prototype immediately revealed that assembly required excessive twisting of the legs, resulting in material failure. The digital model for this prototype was adjusted by changing parametric dimensions for the seat and back in order to reduce the twisting.

A second round of scaled prototypes (Figure 3, 2nd from left) shows that these adjustments resulted in the successful joining of the two pieces. Physically manipulating the model (i.e. playing with it) revealed that the front legs in this configuration tended to toe inward under the seat and would collapse beneath the weight of a force pushing down on it. Again, adjustments were made to the digital model's parameters to further narrow the back and change the profiles of cutouts in order to encourage the legs to splay outward rather than inward (Figure 3, middle) . This iteration, while more stable, seemed overly tall, and still not sufficiently stable in the front legs. A major design change, involving the extension of the front legs to loop back up to clip onto the seat a second time nearer to the front edge, was subsequently developed and tested (Figure 3, second from right, and large detail). This approach produced remarkably improved stability for the front legs, at the expense of an additional assembly step that itself would require detailed refinement at the scale of the joints themselves. The last iterations of this scaled prototype study involved refining the proportions of solid and void in the chair back and legs to balance sturdiness, ease of assembly and comfortable support for the seated body. (Figure 3, right) It is important to emphasize that each step in these physical explorations was interspersed with forays back into the digital realm for parametric adjustment of profiles and joint shapes, as well as for internal stress analyses (Figure 4, top), especially during the final phases of development.

Material Investigation: empirical evidence and performance tailoring

Scaled prototypes are invaluable for quickly developing overall design directions, assessing general feasibility, and refining joinery and visual profiles in a furniture piece, but the precise behavior of the plywood material at specific areas of greatest bending cannot be adequately addressed in the small models. Digital stress analysis gives a visual representation showing areas of predicted stress concentration, and also provides numerical data about the amount of stress being developed, but it cannot show or predict the exact effect this will have on the plywood itself.

To evaluate specific material performance, full-scale prototypes were created and tested to the

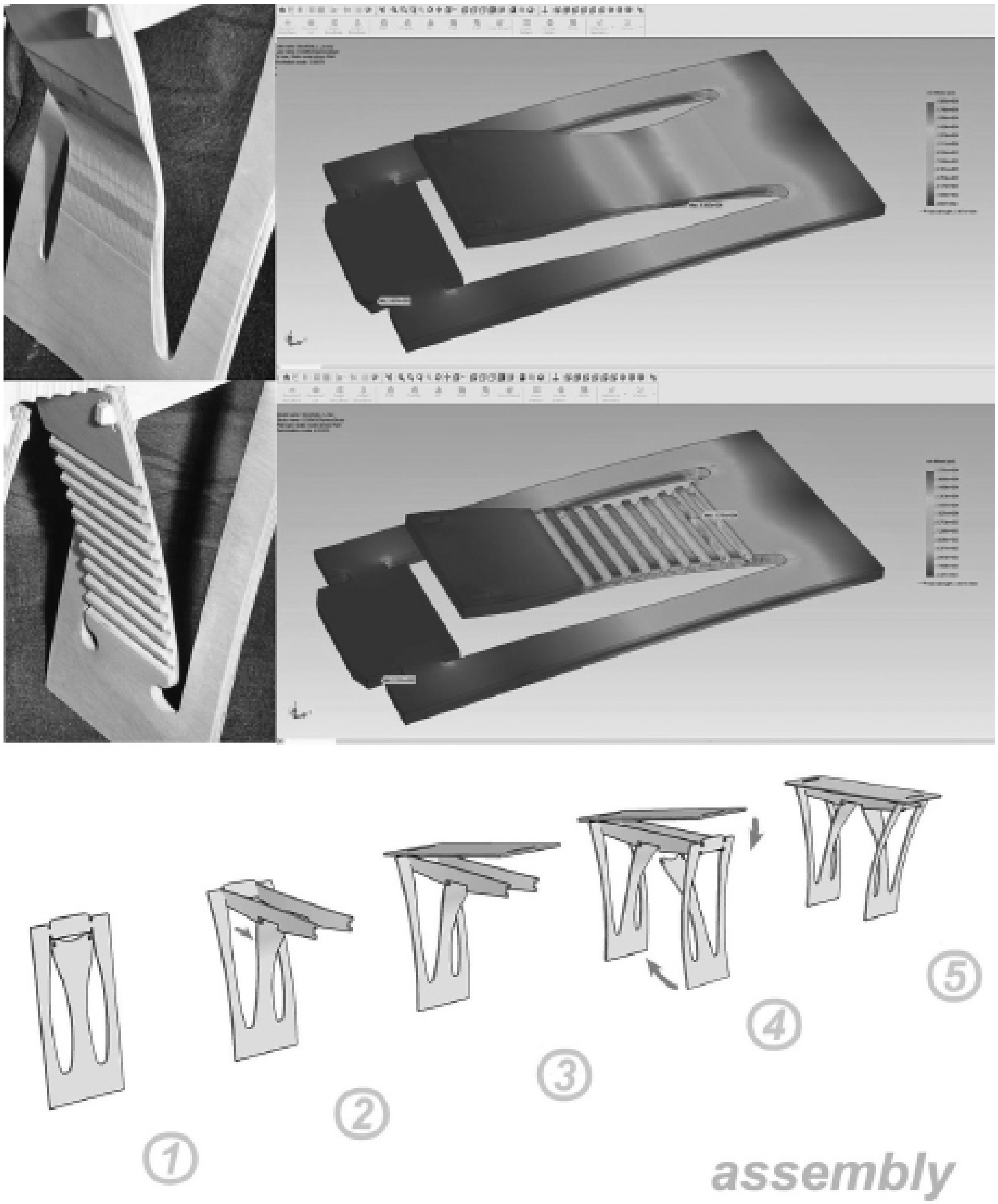

Figure 4. Clip Table -digital and physical exploration of full-scale material performance, testing processes of thinning (top), and ribbing (middle) - Lighter tones indicate higher internal stresses. This radical degree of bending is crucial to the assembly sequence (bottom).

point of failure in order to learn where, how and under what amount of stress the material would fail. This process was carried out in great depth for the Clip Table project, and it provided a wealth of information about the limits of cross sectional area for locations of high stress –information that proved to be crucial for the development of later projects. Direct experience gained during this process also contributed to an embodied understanding of the amount of force required to physically wrestle the half-inch plywood into shape during assembly.

The Clip Table consists of two legs that are pulled open, somewhat like a clothes-pin, in order to clip them onto two transverse rails that also must be bent slightly in order to be clipped by the legs (Figure 4, bottom). The table's top is held in place by tabs that extend up from the outer edges of the legs and splay out to capture the top via slots that are located closer together than the distance between the tabs. The result is a pressure fitting that holds the top in place and firmly down against the top edges of the legs and transverse rails. Bending the legs open to engage the rails originally required a fairly large amount of force. To ease assembly, this force needed to be reduced to a minimum. Assembling the table also generates significant internal stresses that must be accommodated and distributed as evenly as possible in order to avoid localized material failure. During this part of the stress-crafting process, digital analysis was combined with full scale tests carried out on variations of the leg design made of the same plywood as the final products. The smallest version of the table was selected for this experiment because it would experience the greatest concentration of stresses due to the dramatic amount of bending required for the piece to be opened wide over a very short distance (Figure 4).

In order to make it easier to bend during assembly, several approaches were explored that modified the thickness of the plywood. Figure 4 illustrates two of them: scooping material out with the digital router to gradually thin the plywood toward the middle of the leg (top) and carving ribs into the face of the leg in order to encourage easier and more distributed bending (middle). The latter strategy is used quite effectively for the table's transverse ribs, which need to be bent only a small amount at their midpoint. The higher levels of stress generated in the legs, however, resulted in unacceptably high levels of internal stress becoming localized in smaller areas rather than being more evenly distributed. In physical testing, this led to material failures exactly where the material is reduced to its thinnest cross section. As a result of this digital/analog testing, both approaches were eventually abandoned. Instead, shaping of the legs is accomplished solely by changing the cut profile -making portions of the legs narrower where they need to bend most -but NOT reducing their thickness. This new approach empirically was found to be the most reliable way to reduce the amount of force required to open the clip legs manually, while still generating enough resistance to hold the joints of the table firmly together. Limiting the process of material adjustment to the tailoring of the flat cutout profile also meshes well with the ability to make a series of tables of different sizes (with correspondingly different amounts of internal stress) by parametrically adjusting ONLY the dimensions of the pattern's solids and voids.

This example clearly reveals another aspect of the formal development of the Induced-Stress Joinery Project. The formal language of the project began with relatively rectangular or tapering forms outlined with straight or slightly angled edges. But as the stress-crafting process unfolded, a new formal language of linked splines and smoothly transitioning arcs emerged as the most effective way to evenly distribute stresses along the length of bending members -especially around corners where the bending changes direction. Seeing the formal language of the project evolve almost directly from the process of digital stress mapping and the need to accommodate internal forces was initially surprising. But upon further reflection it provides even stronger evidence that a rigorous process of stress-crafting might give greater weight to performative responses than to formal preferences.

Parametric Choreography: digital shaping and organizing of manual assembly

A quality shared by each example of the Induced-Stress Joinery Project is the necessary engagement of the end user in the physical manipulation, shaping and locking together of the furniture's parts. While no digital tool can tell you what it is like to physically bend a flat piece of half-inch birch plywood into a totally new shape, it can give useful feedback on fitting, tolerances, and the

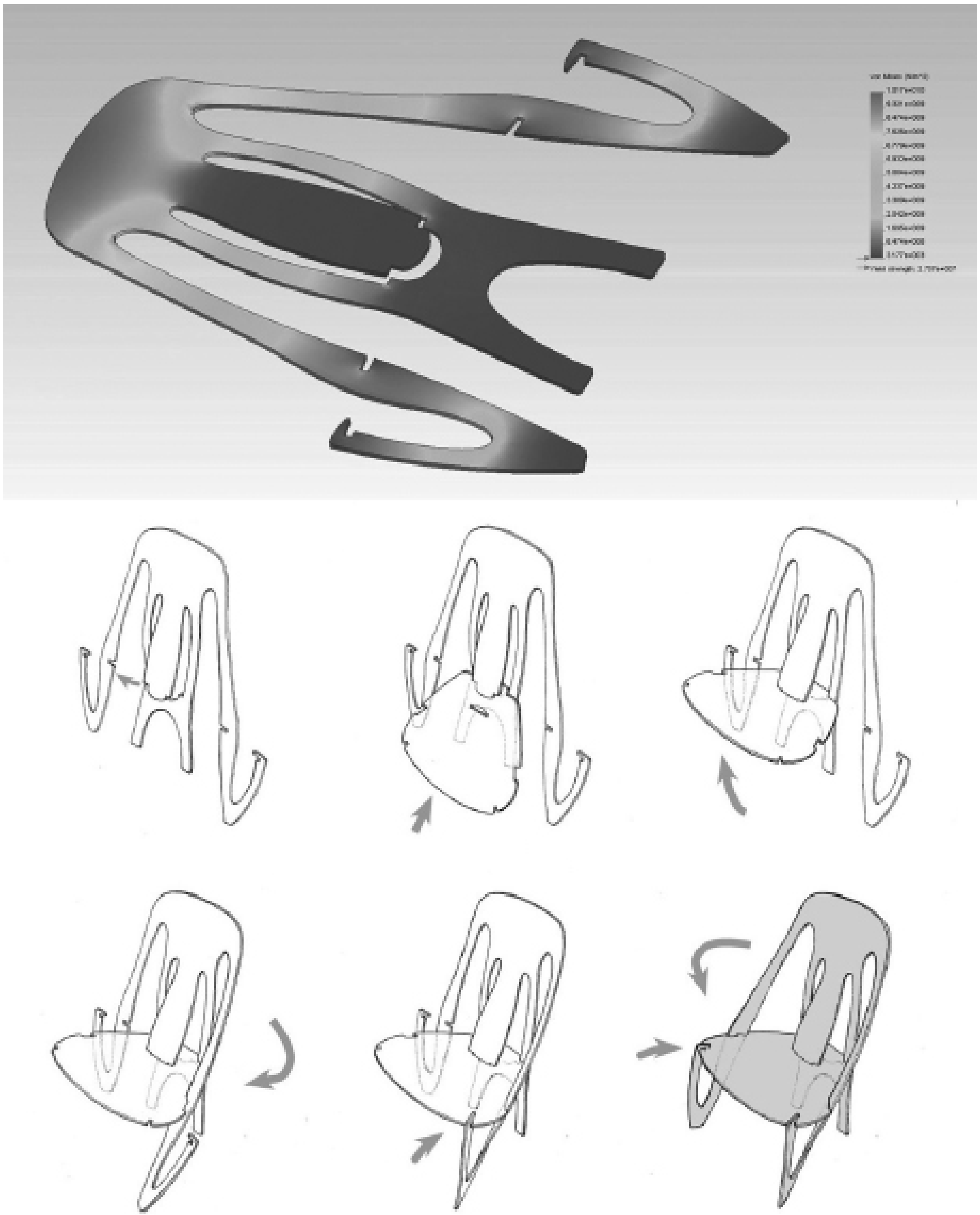

Figure 5. Wrap Chair -digital analysis of stress distribution directly contributes to the shape and formal language of the chair back (top) - Lighter tones indicate higher overall stresses. The assembly sequence (bottom) employs clip type joinery similar to that in the Clip Table’s legs, and a wrapping joint type developed specifically for the structural needs of the chair’s front legs.

amount of resistance that will need to be overcome. Assembly of the Wrap Chair starts with inserting the seat under the tip of a tab in the middle of the back where it opens in a manner similar to the Clip Table's legs (Figure 5, middle). Playing with the small scale prototypes revealed that, once inserted, the seat itself can be used as a lever to help open the clip to the point where its tip slips through a tapered slot in the seat. The tapering of this slot is the only departure from the purely flat pattern cutting used throughout the rest of the project. Visualized and explored in the digital model, this simple re-shaping of the slot allows the tab to pass through the seat at an oblique angle without needing to oversize the slot. The visible face of the resulting joint is crisp where otherwise it would have appeared sloppy –with a wide gap, were it not for the opportunity of tapering discovered through prototype manipulation and 3-D exploration of the digital model.

Once the seat is fixed to the back, each of the side arms is wrapped around the seat and clipped to it in two places as shown on the bottom of Figure 5 and in the detail in Figure 3. The precision of this joinery was achieved through a reciprocal process of digital adjustment and physical testing. The amount and distribution of stresses in the arm was also extensively tailored using stress analysis and the parametric re-shaping of the arm's length and profiles. Again, the formal language, which appears to some observers as a nod to Art Nouveau, is actually shaped around stress distribution and assembly dynamics. The curvy profile shapes are secondary results of these requirements, not primary formal determinants (Figure 5, top).

CONCLUSIONS –WHERE DO WE STAND?

Debate concerning the status and roles of hand drawing and digital media in architectural design parallels a similar dynamic in architecture's other mode of production: the physical fabrication and construction of buildings and other components of the built environment like interiors and furniture. While the former debate is concerned largely with issues of abstraction and formal manipulation, the latter is deeply embedded in material, structural and tactile dimensions. The furniture designs for the Induced-Stress Joinery Project benefitted from *both* digital and analog explorations during the design process. Each mode of design investigation incorporates a unique form of intelligence, with the digital being firmly based in computation and analysis while the analog favors tactility and physical dynamism.

Examples from the development of the stress-crafting process illustrate how digital analysis can reveal hidden flows and concentrations of forces that are crucial to structural performance but are nearly impossible to evaluate adequately in any other medium. Similarly, the manipulation of small functional prototypes embodies aspects of the physical dynamics of manual assembly that cannot be well represented or understood in a digital model. Parametric control of flexible dimensions in the digital model allows for a free play of adaptation and adjustment so that knowledge obtained from interpretations of stress analysis or physical prototyping can be reintegrated in quick iterations of new forms and details. Taken together these three discrete procedures: analysis, prototyping and parametric variation, form the core of stress-crafting.

While the rhetoric of digital design typically favors *integrated* processes that promise a direct, streamlined relationship between design and fabrication, these examples indicate that *interweaving* them as discrete elements of a digital/analog *hybrid* might be more productive. And while some might dismiss as inefficient the necessity of transitioning from one mode of representation to another, it is precisely the *variety* of representational modes and the *iteration* of design studies in different media that allows for surprise and discovery.

Despite differences in scale and complexity, it is possible that the benefits of the stress-crafting process developed for the Induced-Stress Joinery Project are not limited to furniture design or fabrication, but that it might have strong implications for architectural design more broadly. It is possible to imagine how stress-crafting might serve as a model for analogous processes such as *sound-crafting*, *light-crafting*, or *thermal-crafting* that would benefit from similarly interwoven digital/analog hybrids of performance modeling, physical prototyping and parametric variation.

ENDNOTES

1 William Massie, "Remaking In A Post-Processed Culture, *Architectural Design*, v. 72, n. 5, (2002): 54.