MATERIAL, FORM AND FORCE

Toni Kotnik & Michael Weinstock

Conventionally, material in architecture has been treated as the 'servant' of form. An iterative design process, though, that continuously integrates material, form and force has the potential to unfold a new generative logic of form-finding. This offers ways of processing the flow of forces through a material object and balancing variations of form with the organisation and behaviour of material. **Toni Kotnik and Michael Weinstock** present a series of experimental construction projects, developed within the Emergent Technologies and Design (EmTech) programme at the Architectural Association (AA) in London, that explore the intricate relationship between material, form and force.

Architectural Association Emergent Technologies and Design Programme (AA EmTech) and Chair of Structural Design research unity at the Swiss Federal Institute of Technology Zurich (ETH Zurich), AA/ETH Pavilion, Science City Campus, ETH Zurich, 2011
above: The temporary installation in front of the ETH Zurich architecture department building.

left: The pavilion functions primarily as sun shading for parts of the stairs in front of the architecture department building. The construction is based on the bending behaviour of large 11 x 2.5 metre (36 x 8.2 feet) sheets of 18-millimetre (0.7-inch) thick plywood and spans about 8 metres (26 feet).

Every physical being, living and non-living, has to support its materiality against the various forces that are imposed upon it by its environment, such as gravity, wind or atmospheric pressure. Philosophically speaking, the materiality of physical beings can be thought of as embodiment of two intrinsic coincident principles: primary matter itself and its form, its gestalt in space.[1] Both principles are intricately interwoven, and in the physical world one cannot occur without the other: no material is without form and no form exists without materialisation.

The Primacy of Form

Traditionally, however, the discourses within architecture and the visual techniques of architectural design practice have privileged form over material, with material rarely examined beyond its aesthetic properties or its technological capacities to act as a servant to form. In recent years, this tendency has been reinforced by contemporary methods of digital design with its emphasis on information-driven manipulation of NURBS-geometry within a computational environment, an approach that tends to exclude material from the generative process, leaving the corporal aspects of materiality to the later phases of adapting the designed form as a structure in preparation for fabrication and construction.

More recently, digital simulations of physical form-finding experiments, such as the hanging chain models or tensioned membranes originally used by architects and engineers like Antoni Gaudí, Frei Otto or Heinz Isler, have now become commonly available. Both methods produce optimised structural forms from a direct causal relationship between the spatiality of force flow and the generated form. But neither in digital nor in physical form-finding techniques do material properties play a major defining role in the process; material is merely a subordinate means of tracing the form and making it buildable.

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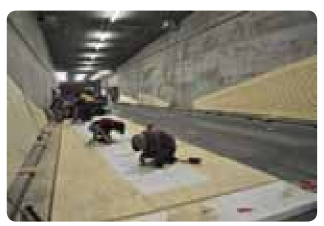
below right: The arch-like form of the building elements is the result of bending under self-weight. The final form was achieved by slowly pushing up the sheet. The amount of force needed was minimal and could be carried out easily by hand; no machines or additional formwork were necessary.



In addition, the digital design processes that exclude simulations of physical form-finding in favour of a process of negotiation between architectural and structural demands generally proceed by an integration of structural analysis into the later stages of the generative process. So they too have a similar hierarchical relationship between form and material, and result in a performance-oriented deformation of the initial form with respect to stress fields caused by the flow of forces along the form. In this way of working, the assumed materialisation of the form mediates between the intensity of the force flow and the amount of deformation. As before, the primary focus is on form as the direct resultant of the acting forces.

The Distribution of Material

In all these design approaches, however, it is evident that form cannot be treated independently of material, even when the strongest architectural interest is in form-finding. It is material through which forces flow, and the arrangement of material in space, the pattern of its distribution, directly influences the efficiency of the flow of forces, the direction of the flow and its intensity. This is evident in all living forms. For example, plants resist gravity and wind loads through variation of their stem sections and the organisation of their material in multiple and integrated hierarchies. It is this hierarchical organisation of subtle and continuous changes in material properties that enables plants to respond to both local and global stresses.

Variations in the section and material properties of 'structural elements' in living biological systems offers significant advantages over the constant section that is conventional in engineered structures. Sectional variations produce anisotropy,[2] a gradation of values between stiffness and elasticity along the length of the structural element that is particularly useful for resisting dynamic and unpredictable loading conditions such as those produced by wind. Growth under the continual stresses of the physical environment produces this pattern of organisation of material; the forces that the living organism experiences while it is growing encourage the selective deposition of new material where it is needed and in the direction that it is

opposite left: Due to the size of the plywood sheets, conventional production facilities could not be used. Necessary cuts were therefore carried out along pre-mounted drawings using a stick saw.

below: A transparent structure can be achieved through small variations in the length of the sheets. Cuts help to reduce the bending stiffness of the sheets and allow for increased bending radius, as well as a functional differentiation between the load-bearing arches along the edge of the sheets and the louvre system.

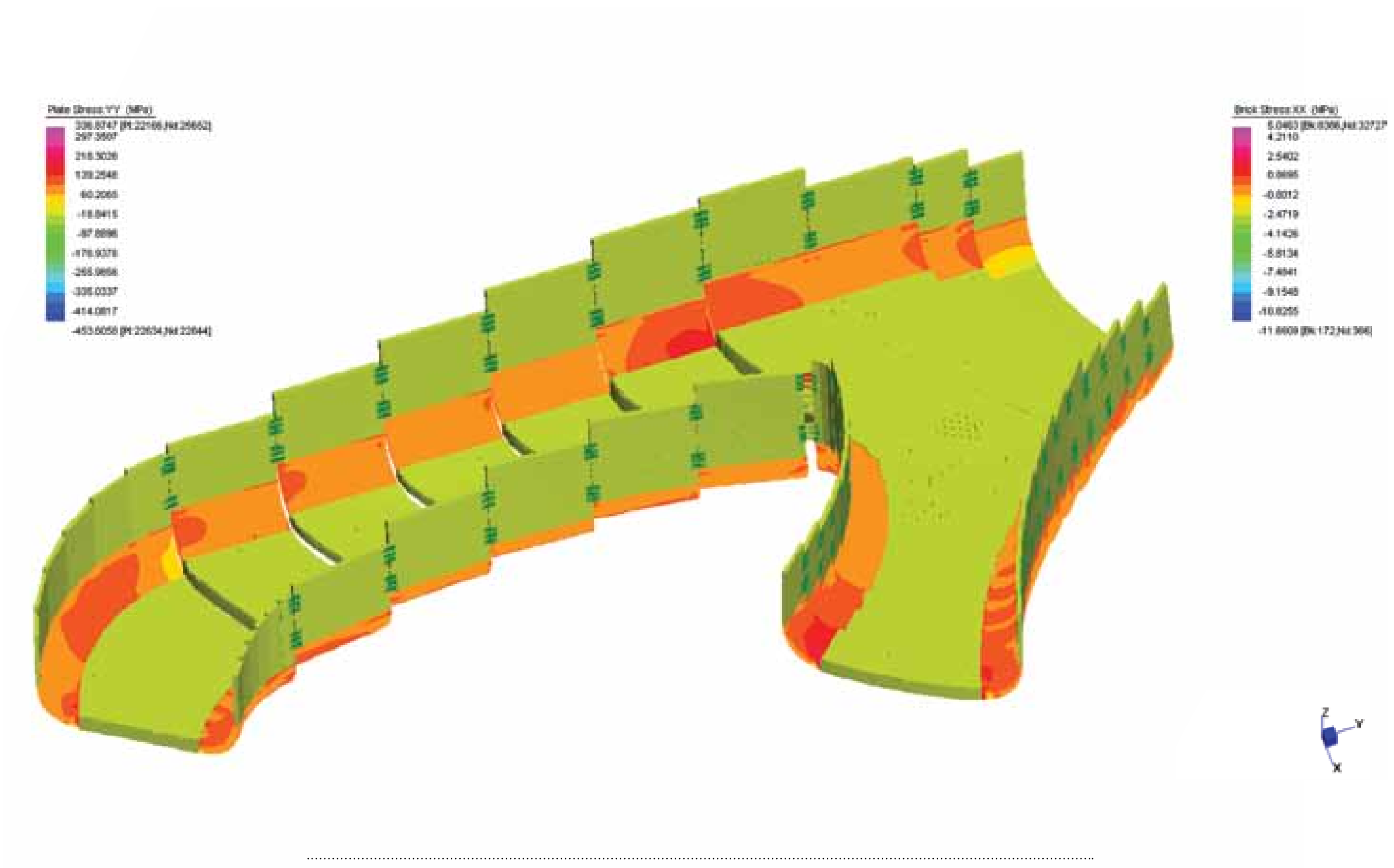
The adaptation of the form and the distribution of material are integrated in living organisms in response to the forces acting upon them. It has been the convention to study and computationally simulate form and material separately, but any adaptation of the form results in the immediate redistribution of matter in space and vice versa.

Steel cables act as cross-bracing of the arches and help to evenly distribute additional loads, minimising further deformation of the construction. Five-centimetre (1.96-inch) wide washers transfer the tension forces from the cables into ply.

needed. This process also continues throughout the whole life of the organism whenever changes in stress and load occur.

The formation of reaction wood in trees, needed to realign a trunk towards the vertical when it has experienced inclined growth or to offset loads from prevailing winds, and the mechanisms of bone remodelling, are perhaps the most widely studied examples of responsive distribution and accumulation of material. Reaction wood has a fibre orientation and cellular structure that is different to that of normal wood, and is produced in successive annual rings that vary in width and density as local circumstances require. In bones, material is removed from any areas that are not stressed and deposited in more highly stressed areas. For example, in the femur, the longest and largest bone of the human body, this leads to an accumulation of material at the greater trochanter[3] where forces have to be redirected and, therefore, stresses are the highest. Among all the living forms of nature there are many differing load-bearing architectures, each a response to the specific set of load conditions that they experience. The evolution of all the multiple variations of biological form cannot be thought of as separate from the spatial distribution of material, and it is the integrated hierarchies of material organisation within their form from which their structural performance emerges.

The adaptation of the form and the distribution of material are integrated in living organisms in response to the forces acting upon them. It has been the convention to study and computationally simulate form and material separately, but any adaptation of the form results in the immediate redistribution of matter in space and vice versa. Materialised forms and formed material are complementary principles of materiality – distinguishable, but not dividable. Form and material act upon each other, and this interaction cannot be predicted by analysis of either one of them alone. Contemporary form-driven design approaches do not yet take full advantage of the possibilities offered by a generative system that integrates material, form and force as continuous iterations in the design process. When processing the flow of forces through a material object, and balancing variations of form with the organisation



The overall arch-like form of the two legs of the bridge has been in part the result of a form-oriented design approach during the initial design phase, with Gaudí's hanging chain model as precedence.

Architectural Association Emergent Technologies and Design Programme (AA EmTech) and the Institute for Computational Design (ICD), University of Stuttgart, Bifurcated Bridge, Architectural Association, London, 2010
Even stress distribution along the components in the final design development. The highest stress occurs at the transition from horizontal to vertical elements, which is at the area of redirection of the force flow.

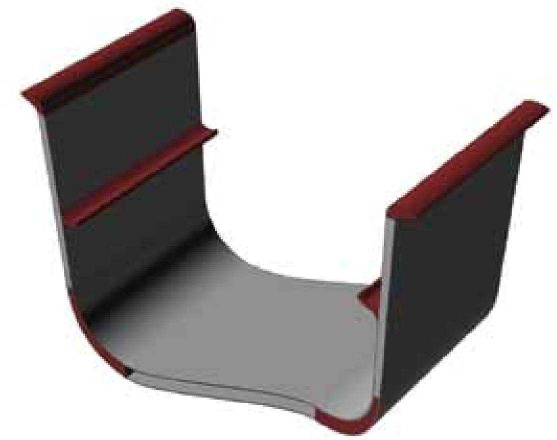
opposite: Final design of bridge component with fully developed differentiation of the cross-section. The vertical section of the component consists of 40-millimetre of ply, the horizontal walkway has been separated into two layers of 5-millimetre ply with additional ribs for stiffening. These two planar surfaces are connected by a curved solid timber inlay in the area of transition from horizontal to vertical section. Further stiffening of the U-shaped bridge component is provided by the solid timber handrail and the solid edge at the top part of the component.

and behaviour of material, the emergent form has the capacity to respond effectively to forces that will be imposed upon it in the physical world. This balancing of material, form and force is the focal point of a recent series of projects conducted within the Emergent Technologies and Design (EmTech) programme at the Architectural Association (AA) in London.

The Pavilion

In collaboration with the Chair of Structural Design research unit of the Swiss Federal Institute of Technology Zurich (ETH Zurich), a temporary light timber construction has been designed that functions as sun shading for parts of the grand stairs in front of the ETH architecture department. It is based on bending behaviour under self-weight of oversized sheets of plywood of up to 11 x 2.5 metres (36 x 8.2 feet).[4] The design activates the material properties as the defining element in the transfer of forces, and the design method is related to the hanging chain model. The resulting form, however, is not achieved as a pure geometry of force independent of material as the chain model is, but instead as a direct reaction of the material to the forces acting upon it. Cuts within the sheets influence their bending resistance and so enable a larger spatial enclosure and reduced wind load acting upon the structure, additionally producing a shadow pattern on the stairs, which are used as a seating area during the summer. Varying the length of the sheets produces small variations of the bending curve that have been utilised for the overlapping and interlocking of adjacent elements. This is the system of self-stabilisation of the vaults, and the intensity of the forces that need to be transferred into the ground along timber plates is kept to a minimum.

The exploration of the sheet material and the manipulation of its bending properties by controlling the number of layers of ply and the fibre direction of these layers was the beginning the design process. The precise geometry of the bending curve emerged out of the distribution of matter, the hierarchy within plywood as the composite material and given load conditions. Based on a systematic investigation into the defining parameters, sheets of 18-millimetre (0.7-inch) thickness with fibres mainly in longitudinal directions have been used for the pavilion. The inscribed louvres within the sheets influence the bending curve by functioning as dead load, adding to the self-weight of the continuous strips along the edge of the sheets. Along these edge strips, two sheets of different lengths are overlaid and cross-braced by a sequence of cables that distribute all other load conditions evenly within the strips, and so reduce additional deformation of the arched form to a minimum.



The Bifurcated Bridge

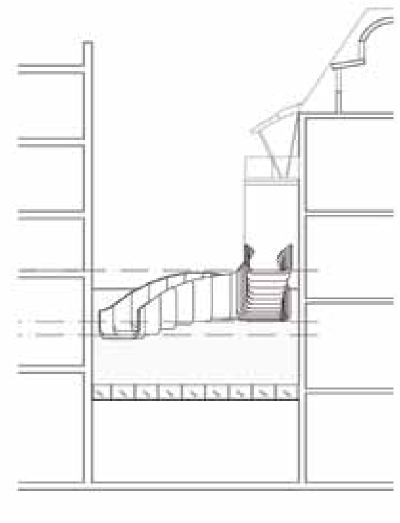
The design proposal for a temporary bridge structure between two buildings at the AA in London was developed in collaboration with the Institute of Computational Design (ICD) at the University of Stuttgart. It is an exploration of the distribution of material with respect to the stress field within a given form. The design is based on a U-shaped component system built out of flat and single-curved prefabricated timber and plywood elements. The components are connected by means of two inlaid steel plates that enable the bridge to function as a 'simply supported' system that rests on the existing brick walls, with load transferred along the vertical faces of the components. The pedestrian surface is attached to the vertical faces by curved elements, and a small gap separates neighbouring components.

The overall arch-like form of the two legs of the bridge has been in part the result of a form-oriented design approach during the initial design phase, with Gaudí's hanging chain model as precedence. Due to the restraints of the support conditions, however, the bifurcating bridge cannot act as an arch; instead, the force flow is comparable to those within beams. In consequence, an uneven distribution of stresses occurs along the bridge. The subsequent refinements of the bridge design focused on the redistribution of material rather than on adaptation of the overall form.

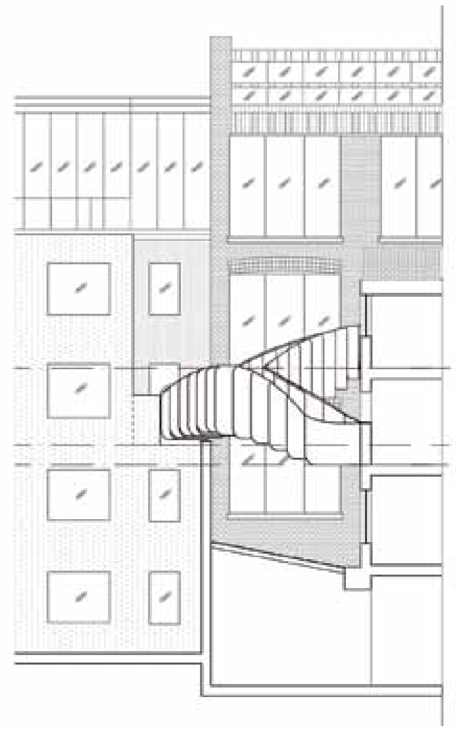
As in the processes that govern the growth and development of bones, information from stress analysis was used within a feedback loop to successively relocate material along the U-shaped section of the components. This resulted in a differentiated distribution within the profile: a hollowing-out of the pedestrian surface, a thickening of the vertical load-bearing elements, and a concentration of material along the edge of the components. In addition, the process generated the formation of the curved top part of the U-shaped section; the integration of handrails as additional elements stiffened the bridge with respect to lateral loads.

below top and opposite: The bridge connects three points of interest on three different levels: the reception area and central outdoor terrace with the main studio space.

bottom: Early prototype of a bridge component with even cross-section. Components are tied together by steel cables, which later had to be replaced with steel plates due to the amount of sheer force within the vertical sections of the components.



SOUTH ELEVATION



WEST ELEVATION

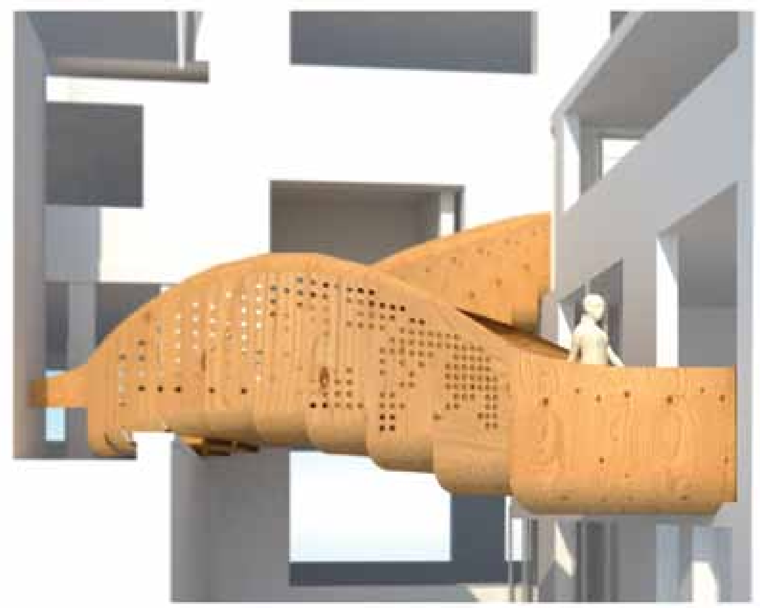
Both of the construction projects above show that material properties have the potential to unfold a generative logic of form-finding, a potential comparable to the use of geometric sets of rules within contemporary digital-design approaches.

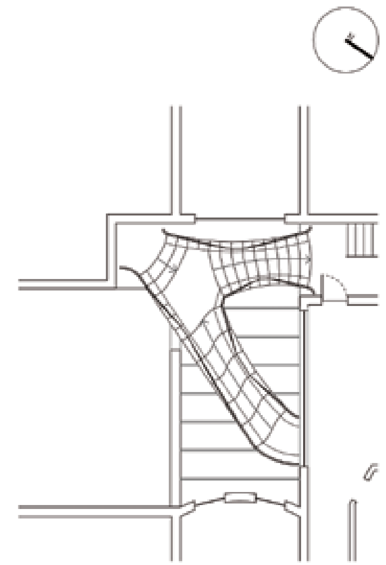
Generative Material Logic

Both of the construction projects above show that material properties have the potential to unfold a generative logic of form-finding, a potential comparable to the use of geometric sets of rules within contemporary digital-design approaches. In this sense, materials have the inherent ability to 'compute' efficient forms, and to guide refinements as shown in the shaping of the components of the bridge. This material-immanent logic can support the fabrication and assembly, as in the pavilion project where no additional formwork was required in order to achieve the curved form. Using properties of the material world within the design process can help to simplify construction and make designs attainable. The incorporation of physical necessity of material behaviour as generative input, therefore, can help to unfold the freedom of design. Material constraints do not have to be understood as limitations to the design, but rather as sets of rules complementary to the geometric constraints defined by architectural intention. Form and material work hand in hand to process various load conditions; deformation of form and the distribution of material are reciprocal methods of design that help to 'digest' the flow of forces imposed upon the architecture. Freedom of design arises from the balancing of these two principles. AD

Notes

1. For a review of the relationship between form and matter, see Katie Lloyd Thomas (ed), *Material Matters: Architecture and Material Practice*, Routledge (London), 2007.
2. The condition of having different structural and or dimensional properties along different axes.
3. The bony protuberances to which muscles are attached to the upper part of the femur.
4. 'Precedents to this field of work commence with the work of Alvar Aalto and Charles Eames in plywood, and the techniques of scoring, cutting and bending to achieve curvature have been established in a variety of materials in jewellery design, surface ornamentation, paper and other craft practices, as well as in airplanes and boats. Recent contributions include Skylar Tibbits' Surface Ornamentation at the Massachusetts Institute of Technology (MIT) (2008), and The Probotics by Knut Brunier, Anica Kochhar, Diego Rossel and Jose Sanchez of the Architectural Association Design Research Laboratory (AA DRL) (2010).





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