Self-regulating Fields and Networks

Elasticity in material performance and spatial organization: design tool development and material studies

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Abstract. This paper will explore the connection between two theoretical models, initially identified as the Field and the Network Conditions (Allen, 1997; Wigley, 2001) and material based studies in architectural design, conducted as a sequence of experiments. A number of prototypical models have been produced to test the practical and theoretical dimensions of the design approach which employs elastic material performance to achieve highly versatile spatial organization. One of the concrete outcomes of the exploration is the specific software extension produced by the authors of this paper. Its purpose is to enable designers to maintain an indirect control of complex spatial models based on the use of two parallel sets of algorithmic protocols which define: a. geometric logic and b. intrinsic material behavior.

Keywords. Elasticity; material performance; self-regulating systems; prototypical models; physics based simulation.

INTRODUCTION
At the turn of the twenty first century two North American based writers presented stimulating visions of plausible spatial organizations based on knowledgeable overviews of historic precedents in art and architecture. The first one was Allen (1997) who depicted the Field Conditions as bottom-up phenomena, defined not by overarching geometrical schemes but by intricate local connections. A few years later Wigley (2001) described the Network Conditions as an effect that cannot be designed, something that does not have an interior or exterior, a system of interlocking elements with many similarities to biological organisms. Instantly after their publication, both essays became an integral part of a great many agendas in architectural education and research. Yet, after a period of time, which now exceeds a full decade, we still feel obliged to pose the following questions: why do we still lack Fields and Networks in architecture? What are the material repercussions of these ideas? And how do we create spatial qualities promoted as such Conditions? In response, this paper will document a series of design experiments resulting in a series of prototypical models aimed at the development of architectural workflow based on the interpretation of the ideas from the essays “Field Conditions” (Allen, 1997) and “Network Fever” (Wigley, 2001) through the notions of material performance and organizational properties.
MATERIAL PERFORMANCE AS SPATIAL ORGANIZATION

This study establishes connection between the two ideas, briefly described above and observed here as two theoretical models, and material based studies in architectural design, conducted as a sequence of experiments and resulting with the series of prototypical models. More precisely, the paper investigates analogous relationship between what is now broadly considered in architectural thinking as a complex spatial organization and the elastic performance of building materials.

Before we embark on the discussion about the possible importance of elastic material behavior in the formation of complex spatial originations, structures and environments, let us consider what it is that brings together two theoretical models adopted here as a departing point of the study. At first glimpse there is not much in common between the ideas of these two American writers. Yet, through a necessary level of theoretical abstraction, reducing the entire vision to the level of structural reasoning, we could just agree that, what binds them together is that both are equally remote from thinking of spatial order through geometric arrangements. They both embrace the logic of locally regulated interdependencies between their constitutional elements to achieve continuous growth and adaptability of their internal structure. They are likewise characterized with the lack of centrally imposed organization. Their form is distributed and non hierarchical. At the simplest level of comparison, a parallel may be drawn between points and lines of the Field model with the nodes and edges or vertices and connections of the Network model. Importantly, for the purpose of this study, two theoretical models are also complementary in their dependence on the similar but different local connections leading to the intricacy of the overall structure. The idea dates back to early critics of the geometric reasoning in production of the built environment. Lionel March and Philip Steadman (1971) were able to point out the importance of the “new mathematics“ and relational reasoning in the understanding of complex spatial organizations.

Present day interest for the material performance in architecture, fuelled by the increasing ability to compute and control material behavior, is offering an intriguing way of thinking about complex spatial organizations. In relation to the number of key spatial features which have been accurately described by Allen and Wigley, this study recognizes the role of elastic material behavior as:

- an enabler of the diversity and interconnectivity throughout the construction of spatial models;
- an essential ingredient in the continuous growth of spatial structures;
- a mechanism for the systemic self-regulation in respect of any externally imposed influences.

In response, the study explores ways of employing elastic material performance within the analogue modeling and the custom computation techniques in the search of diverse, interconnected, continuously growing and self-regulating spatial organizations, structures and environments.

ELASTOMER: THE MODELING MATERIAL

The experimentation begins with the selection of elastomers as our building material, above all for their form-changing capacity. Their main characteristic is elasticity, the ability to withstand transformation and return to their pre-deformed condition. Elastomers promisingly fit into the ideas of systemic self-regulation for their aptitude to adjust their internal structure according to external stimuli. Interestingly, their chemical structure shares more characteristics with fluids and gases than with the solids that are most commonly used in the building industry. At the same time, by their behavior, elastomers resemble soft biological tissue able to change and adapt far easier than mechanical constructs which have been the dominant solution in the realization of responsive environments, up to the present day.

A brief look at the molecular structure of elastomers explains the resemblance better. They belong
to the group of materials called polymers, characterized by long molecular chains which are connected between themselves with covalent chemical bonds. Under the normal conditions these molecular chains are conglobated, but when external stress is applied they become parallel to each other, allowing for the elongation of the material. Once the stress is removed, molecular chains regain their original configuration, relying on their covalent cross-linkages. Such a particular molecular structure makes elastomers known for the magnitude of their elastic range, defined with a very low stiffness threshold and extremely high yield point. Other building materials behave elastically too, but less visibly since their reversible deformation range is significantly smaller. Many of them obey Hook’s Law of elasticity which states that strain is directly proportional to stress. Consequently, mathematical description of a material’s tendency to be deformed elastically is defined through the elastic modulus, equal to the ratio of tensile stress to tensile strain. For elastomers Hook’s Law is applicable only approximately because their hard-to-control chemical structure is sensitive to loading rate and many other external factors. It is important to note that the performance of an elastomer based materials is highly dependent on the conditions of their environment, such as temperature and humidity, and also highly susceptible to loading rate and direction of any physical force that could be applied, such as wind force (Stojanovic, 2012).

GEOMETRIC AND ELASTIC PROTOCOLS: THE MODELING TECHNIQUE
After having provided an account of elastomer based materials and their elastic behavior, we will now focus on a more difficult part of the research which deals with the problem of how to employ and cognitively comprehend reversible deformability as a generative mechanism directly within the design process. For the purpose of efficient research flow, we kick-start the experiment with a physical modeling technique and the use of affordable, recycled and omnipresent form of an elastomer based material: the rubber-band. The proposed model-building technique is founded on an accumulative assembly of components according to two parallel sets of principles. The first one is the algorithmic logic of consistent growth, whereby components are combined according to a geometric rule-based system; its logic is to be exhibited in a series of steps leading to the growth of the overall structure. The second set of principles is equally important but infinitely less apparent. As it only gains momentum through the modeling process while initial geometric logic dissipates and becomes restrictive to further growth; it is related to inherent properties of the proposed building material, chosen for its intrinsic or chemical structure that permits change and diversification between previously identical components. Through elastic material behavior, the entire physical model acquires the autonomous ability to recalculate itself in real time according to any amendment or the addition of a new component.

At the outset, the elasticity is employed intuitively in the form-making process, but throughout the experimentation, the understanding of its formative potential gradually progresses from the approximation toward more explicit and parameter-based control achieved through custom computation. Along with the geometric rules, the nature of the elastic deformation is translated into yet another set of rules, to form an algorithmic protocol based on Hook’s Law. The manifestation of elastic behavior is observed via the elongation of the individual components according to the changing amount of stress imposed on them and relative to the material’s tendency to be deformed elastically, or its elastic modulus (Stojanovic, 2012).

ELASTIC DIARIES
The experimentation is conducted as a sequence of design workshops resulting in a series of prototypical models. Over a two-year period, four workshops have been held within the scope of this research. Approximately sixty architectural students from different architectural schools have participated. The initial workshop took place at the University
of Belgrade within the framework of the Graduate Design Studio Course. The exercise was carried out with sixteen participants, over a short period of time and with an aim to initiate thinking about adaptable spatial configurations and introduce appropriate design techniques to be utilized throughout the semester. Students were asked to use rubber bands and construct spatial assemblies by exploring algorithmic logic and employing rule-based system to achieve geometric complexity. In parallel, students were suggested to explore elastic material properties while assembling their models. The task proved to be challenging as the material lacked stiffness and any spatial configurations had to rely on the surrounding environment to achieve structural stability. At the same time, the inconsistent chemical structure of the material proved to be intriguing to students. Its potentials in structural and formal thinking became apparent through model building, to the extent that the inconsistency of the material structure lent itself to the title of the entire workshop series. As a result, the students produced a number of models which were able to respond to externally applied force by changing their geometric configuration and resuming their initial form thereafter. The process of structural change was recorded with a time lapse sequence of photos, which were composed into short films by the students (Figure 1).

Almost a year later, the second workshop took place in Tehran within the Visiting Programme, a platform created by Architectural Association to further extend its educational setting through international engagement and collaboration with a diverse group of local partners and schools. At the outset, participating students were shown the results from the previous workshop and were asked to respond by making their own models using the
same material and similar techniques. With a different working regime to the workshop in Belgrade and a formidable level of commitment, students produced comparable results on the third day of the workshop. With ten days remaining, this was an opportunity to expand the agenda and move toward the making of larger structures and full-scale models. Students were grouped into five teams based on social ties, but also according to the common threads identified in the models they had produced in the opening stage of the workshop. Two teams opted to substitute rubber bands with other elastomer based components, while three other groups decided to continue with the same material. A four-member team (Amir Reza Esfahbodi, Abolhassan Karimi, Imman Shameli and Mohammad Habibi Savadkuhi) working closely with their tutor, proved to be the most effective and able to assimilate structural reasoning into their modeling technique. As a result, in the concluding stages of the workshop, they had produced two large-scale prototypes. The initial models made of rubber bands were replaced with models composed of more durable elastomer strips, measuring 100 mm in width. The second prototype, being the larger of the two, reached the height of 11m. Similarly to the models from the first workshop, this model was designed to respond to externally applied force by changing its geometric configuration and then resuming its initial state after the action, yet now this is done in relation to the force imposed by the weight of a grown person. To everyone’s amusement, at the final day of workshop, visitors and fellow students were invited to test the model by swaying in it with the amplitude of 3 meters (Figure 2).
Later in the same year the third workshop took place, although it was organized differently to the first two. The most important change was that students were not asked to create their own models but to participate in the making of a single structure based on the established design protocol. There were neither drawings nor computer models made prior to the construction process, only verbal instructions formulated from the knowledge gathered in the previous workshops. Namely, a particular failure from the previous workshop in Tehran, a never completed model, was recalled for its construction technique. What had been started there, together with the understanding of advantages and disadvantages of rubbery materials acquired throughout construction of other models, became the design protocol for the growth of the structure. The event took place in O3one art space in Belgrade (Figure 3).

The construction started simultaneously from five points in space from which a number of tentacles were established in relation to the structural considerations of the most suitable supporting points within the given environment. From there the structure grew in a systemic way through the insertion of a new tentacle at the mid-point of an existing strand. A total of sixteen students worked simultaneously and independently, or in small teams of two or three members, on the model. As anticipated, after a number of recursive steps, the initial rule based growth process became less apparent and had to give way to a new logic related to elastic material behavior or the inherent property of the employed building material. As noted by Branko Kolarevic (2012), one of the most prominent characteristics of the structure was the distinction between the initial and the emergent set of rules employed throughout the construction process. Such emergent rules are directly related to the material performance.
Through the effect of elasticity, the entire physical model acquires an instantaneous ability to recalculate itself according to any amendment or addition of a new component. At any moment during the growth process, the overall stability of the structure was reliant on the multitude of local conditions and the ability of initially identical modular components to react to tension forces and go through a process of gradual adaptation according to continually changing structural circumstances. When presented with the images of the end result of the workshop at O3one Art Space, in the context of the much broader conversation on relevance of network organizations in architecture, Marc Wigley (2012) was able to point out the resilience of the system by looking at the model, which he then recognized as an essential enabler of the curious spatial condition defined by the lack of distinction between the interior and the exterior of the structure created. In reference to that, we would like to suggest that prototype “Inconsistencies v.03”, resulting model of the third workshop, could be simultaneously examined as a specific environment created in between elastic lines and an object with its own structural logic. We can also observe variations in the density of the structure. Closer examination of different parts of the model reveals their individual properties. Majority of segments with higher densities of elastic lines resemble objects with their own identities and boundaries, while other segments positioned closer to the existing walls reveal features of the environment allowing visitors to walk through them (Stojanovic and Cerovic, 2013).

Exactly 12 kg of yellow rubber bands measuring 70mm in length and 5mm in width were employed as construction components of the model. In addition, approximately 8000 metal clips were used as joints between bands. The resulting structure occupied the room with a footprint of 50 square meters and a height of 3.5 meters. It took five days to complete the assembly. The intention for the next prototypical model was to build with more parts, from more durable materials and at a larger scale. Simply put, the idea was “the bigger the better”, with an aim to close the gap between the model and the actual building (Figure 4).

Equally defining was the ambition to construct the structure in the open to include influence atmospheric conditions such as temperature (°C), humidity (%), wind force (m/s) as well as the influence of the material performance on the rule base geometric protocol of the model building or structure’s growth. The fourth or the final workshop was held in the pool-like space with exposed concrete floor and walls. At the time, the given site was formally under construction court-yard of the newly refurbished historic building in Belgrade. The structure was built according to the plan tested in the previous workshop based on the design and build protocol and the participation of sixteen students from the University of Belgrade. Instead of the rubber bands, rolls of elastomer based strips were used and in the place of metal clips there were purpose designed joints made of two laser-cut, steel plates and two plastic ties to hold them together. The shorter span between two ends of the structure was thirteen meters and its height reached just over 5 meters. Due to the size of the model and the need to establish joints at high altitudes, the assembly process was significantly slower than the previous time. But after several steps of construction following the rule-based protocol which implied continuous subdivision of the existing spans with the insertion of the new ones, we were able to observe importance of the elastic material behavior and take note of the influence of oscillations in temperature and wind force upon the entire geometric configuration of the model. Importantly and in contrast to the previous workshops, this time we have relied on the digital model and the simulation of the material and physical processes to predict, prepare and coordinate construction on site (Figure 5).

Comparison between the digital and the physical model was done and recorded nineteen times during the assembly process. During the first seven steps the growth process followed the digital model, while the remaining twelve steps were carried out with the reverse logic whereby digital modeling fol-
ollowed the activity on site. Minimal dimensional discrepancies at different stages of the assembly process proved the validity of the method to compute material and physical processes and their implication on the geometric configuration of the structure.

CUSTOM COMPUTATION FOR THE MODELING WITH THE MATERIAL PERFORMANCE
One of the concrete outcomes of the exploration is the specific software extension produced by the au-

Figure 5
Feedback loops: digital vs. analogue model of the elastic structure.
Authors of this paper in collaboration with the Group for Mathematics, Architectural Geometry and CAAD at Faculty of Architecture, University of Belgrade. Custom programming is done by Bojan Mitrovic. The software created is now made available, in the form of the plug-in for the Rhinoceros platform, under the brand name “Spider” (free download from food4Rhino website 2012). Its purpose is to enable designers to maintain an indirect control of complex spatial models, based on the use of two parallel sets of algorithmic protocols which define: a. geometric logic and b. intrinsic material behavior. The tool enacts simulation of elastic material behavior throughout the process of geometric modeling and provides for more precise inclusion of material performance throughout the design process. It contains features for parametric control of reversible deformation range and elastic modulus, to allow iterative testing and enable parallel consideration of different building materials (Figures 6 and 7). It also provides for the parametric control of environmental parameters, including the wind force and direction. The programming approach rests on the use on the particle-spring systems commonly used for creating physics based simulations. It is anticipated that the tool created for the purpose of this investigation might be applicable to other research related to form-finding and optimization of spatial structures, as well as the strategic planning of spatial organizations.

CONCLUSIONS AND PROSPECTS
A number of prototypical models have been produced to test the practical and theoretical dimensions of the design approach which employs elastic material performance to achieve a highly versatile spatial organization, initially identified within the ideas of the Field and the Network Conditions (Allen 1997; Wigley 2001). The study has introduced specific workflows in which the architect assumes only an indirect control of the model, allowing for the more open negotiation between material performance and the environmental influences in the design process. The research was unfolding as a series of feedback loops in which material performance, intuitive decision making and computational tools were all combined. Material testing was conducted in parallel with the formal modeling and the development of the custom computational tools.

Prospects for the development of the research presented in this paper include two plausible routes. The first one would be pragmatic in its nature and could relate to the continuation in production of prototypical models with the purpose of developing a specific structural solution. The particularity of such a system would be based on the immediate inclusion of building physics during the process of architectural design. If we accept elasticity, as one of the key characteristics of building materials, we can then begin to evaluate the relevance of designing and building spatial structures according to the
principles of elastic material behavior. Design tools and workflows developed during the research with elastomer based assemblies may equally be applied to building materials with less apparent elastic properties. Prospects for further research could include more efficient uses of wood, steel and other materials used regularly in the building industry. Iterative modeling techniques, use of prototypical models and better prediction of the material processes are seen here as means for understanding and employment of the elastic material behavior in the design process.

The second route is related to strategic thinking of spatial organizations and would be inclined toward contribution in the development of the systemic approach in architectural design. As it has been pointed out, in the example of the model “Inconsistencies v.03”, the understanding of elasticity as a capacity of a reversible change, has been transposed form the material behavior into the characteristics of the overall structure. Roderic Lakes (1993) points out that that many natural and man-made materials, including polymers, exhibit structures on more than one length scale and concludes that structural hierarchy can play a large part in determining the bulk material properties. In the research documented in this paper, Lakes’ idea of the hierarchical transposition of structural properties through different scales of material was expanded to include the transposition from the material to the entire structure of the prototypical model. Prospects for further research include the aim for better understanding of structures with the capacity of self-regulation or the ability to maintain stability or constancy of the internal organization in spite of the changes of their environment. Tested workflows provide for highly adaptable design solutions that could easily be adjusted to different locations while keeping their material, structural and organizational logic. With the knowledge acquired through further experimentation, we would like to continue exploring the importance of elasticity as a structural change at the material level, within the boarder significance of architectural strategies.

ACKNOWLEDGEMENTS
The documented study combines research and teaching efforts; it is planned as a collective effort and would not be possible without contribution from our students form University of Belgrade and Architectural Association, Visiting School. The authors would like to thank Branko Kolarevic and Nate Kolbe.

REFERENCES
Wigley, M 2013 ‘Interview with Djordje Stojanovic’, In: V. Djokic V. and P. Bojanic (eds), The Specter of Jacques Derrida, University of Belgrade, Faculty of Architecture, Belgrade, pp 34-49.