Reflections on Kinetic Reticulated Frameworks

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SUMMARY

This contribution is reflecting on kinetic reticulated frameworks, structures composed of linear elements, that adapt to different climatic conditions or reconfiguring to various functions. Kinetic systems are devised to adapt and change in shape, therefore their assessment shifts from static behavior to dynamic performance. The esthetics and technology are linked to movement and variability, revealing ephemeral aptitudes.

The goal is to explore a new vocabulary for kinetic architecture, expanding the established range of static buildings with adaptive, convertible and kinetic architectural systems.

The novelty of the approach is the identification and exposure of a comprehensive survey of load-bearing principles in architecture structures and to develop for each of the fundamental structural behaviors a measure to convert a static structure into a kinetic mechanism. On this basis several new basic kinetic loadbearing systems could be developed. More complex systems can be synthesized through combination and hybridization.

INTRODUCTION_FLUXUS

In classic terms architecture reflects immobile, static and enduring virtues. Masterpieces of architecture are appraised for their timelessness, lasting for centuries. Yet this addresses only a partial domain in the perception of building culture. Nomadic shelters, perhaps among the first human dwellings, were collapsible and transportable; they accommodate the lifestyle of transhumance, and incessant migrations to fertile grounds and better trade.

Globalization during the recent decades increases flow and inter-connectivity of trade, finances and political/social/cultural interests. Furthermore, vast and instantaneous sharing of intellectual ideas, experience, trans-disciplinary collaboration across conventional borders lead to increased mobility, exchange and cross-fertilization. This is reflected in the lifestyle of the urban nomad, where digital communication and entertainment pairs with global exchange and geographical mobility.

DEFINITION_KINETIC RETICULATED FRAMEWORKS

Kinetic architecture structures are convertible, deployable and kinetic building constructions, actuated by mechanisms or flexible parts, adapting to different climatic conditions or reconfiguring to various functions. They can change their form through the flexibility of the entire system or with discrete flexible elements allowing the change of the relative position of its structural elements.

Here the focus is on reticulated frameworks of linear or two dimensional elements connected with axial hinges or spherical joints and actuated with linear actuators, able of changing their geometry while maintaining loadbearing functions. In contrast to a structural continuum, reticulated frameworks refer to mesh-like structures, composed of linear or two dimensional elements. As examples, a concrete shell represents a continuous structure, whereas a geodesic dome refers to a reticulated framework.

PRINCIPLES_MOVEMENT AND STIFFNESS

The essential feature of all convertible constructions is movement, which is governing also their principles. Whereas in architecture material defines space, in convertible structures – like in dance – the movement activates space.

Distinguishing convertible structures can be conducted through classifying the properties of stiffness: flexible systems and rigid mechanisms. In flexible systems the reduced stiffness allows for motion in a substantial part of the structure. Flexible systems achieve therefore a higher freedom of movement. Rigid mechanisms are motioned without changing the form of its elements. The movement is induced here in discrete elements, like hinges and joints. As a consequence rigid mechanisms adhere to more severe morphological principles and stricter motional sequences.

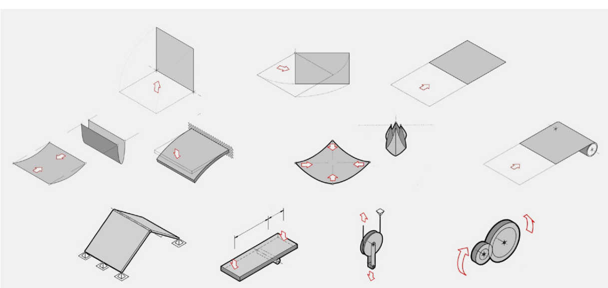


Figure 1. Movement occurs either as parallel translation and rotary motion [Otto 1972]; Flexible systems with the types of motion: bending, rolling, folding and gathering [Otto 1972]; and rigid mechanisms: hinges, levers, winding tackle and toothed gears [Sill 2005].

ALGORYTHM_WORKING METHOD

The working method of this research is: Identifying and exposing a comprehensive survey of the loadbearing principles in architecture structures and then to develop for each of the fundamental structural behaviors a measure to convert a static structure into a kinetic mechanism.

The intent of this research work aims to cultivate new vocabularies of building technology, expanding the established range of static buildings with adaptive, convertible and kinetic architectural systems.

Once the basic kinetic components are identified, more complex systems can be synthesized through combination and hybridization. This basic and broad work is then carried to applications on frameworks of metal struts or in suitable materials connected with axial hinges or spherical joints and actuated with linear actuators, able of changing their geometry while maintaining loadbearing functions.

Sensing, controlling and steering contribute essentially to the intelligence of such alterable systems. This offers potential for trans-disciplinary application, but it is not discussed here further in detail.

The novelty of this approach lies in the identification of essential loadbearing principles for basic structural modules and their correlation with actuation modes. This leads to in a new method for classification and design development of kinetic structures.

Figure 2. 2 Summary of loadbearing principles for vertical structures [Sill 2007, 2011].

POINT OF DEPARTURE_STATIC LOADBEARING

Loadbearing principles for horizontal structures, such as roof and bridge structures, include bending moments and shear in simple beams, superposition of bending moment and axial forces in vierendeel / frame systems, mainly axial forces in king and queen post systems, axial forces: compression and tension in triangulated truss systems, the arch with compressive forces and bending to resist buckling, suspended cables solicited with tensile forces only, hybrid systems with beams supported by “flying” struts supported by tensile elements, to the more complex cable trusses and tensegrity systems.

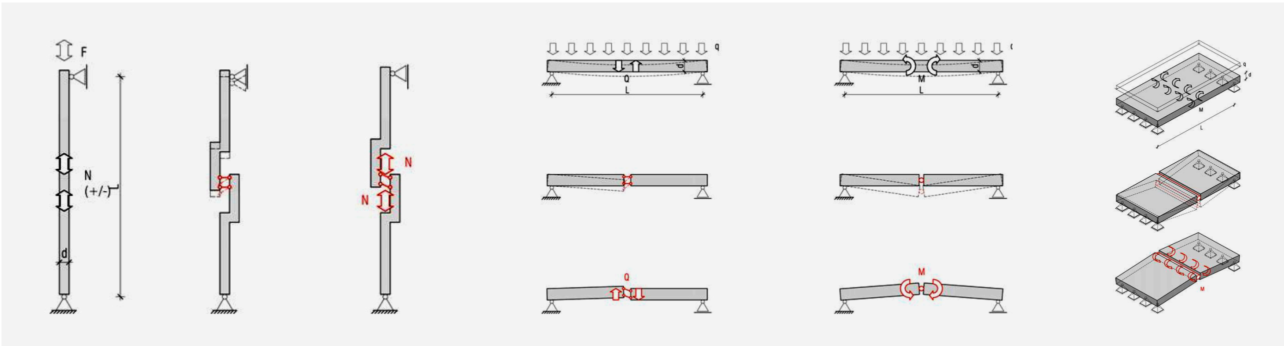


Figure 3. Basic kinetic modules – resulting through releasing the main loadbearing component [Sill 2005]:

structural element: bar,	beam	beam	plate
loadbearing: axial force,	shear force	bending moment	bending moment
actuation: linear actuator	linear actuator	rotational actuator	rotational actuator.

On the other hand, loadbearing principles for vertical structures comprise buildings such as towers and high rises. They include bending moment and shear in a cantilever, the superposition of bending and axial forces in vierendeel / frame systems, axial forces: compression and tension in triangulated truss systems, to the more sophisticated hybrid systems of cable-stayed masts, outrigger and tensegrity systems.

PERFORMANCE_ACTIVATING KINETIC STRUCTURES

Once essential loadbearing behaviors of the basic structural systems are identified, the strategy will be to respond to each of them through releasing the main loadbearing component: bending moment, axial or shear force. This will convert the static determinate and indeterminate structural systems into unstable mechanisms, therefore immobile constructions becoming animated. However the unleashed beasts, unfortunately, have to be controlled to maintain the loadbearing function and to prevent collapse. It is appropriate to handle this double intervention of release and control of each degree of freedom with one actuator, either with adjustable length or angle, with the aid of a linear or a rotary actuator.

CTRL_STEERING OF CONVERTIBLE STRUCTURES

Such systems can become highly complex the more degrees of freedom involved. Further, this research investigates opportunities to generate convertibility in truss and folded structures with a reduction of the degrees of freedom. Intelligent optimization to maximize the convertibility while reducing its inherent mechanical complexities reduces the efforts for technology, manufacture, controlling and maintenance to reasonable limits.

ACTUATION_MEANS AND TOOLS

In this approach linear actuators have been envisioned for all actuations, such as hydraulic or pneumatic cylinders, linear electro mechanic actuators, cable winches, fluid muscles or piezo-ceramics. Hydraulics and pneumatics are the choice for high forces, cable systems can carry tensile forces over long distances and piezo ceramics are limited to short strokes but offer extreme precision.

DESIGN_APPLICATION TO ARCHITECTURE

The newly developed methodology is applied to distinct examples of convertible structures. The following studies for actuated form active structures are developed by the author as an application of the discussed systematic of loadbearing behavior correlated with resulting actuation. Some of the studies presented here are inspired by precedence projects; others extrapolate technology from various disciplines. The buckling truss, for instance, transfers technology from excavators [Sclater 2007]. The adaptive vierendeel girder simplifies a proposal for a rapid deployable military bridge developed to carry heavy loads [Burgoyne 1991]. The relocation of the bridge is not discussed here; the focus is rather on a virtual stiffness developed with the responsive suspension, reducing thus the material

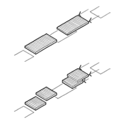
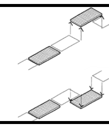
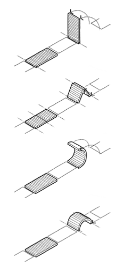
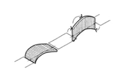
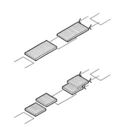
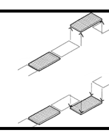
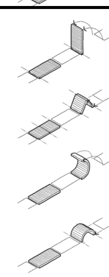
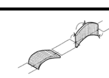
Structural Element	Loadbearing Behavior	Degree of Freedom	Direct Actuation	Indirect Actuation	Technology, Construction	Examples, Application
Bar, Beam (1-d)	Axial Force	Axial Force Release	Linear Drive parallel to Element Axis: hydraulic/pneu matic Cylinder, Thermal Expansion, Smart Materials	Rotational drive with Cable Winch or Threaded Rod ...	Linear Drive, telescopic Element, Truss and Reticulated System with length-active Elements ...	
	Shear	Shear Release	Linear Drive transverse to Element Axis	Trusses with length-active Diagonals	Bar / Beam with alterable transverse Displacement	
	Bending	Moment Release	Rotational Actuator	Lever Arm with Linear Drive, Truss with length-active Elements, Composite Laminates with length active External Layers of Smart Materials	Bar / Beam with variable Bend: Hoisting Device, Moveable Bridges	
	Torsion	Torsional Release	Rotational Drive, Rotation about Element Axis	Live Ring with Rotational Drive, Truss with length-active Diagonals (spiraling movement)	Motors, Mechanisms with alterable Orientation, Live Ring, Tower Crane, Wind Mill ...	
Structural Element	**Loadbearing Behavior**	**Degree of Freedom**	**Direct Actuation**	**Indirect Actuation**	**Technology, Construction**	**Examples, Application**
Shear Wall, Plate (2-d)	Axial Force	Axial Force Release	Linear Drive in Wall Plane: hydraulic, pneumatic Cylinders, Smart Materials	Rotational Drive with Cable Winch, or Threaded Rod ...	Wall / plate Elements with variable Length	
	Shear	Shear Force Release	Linear Drive perpendicular to plate	Trusses with Diagonals of alterable Length	Plate Elements with variable transverse Displacement	
	Bending	Moment Release	Rotational Drive	Folded Plate and Truss Structures with length-active Elements, Composite Laminates, with length-active exterior Layers in Smart Materials	Plate Elements with variable Bend: Convertible Roofs, Adaptive Façades, Moveable Bridges ...	
	Torsion	Torsional Release	Rotational Drive	Truss System with length-active Elements	...	

Table 1: Summary of Loadbearing Principles for one-dimensional and two-dimensional Elements and Actuation Response with Means of Actuation, Technology and Examples/Application [Sill 2005]

needed to resist the dead and live loads. Recent research at the IL Institute of Lightweight Structures, University of Stuttgart is reflecting more in depth on replacing the traditional structural materials devised to provide rigidity with the notion of virtual stiffness in adaptive systems [Sobek 2006].

The lenticular horizontal girder and tapered vertical structure apply a phenomenon observed in nature: Fish can activate their fin ray for propulsion with a minimum set of muscles, thus simplifying actuation and steering [EvoLogics]. The cable stayed mast, the second vertical structure in figure 5, is adopting the familiar pattern of a spine, consisted of vertebrae with rotational articulations, stabilized and activated through pairs of tendons. Experimental precedences are provided with projects at the TU Delft [Oosterhuis 2004] and the MIT [Block 2006]. The latter of the vertical systems in figure 5 is a classical outrigger system, known from the rigging of masts for sailing boats, with the activation inspired by Frei Otto's study for an adaptive crane [Nerdinger 2005].

Early fundamental research has laid the grounds for convertible structures and continues to inspire today [Otto 1972]. Contemporary and practice oriented work has been carried out by the research team of Sergio Pellegrino [dsl 2007]. Pantographic or scissor systems, have been explored among others by Santiago Calatrava [Calatrava 1981], Sanchez and Escrig [Sanchez 2001], and Chuck Hoberman [Hoberman]. These systems offer thrilling dynamic performances; however they seem to be limited to small spans.

The fascination of all these works is their involvement of movement in loadbearing systems. Most of the discussed contributions concentrate on a particular kinetic system and explore it in depth. However the goal of this contribution is to set many different developments in one coherent survey and to draw conclusions beyond the individual precedence and particular application.

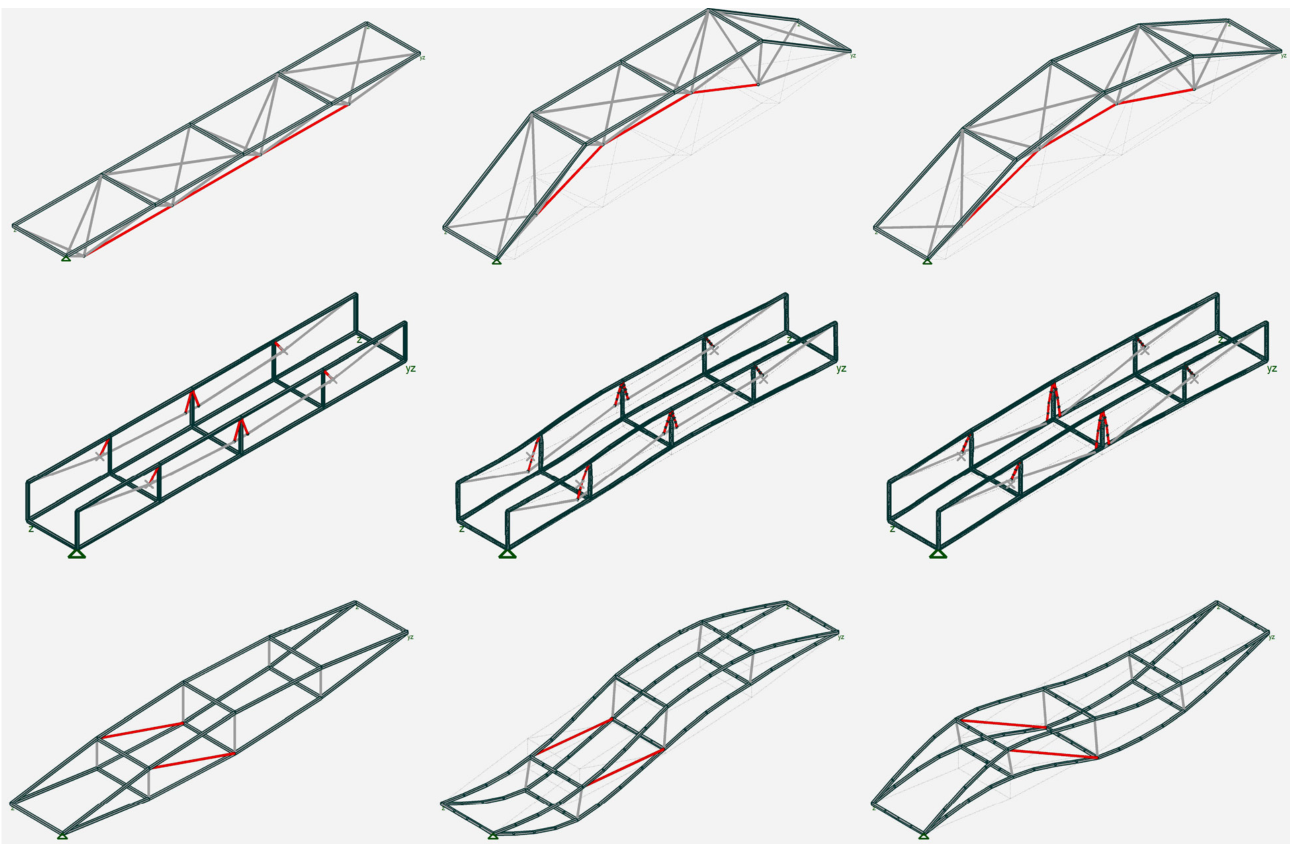


Figure 4. Top: "Buckling" Truss where contraction of the lower chord causes the bridge to "arch its back"; Middle: Vierendeel controlled by suspension cable and actuators to resist excessive deformations [Burgoyne 1991]; Bottom: Lenticular Girder deformed with diagonal linear actuators [Sill 2011], using the FinRay effect [EvoLogics].

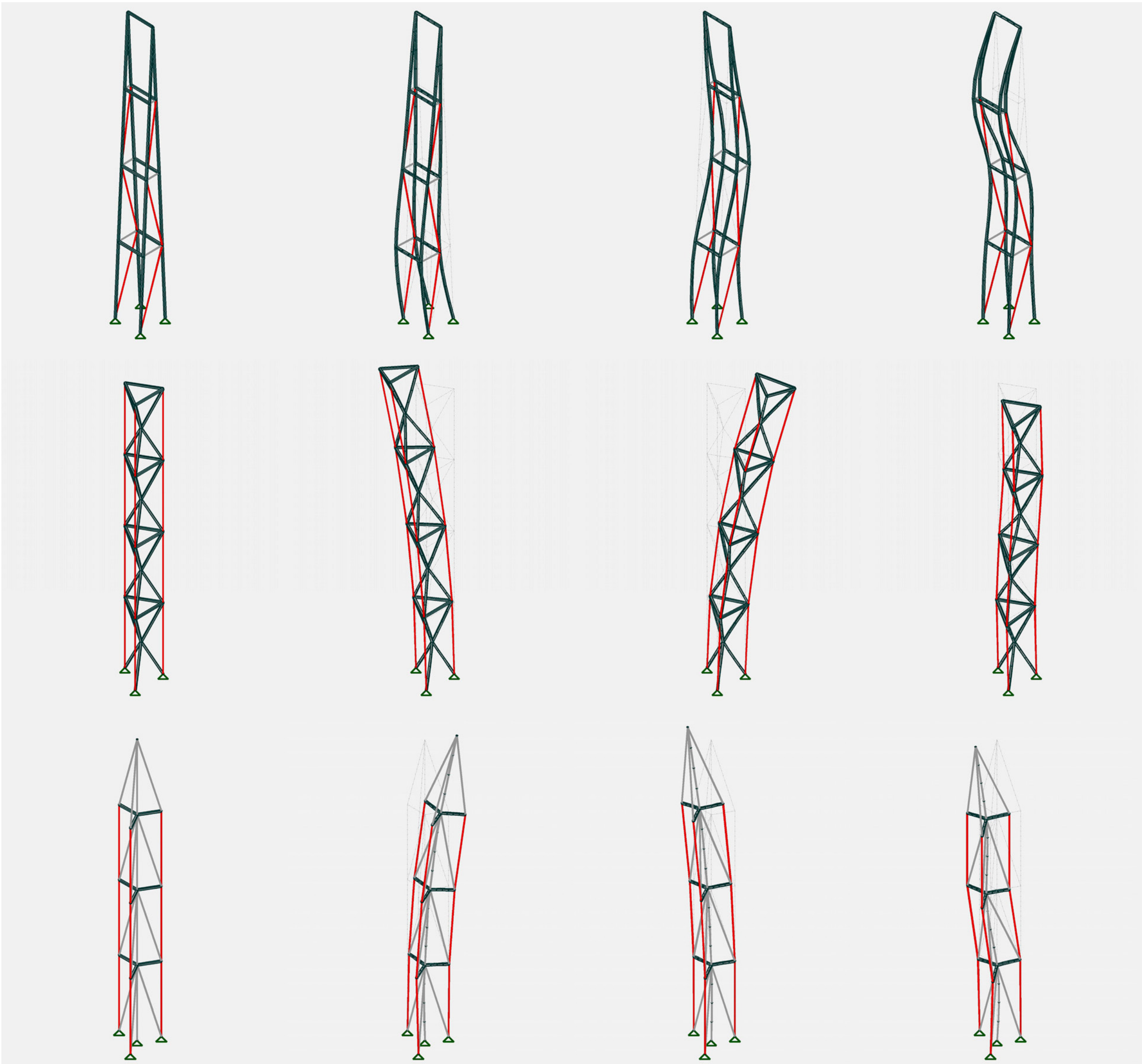


Figure 5. Top: Vertical Structure actuated by linear actuators [Sill 2011], with the Fin Ray pattern [EvoLogics], Form-Active Cable Stayed Mast: active cable stays bend the spine, the tower twists and starts to dance [Sill 2011], Form-Active Outrigger Mast: shortening of the cable stays (entirely or in segments) deforms the mast [Sill 2011], inspired by Frei Otto's project for an adaptive crane [Nerdinger 2005].

CONCLUSION AND OUTLOOK

With the new approach for classification and design development of the discussed kinetic reticulated frameworks, a new vocabulary for kinetic architecture could be introduced, expanding the established range of static buildings with adaptive, convertible and kinetic architectural systems.

The comprehensive survey for loadbearing principles in architecture structures and linking this to a comprehensive development for kinetic structures offers advantages for the design of such systems. The goals, conditions, governing parameter are clearly exposed and better accessible for creative architects, who a priori don't have the relevant knowledge and methods available that these systems require: structural and mechanical engineering, dynamics, computing and controlling.

The next steps in this research will develop further kinetic solutions with reductions of the degrees of freedom to generate functional variability with a reliable performance and reasonable durability. The proposed studies offer opportunities for detailing, examination of their structural and kinetic behavior, and investigation of their performance and robustness. Furthermore the studies are optimized with respect to applications to architecture and building industry.

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