Adaptable Structural Surfaces

by

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In Architecture Studies

ABSTRACT

The framework for this thesis are the lightweight constructions that have been developed during the 20th century. As part of this thesis, a prototype for a column has been developed, that is a hybrid construction out of a lattice and surface structure. It follows the principle of adaptability instead of rigidity through taking advantage of the distributive qualities of weaker materials. Through this development as well as through the study of the history of lightweight structures, a set of principles has been developed that can serve as the basis to a different approach to structures. This approach deals with questions of how structures can support architectural ideas without becoming the center of focus themselves, how structures can be applied in a topical way in today’s postindustrial situation, and how architects can deal with a special field within architecture and how their way of working can be complimentary to engineers’ and scientists’ way of working.

Thesis Supervisor: John E. Fernandez
Title: Assistant Professor of Building Technology
Robert Le Ricolais, structural engineer, 1894 - 1977, essential contributions to the field of lightweight structures, especially on space frames. Worked at the University of Pennsylvania. His main technique was to build structural models and then to test them physically. His work did not have any indication of scale, nor did he try (with some exceptions) to translate the structures directly into architecture.
a maison le ricola | axonometric view
plan rooftop 1/100
acknowledgements

this work is dedicated to my parents
for giving me a horizon and confidence

and it is dedicated to Janet
for enlargening this horizon

I would like to thank Laura Harper, Lydia Kallipoliti, Axel Kilian, and all other students at MIT who helped and supported me during this work.
for advice on the technical level I would like to thank Professor Lorna Gibson and Professor John Ochsendorf.
for her helpful and constructive critique I would like to thank my reader Professor Ann Pendleton-Jullian.
for the financial and organizational support I would like to thank my advisor Professor John Fernandez.
for the access to the archive and their willing support I would like to thank the staff from the archives of the University of Pennsylvania

I am greatly indebted to Georgi Petrov for his contributions in form of critique, suggestions and concrete work. This thesis could not have been done without him.

This work is rather looking for a dialogue than providing the correct answers to set questions. It is an attempt to create a basis for collaboration between architects, engineers and scientists. Any critique and comment in this spirit, sent to hmf@alum.mit.edu, will be appreciated and answered. But do not try to prove that Le Ricolais is dead already.
one enters the house directly through the workshop. the workshop is situated on the first and the second floor. in the workshop are the machines for load testing and the tools for building structural models in steel and wood.
The main structural model in the workshop is a column which is woven out of flat strips of metal. At each intersection, the strips are held together with rivets, which allow rotation on the surface of the column relative to the other stripe, but give a force transferring connection between the broad sides of the strips. Interior cables link opposing nodes, thus keeping the column from expanding under load. At the base and the top the strips are connected to wooden plates that transfer external loads into the column.

Standard detail of one of the tested columns

All columns (nr.1 to nr.14) that have been tested
There are some basic geometrical rules that are constant in all columns: the strips are continuous from the top to the bottom of the column. The angle of the strips is along with the number of strips responsible for the density of the weave. The strips are twisted around their own axis and describe with their broad side the form of a cylinder. Untwisted, each stripe forms a large arch which is determined by the radius of the column and the angle of the stripe against the vertical. Each stripe is being held in its position in each node through a multiple equilibrium out of antidromic stripes and interior cables.

The field length is the length of a strip between two intersections. This length is in the initial model the defining buckling length.

When the field length in one column is being changed, the straight overall shape of the column changes to concave or convex and the axis of each stripe’s section does not point to the center of the column any more. This also causes additional tension within the surface which can make the column stronger. But this possibility has not been subject to further research. In the research which has been done in this case, the final field of concentration is the straight column.

A test series with 13 columns has been done. The tested columns are identical in height (about 100 centimeter), and in radius (about 6 centimeter) as well as in the properties of the strips, but are different in the density of the weave and therefore the field length, in the overall shape (straight/ concave/ convex) and in the properties and links of the internal cables. The load bearing capacity varied widely between 150 and 400 Newton.

The behavior under load up to failure can be described as following:

optimally, the radius of the column expands under the initial load relatively regularly over the entire height of the column, until the maximal load is being reached. Yet already on the second image one can detect the element which will fail first, where two nodes on one level move parallely to one side instead of establishing an equilibrium of forces in opposite directions.

the level of these nodes is weaker from the beginning and the
stress on the other nodes by a certain degree higher. When the stress transcends a certain point the other nodes on this level start to move horizontally as well and the entire level gradually collapses. There is a slight recovery (see the graph on p. 41), when two strips being pulled inside, meet, and establish an equilibrium for a short moment which can take some pressure before it gives in. Other levels adjacent to the collapsed one follow. In most cases the failure appears locally.

The load to displacement diagram, which displays the behavior of all columns in the load testing, shows the high initial vertical displacement before the columns reach their strongest point. The displacement is up to 20 mm, which is about 2% of the overall height. After reaching the strongest point, the graphs do not fall rapidly towards zero, but drop relatively slowly. This
the model and the testing

<table>
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<tr>
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<th>Height (mm)</th>
<th>Number of Strips</th>
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<th>Total Length</th>
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means that the columns do not experience a sudden failure but have a rather smooth transition from one state to the next. The following graphs show the relation between the load, the vertical displacement of the column and the angle of the stripes. The parameters which are being compared in these graphs are load to angle, load over deflection to angle, load to field length, load over deflection to field length, and load to displacement. The graph with load and angle as parameters does not have a maximum within the tested range, yet it shows substantial improvement between 15° and 25°, between 25° and 30° the increase is not that big any more.
the model and the testing cables

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<th>Tra</th>
<th>BIC [mN/m]</th>
<th>λ [N/N]</th>
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<th>shape</th>
<th>cables</th>
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The load/deflection – angle graph reaches an inflexion point at ~ 22° and stays at the same level as the angle rises. The maximum load – field length graph shows a constant drop as the field length increases. Parallel to the load/deflection – angle diagram, the load/deflection – field length diagram has an inflexion point at 130 mm, after which the load/deflection ratio is falling faster as the field length rises.

At this point it is clear that changing the overall shape of the column is not yet a relevant question and complicates matters more than it clarifies. The geometry of the column is like a rigid
the model and the testing

Load tests 1 & 2: relation between load and angle

Load tests 1 & 2: relation between load and field length

Surface pattern twisted to a cylinder. The addition of one basic element forms an overall shape. The departure is clearly from the basic unit, in this case the rhomboid consisting out of four different strips, which has to be optimized before it can be multiplied. The third series of tests was developed to deal with the basic unit.

The number of variables and parameters, which come up in testing, is being reduced to only one segment of the entire column. Yet there is an inherent contradiction in reducing a continuous or highly interacting system to one segment, still the test of a separated segment has its validity as long as one is aware that this is not the operational mode of the smallest entity of the column but a tool to specify more the different parts of the column. It is clear that the column is built up completely on the interaction between its members and relies on the synergetic effects emerging out of this. The second important point about
the model and the testing

load tests 1 & 2: relation between load, deflection and angle

load tests 1 & 2: relation between load, deflection and field length

this is the change of the edge condition. Le Ricolais describes a pattern as consisting of the field and the edge. The conditions on the edge are different from the conditions in the field, and the edge condition can have an impact on the entire field. This can be seen very clearly on the example of the reduction of the column to one segment: the buckling behavior is changed because of the different condition of the nodes - all nodes are precisely defined on their level and do not have any degree of freedom in relation to each other.

The central question from the first tests is: how does the conversion of a purely axial load into a combination of axial load and bending effect affect the strength of the column? This test series gives two central pieces of information about angle and material of the strips. The fourteen tested columns have strips with angles from 15 to 45 degree. The test columns with
The model and the testing

Single segment columns made out of low carbon steel, basswood and plywood strips, precise description next page.

An angle bigger than 30 degrees show a big displacement before reaching their strongest point – the elements fail slowly, the transition from functioning to broken is smooth, the element behaves almost like a spring in one direction. The test showed that one increases the angle from vertical there is an improvement in strength until about 20 degrees. At angles bigger than 20 degrees, the elements lose strength. As far as the materials are concerned, the result shows the strength of the plywood. The other wood type in the test, basswood, reached the limits of its capacity very early, but plywood (1.6mm in triple layer airplane birch, cut along the grain of the two exterior layers) is strong and brittle enough to develop enough lateral resistance for a strong twisted column.
the model and the testing

When assessed in terms of efficiency (strength/weight) the results are even better. The importance of the moment of inertia (I), which is mainly defined through the thin side of the section, is clear when looking at column segment n. 7 and n. 10, where n. 10 has the double thickness of n. 7 but takes nearly five times the load of n. 7. This shows that the moment of inertia (I) is more important than the strength of the material, expressed through the high Young’s modulus. The steel has a Young’s modulus of about 180 000 N/mm², which is about twenty times higher than the Young’s modulus of ply wood (8000 N/mm²), and is still weaker than the wood. The important requirement here is the material’s resistance against bending.

One aspect which became clear during the testing is the relevance of the performance of the nodes for this system. The relationship between the basic element and the overall column is being decided mainly through the nodes. The hypothesis is that the number of basic elements, the number of nodes can increase the strength. This would mean that a higher or a wider column with the same density is stronger than a small one.

<table>
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<th>no.</th>
<th>material</th>
<th>section [mm]</th>
<th>angle</th>
<th>height from node to node [cm]</th>
<th>weight [kg]</th>
<th>height column/length stripes [m]</th>
<th>max load [N]</th>
<th>deflection under max load [cm]</th>
<th>node</th>
<th>load/weight</th>
<th>load x height col</th>
<th>BIC (load x col/height²)</th>
<th>Young’s modulus [N/mm²]</th>
<th>(bn/3t12) [cm⁴]</th>
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the model and the testing

Load/Deflection v.s Angle

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</tr>
<tr>
<td>1600</td>
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<tr>
<td>1200</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
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<table>
<thead>
<tr>
<th>Angle</th>
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</thead>
<tbody>
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</tr>
<tr>
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<tr>
<td>45</td>
</tr>
<tr>
<td>50</td>
</tr>
</tbody>
</table>

since it has more nodes to distribute the loads. The hypothesis goes on for the column growing in height, that this increase in strength is limited through the buckling behavior of the entire column - if there was an ideal interaction between the members through the nodes, the column would work as a whole and also fail as a whole.

It also means that there are some aspects which can be optimized to one point under a strict set of parameter; this is where the “interests” of the overall shape are opposite to the “interests” of the basic element. One example for this is the radius - for the single element it is better to have a small radius since the bending is stronger, for the entire column it is better to have a wide radius to prevent from buckling.

What these tests show apart from all information, is that there is still a very high degree of imprecision in the models. It would

Max Load vs. Angle

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<th>Max Load (lb) (related to height)</th>
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<table>
<thead>
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<tr>
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<td>45</td>
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<tr>
<td>50</td>
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</tbody>
</table>
be necessary to have proof test in order to eliminate a bit the imprecision of model building. Buckling starts at the weakest element, which is the one that has been made with the least precision. It would be necessary to make another series of tests to prove right these two theories.

Besides this proof the next step in this unfinished research would be to show that this type of column behaves for a certain length not following the natural principle of weight to strength ratio (which would mean that it gets weaker with increasing height), but to the contrary, that it becomes stronger with increasing height.
le ricolais’ house is devised as a monofunctional solid, where the empty spaces and additional functions behave like the figure on the ground of the house. they are taken out of the solid of the house and rely structurally and programatically on the solid. the solid is not actually solid but has a high mass of structure and filling and an inverted ratio of solid to hollow. in terms of program the solid part of the building is the archive and the library, and plays the role of an omnipresent active memory.

stacks
In the bottom part of the building, the stacks are filled with objets trouves from nature, different kinds of shell and bone structures, comparative studies between elements of different sizes. The other group of objects clearly belongs to the field of geometry, all kinds of different polyedra, as well as spheres with geodesic lines, spheres with surfaces divided in rectangles, or triangles, or approximated to polyedra, just the same way Buckminster Fuller worked with the icosahedron as the closest approximation to the sphere and developed the system of geodesic lines on the surface of a sphere. Next to the platonic solids are books about the relationship between mathematics and form, and books on mathematicians who deconstructed the notion of cartesian/Euclidian space, like Gaspard Monge, who has developed the laws of orthographic projection, and understood form as the boundary of a three dimensional body, which did not have any internal relevance; Karl Friedrich Gauss, for who form was a purely mathematic entity with “intrinsic properties”. Through “specification and comparison of certain relationships”, mathematics could be used for issues of form finding. He claimed that it could not be proven that two parallel lines do not meet; and some books on Riemann and his concept of the topology of surfaces, both the Gauss and the Riemann books in a very worn state. Another book by Lord Kelvin, for who form is “the homogeneous partition of space” - Le Ricolais considers this to be the most important contribution to geometry since Platon’s five solids.¹
Geometry is based on mathematics, and the geometry that can be derived from nature is the geometry that breaks the cartesian ideals of the grid. Nature serves as the creator of new shapes, as provider of new ideas, and in the end, based on structural reasoning, as the legitimation behind the form.

Frei Otto worked on the direct translation of natural phenomena into architecture. His examples of minimal surfaces, developed through soap bubble models, double curved surface structures, developed from reticular structures, and tent structures suggest a new formal language with a strong structural reasoning. His architecture is purely form not texture, it is the scaling of natural phenomena into an architectural scale based on the understanding of the flow of forces. One can understand his holistic approach, when he describes galaxies and luminaries as optimal structures, when he describes the development of life on earth as a matter of structures and energy, when he declares his structural thinking to be an abstract system based approach valid for different systems of structure and infrastructure.

The roots to this lie in the scientific analysis of nature’s principles and manifestations, rooted the 19th century. The first cross linkings between different sciences take place, for example the analysis of a bone under anatomical, mathematical, physiological and structural aspects. D’Arcy Thompson’s book “On Growth and Form” is probably the best known among architects and highly relevant to the understanding of the mathematical relationship between absolute sizes and forces. One of the most important findings about structures in nature is the existence of absolute sizes, of the fact that not everything is defined through its relative relationship to another thing but has an absolute value which is defined through its volume, surface, weight and strength.

D’Arcy Thompson used his engineering knowledge to provide an analysis of biological phenomena. He constructs the image of natural beings reacting constructively to (physical) conditions in their environment.

Frei Otto translates the findings on absolute sizes and on scaling into structural thinking through the introduction of relative slenderness and the efficiency of structures (BIC). Weight, size and strength as well as between volume and skin are related to each other but depending on different scaling factors. Frei Otto’s studies of how to assess lightweight structures, namely the relative slenderness and the BIC, deal with these questions.
BIC

BIC: \( m/ Fs \ [g/Nm] \)

relative slenderness: \( \lambda = s/F^{1/2} \)

for elements under bending or compressive forces, the BIC increases rapidly when the relative slenderness increases. Under tension, the length does not play an important role. The BIC diagram in combination with the relative slenderness are an easy method for the assessment of different structures. Only constructions within the same \( \lambda \)-range can be compared to each other. With the increase of \( \lambda \), the BIC rises as well. Objects with a small BIC have a bigger maximal size than objects with a big BIC. BIC and maximal size are (with most forms) in a

BIC diagram with the red dots indicating the values of the tested columns in Le Ricolais' workshop. The green field indicates the area of the relative slenderness of the tested columns.
reciprocal relation. Dead load becomes the limit load leading to self destruction or at least form change.

BIC and maximal size are (for most shapes) conjugates. In case the maximal size is being reached, dead load becomes the limit load, leading to self destruction or at least change of the shape. Therefore structural models, like the one being tested, have only limited validity in giving information about the strength of a structural system, since aspects which can be hidden well at the small scale can prove to be crucial at a habitable scale. The relationship between size, weight and strength is by square and cube. If \( n \) is the factor for changing the size, the strength of the element increases by the square but the weight increases by the cube. This means that the process of scaling also can mean a change of material or a change of the construction type, and definitively has to mean an improvement of the size/weight ratio. Here Le Ricolais' saying becomes clear, when he calls structures "the art of putting holes" - structural engineering has much to do with taking away the material from where it is not necessary.

The other aspect where the ratio changes with the absolute values is the volume/skin ratio. With a growing body, the surface becomes smaller and smaller:

- size goes \( n \)
- skin goes \( n^2 \)
- volume goes \( n^3 \).
the space of the terrace is half taken out of the
house, half on the roof of the box which is
cantilevering out.
The third test series with the single segment hints at the relationship between the material properties and the construction and poses the question to what degree the construction and to what degree the material has impact on the efficiency of the structure. As one could see from the results of the tests, the construction has in the given case a higher impact than the material properties, which are, in case of bending and buckling, expressed through Young’s modulus. A higher moment of inertia, reached either through the shape of the section or the thickness of the material is more efficient than an improvement of Young’s modulus.

The mathematical reasoning behind:

\[ S = \text{Stiffness} \]
\[ \delta = \text{sag} \]
\[ \rho = \text{density} \]
\[ E = \text{Young's modulus} \]
\[ P = \text{force} \]
\[ t = \text{sidelength of the section} \]

stiffness \( S = \frac{P}{\delta} \)

\[ \delta = \frac{P t^4}{48 E I} \]

for a square section with side length \( t \):

\[ \frac{P t^4}{E t^4} \Rightarrow t^4 = \frac{P t^4}{E \delta} = \frac{S t^4}{E} \]
\[ M = \rho t^4 \] with \( \rho \) being the density

\[ M = \rho \left( \frac{S t^4}{E} \right)^{1/2} \]
\[ M = \rho E^{1/2} (S t^4)^{1/2} \]

With \( \rho E^{1/2} \) being the material properties and \( (S t^4)^{1/2} \) the stiffness due to the section.

The relevant material property for bending and buckling is defined as \( E^{1/2}/\rho \) (stiffness over density). A low density has the square impact of a high Young’s modulus.

Material and assembly/arrangement are the two features which make construction. Each material has its inherent properties, and each construction favors different properties, or make even distinctions in the different dimensions: a high Young’s modulus of steel does not help for the column, a material with a lower density but higher brittleness (like plywood) is better.
the house has been built completely out of wood, the furniture being part of the construction, with big thin sheets of wood in one direction, carved out wherever necessary, leaving the circulation to pass through perpendicularly.

**main structural elements of the house, solid and carved out**
All lightweight structures are about finding the ideal line between strong and light. There are two possible approaches for dissolving a solid piece of structure with an unidentified flow of forces into a filigrane construction: one is based on the surface action and one based on the beam action. The surface works with either single or double curvature, repetitive or in one big shape, and can be additionally reinforced through ribs (sandwich) or a second layer (laminate). In every case, the surface creates an inside outside boundary. In a way, the surface can be understood as the perfect example of Le Ricolais’ “art of putting holes”, when one imagines the hollow tube - all mass is concentrated as far away from the neutral axis as possible, where it has the biggest efficiency, and there is no additional weight in the body - the space is being completely defined through a structural surface. The fathers of the thin (metal) sheets in architecture are Hugo Junkers and Jean Prouve, and it is no incident that Junkers was one of the great pioneers of aerospace: the references to the early airplanes, cars and trains, which were developing aerodynamic shapes during the 20th century, are obvious. These aerodynamics are being expressed through the smooth skin and the fish and bird metaphors in form. The surface thinking has produced the sandwich and monocoque systems, but also, as a result of Frei Otto’s studies, all surface structures which are in tension.

For Frei Otto, surface structures can be classified after the following principles:
- dimensions
- surface structure and texture
- edges, highpoints and lowpoints
- synclastic or anticlastic shape
- character of load (one/ twodirectional, tension/ compression/ bending)
- character of support
- pneumatic constructions.
lightweight structures - definition

The always three dimensional lattice does not create an inside - outside condition but the necessary “structural space” is being defined along its edges and divided regularly through cross links and diagonals. The lattice is based on a pattern, on geometry. Maybe one can assign the surface action to the technical development of aerospace and car manufacturing, and the beam action, expressed in lattice, to natural phenomena. Lattices have the bigger flexibility, in terms of use, construction, repair, and are isotropic, whereas the surfaces has a very distinct section and creates formally and spatially clear conditions. The lattice has nodes, and due to the nodes it can be altered. Both systems have in common, that they exclude bending forces as much as possible. The lattice takes loads only on the nodes, and the surface works like an addition of small domes.

A subtype of the surface that has recently generated major excitement in architecture, is the weave, a kind of weak surface with a certain embedded adaptability, no lateral stiffness, but a high redundancy. The weave incorporates the promise of ephemeral, very body related architecture, but since it basically behaves like a weak surface with bad shear behavior in certain directions, it is more used rather as a metaphor for the use of a high number of weak elements than as a real construction concept.

The column type which has been tested earlier in the workshop is a hybrid of a lattice structure combined with a curved surface, put together in a woven arrangement. It can be understood as a dissolved curved surface, having a composition like a weave but distinct properties in the section of the basic element.

Joerg Schlaich describes the main characteristics of lightweight structures in the book “L’art de l’ingénieur” to be the replacement of physical effort through intellectual effort. He calls them ecologically valid structures, since they use the material in the best economical way, can be taken down and reused. But not only are they ecologically valid, but socially as well, since they create work, intellectual work as well as manufacturing work. Unfortunately this is the reason which makes them so expensive in our economical system. Their elitist appearance is actually very different from the democratic mindset of its developers in the beginning of this century, like Fuller, Choukhov and Otto.
The library houses a collection of broken columns, which have lost their full ability to carry loads due to the testing. Le Ricolais understands them as equally instructive as the process of building them. Seeing the potential of failure, he talks about the beauty of failure. He refuses to make the distinction between functioning and broken and rather tries to see the potential of failure, seeing failure as a process still within the life of the structural element. The gradual failure of the column goes through various stages, and sometimes the column regains some of its strength in new configurations. The different kinds of failures can be revealing for the behavior of the columns - there is local failure against the overall failure, as well as there is gradual failure against immediate failure.

Le Ricolais accepts failure as a process itself leading to different configurations and through different stages. To the left the graph of Column 5 shows an impressive recovery when two members in the process of horizontal displacement meet and form a new equilibrium.

Another example from Le Ricolais' earlier studies can be seen on the left, where the strength of the construction has been achieved only after partial failure of the members.
Buckling is the main reason for failure under axial load due to excentricity. The bigger the force the smaller the excentricity can be, the more sudden the buckling will take place. It has to be understood as an uncontrolled horizontal force. Any failure can be sudden or gradual. The gradual failure makes it harder to distinct when the real state of failure has been reached. When the element has a certain degree of elasticity, the process still can be reversed before reaching the stress-strain limit. The elasticity can be embedded either in the material or in the construction. If it is embedded in the construction, it is helpful to understand the system rather as a mechanism than as a rigid system.

The dissolution of a structure in two components is a way to delay the buckling without making a heavy rigid system. One component, which is stronger and more brittle, is responsible for the pure vertical load transfer. The second component, which works as a surface and has a certain degree of adaptability, has the function to keep the load transferring element in place. The problem is now to define the buckling direction of the first component.

The analysis of the failure modes of the column makes it clear that through the positioning of the wood in the right angle and with a strong enough horizontal – which means centrifugal – component, the compressed element on its entire length could be held in position. The top example shows, although no numbers are available, a fascinating strength even though just a pantyhose nylon was applied.

The bottom example, from Ricolais’ earlier work, uses the component which works as a surface, for the load transfer and the metal cable structure as the pretension - holding the resin in place.

Le Ricolais says that structural engineering is always an idealization of a problem, like the problem of the anisotropy of materials: there is hardly anything really straight under compression. The fact that engineers deal with the elements as if they were straight gives the idea that they are disregarding an aspect which might prove fruitful.

Yet when it is being admitted that there is hardly anything straight, then when is the precise point of buckling?
The question of equilibrium is highly important for the design of lightweight constructions. The character of the equilibrium determines the degree to which the environment can have impact on the construction. The difference between rigid and adaptable systems lies in the nature of its equilibria: Nature has weak equilibria, which need less material since they can absorb certain tensions through giving in. There are two parameters for the assessment of equilibria – fragile and safe, and weak and strong. The first opposition relates to the tolerance the system has, or the relative strength compared to the forces in the environment. The fragile equilibrium can be easily broken and cannot be reconfigured. If the forces in the equilibrium are very high but do not have much tolerance, the equilibrium is fragile. If the tolerance is high, the equilibrium is stable. If the tolerance is low but the forces in the equilibrium as well, then the equilibrium is weak, even though it might have the ability to regain this state, as can be found in nature.

An equilibrium basically gets stronger the more directions or dimensions it covers: the more directions a load is being transferred in, the less material is necessary. Le Ricolais’ space structures, in which he departed from the basic elements, are an example for this efficiency through multiple directions (trihex structures).

Pretension is a way to establish such a strong equilibrium in a system, that the outside forces are negligible in comparison to these forces. It is the exclusion of all but one load case. This possibly very elegant system is being ascribed to the French engineer Freyssinet, who developed the system of pretension in concrete constructions, such as bridges and tubes, and hangars: “Freyssinet replaced mass through force.”

Its potential can be understood on the difference between the models on the left - one has excluded the loadcase of axial load on the tambour through using a pretension force that is bigger than the axial load can possibly become. Therefore the vertical members can be purely tensile, in contrast to the example below.

weak equilibrium, highly influential from the environment

Alexander Calder’s mobile sculptures

two models from Le Ricolais’ earlier studies - pretension

fragile stable neutral
different cases of equilibrium
The tested columns also display a system of equilibrina on different levels, all of which rely on the round plan of the column: the equilibrium between opposing nodes, the equilibrium between intersecting stripes, the equilibrium between adjacent fields. These relatively weak, not fragile equilibria are supposed to act together in a way that it makes a strong overall system.

The idea of fabrics in architecture is not new at all, yet it does not seem to have produced anything much beyond the tent and the curtain. The weakness against any lateral load or any kind of dynamic load and the missing strength against shear are the main reasons. It cannot be used on horizontal surfaces since there would be no resistance against vertical forces; the horizontal pretension has to be huge in order to secure it against dynamic forces that might put the fabric into vibration. Yet in vertical and roof surfaces, fabrics are already being used. This model here bases on the idea of "prebuckling". Buckling as the uncontrolled horizontal force. The bending of the material is an attempt to make it controllable through defining the direction in which it will buckle as well as through making it gradual rather than immediate.

The approach is to dissolve everything into tensile equilibrina knowing that it will not be enough, and then just add the rigidity where is being required. Classical dome structure has the material directly in the neutral line. In terms of systems thinking this structure can be optimized only to a certain point but has the danger of buckling through inherent imprecisions always embedded in the system. The pre-buckled example requires a thin and broad section in order to have adaptability in one direction and at the same time lateral stiffness.
The difference about prebuckling to a simply additionally braced beam/column is that the prebuckled construction has already entered the buckling phase and thus is determined in which direction it will fail. A simple bracing would just delay the buckling but would not work as a tool to define the buckling direction.

The column with the pantyhose wrapping works the same way - the load bearing members have to be already in the state of buckling, so that it cannot change its buckling direction any more. The necessary precaution in this situation is to absorb the big horizontal forces.

It is Le Ricolais' goal to replace shells with membranes. The prebuckled constructions might be a way.
the vertical element is more important than the horizontal elements. There is an overdensity of the vertical elements. In the rectangular array of stacks and decks the stairs in free module based arrangement are bracing the house.

stairs

$h = 225\text{ cm}$

$h = 75\text{ cm}$

$h = 150\text{ cm}$
This model is not only based on the idea of pre-buckling and the definition of the direction of failure, but it is also what Le Ricolaïs would call composite thinking. It is the principle of composite materials applied to a bigger scale. The two component system works with two materials with distinct properties which are in a complementary relationship. What fiber and resin is on the material level, is fabric and metal stripes on the building element level. One material is responsible for the distribution of forces and tensions and the other one takes up the compressive forces. One is light, adaptable and can only take up tension, the other one has a high density, high Young’s modulus and therefore a bad buckling behavior. Pretension can secure the construction against lateral and dynamic forces.

These models are the result from the load tests that have been done in the workshop. They are built as arrested mechanical systems with continuous elements from top to bottom which could in theory be deployed in two directions, either to complete torsion (long and thin) or to complete one-directional curvature.

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<td>0.73 g/cm³</td>
</tr>
<tr>
<td>Weight strips</td>
<td>382 g</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>180</td>
</tr>
<tr>
<td>Cable length</td>
<td>ca. 1500</td>
</tr>
<tr>
<td>Angle of strips</td>
<td>25°</td>
</tr>
<tr>
<td>Height overall</td>
<td>200 cm</td>
</tr>
</tbody>
</table>
The column with the cables consists out of two layers, which are interconnected through nodes. Both layers work in a distributive way. The wooden rhomboid pattern is assembled out of optimized basic elements, based on the findings from the load tests. The material being used for this layer is aircraft three layered laminated birch wood, 1/16 inch thick. It is cut along the grain of the two outer layers and against the grain of the interior layer. The section is ½ by 1/16 inches.

The interior layer consists out of six cables which run parallel along a helix line from top to bottom. They are not interconnected between each other but they are linked via pulleys on every node to the outer structure. The angle of the cables has been chosen in a way that when the column expands under load, the cables are being put in tension. These tensions and strains between the elements are being distributed via the cables at an approximated equal rate to all nodes. Thus, the first measure against buckling is not the stiffening of the basic element, but the securing of the equal and quick distribution of forces. The basic element, which is the wooden stripe between two nodes, is being kept so small through the introduction of an additional node and stiffened through the twisting around its own axis, that the buckling load of the entire construction lies close to the buckling load of the basic element multiplied by the number of stripes.

The edge condition is still a problem - even though it is just a plywood ring, it is perpendicular to the flow of forces (which means that it reacts directly to the forces without any delay) and therefore belonging to a different type of construction. It confronts the gradual load transfer, bracing and locking with an immediate bracing system without redundancy. The stresses in the edge members are therefore higher than in the central members.

The second type of column corresponds to the earlier presented type of “composite thinking” - the combination of a brittle load bearing material with a defined buckling direction, and a continuous layer of fabric which holds the compressed members in place. The elasticity of the sheet defines the degree to which forces are being distributed from one element to the other. Both types should be put under pretension from inside or through deadload, since the degree of pretension defines their strength to resist lateral impact.
The word “adaptable” has to be introduced in contrast to rigid and kinetic. The difference to rigid is that it can react to forces and can change slightly its geometry. This will be explained more thoroughly later. The difference to kinetics is, that it only could move and change its state, but it has a second layer which keeps it from being kinetic - it has one defined state.

in German, the word for ‘structures’ is ‘Statik’ – the non-moveable. Even though the word means all structures related to building, it clearly shows how the structural thinking is restricted to the rigid constructions. In contrast to this, the word ‘structures’ describes a much wider field, which can also include structures with a degree of adaptability, be they kinetic or just adaptable in the sense of the columns presented here.

The comparison between the two columns in Ricolais’ house shall make clear the basic differences between the two systems. This comparison can serve only as an initial thought - a close inspection already makes the boundaries between the two systems blur.

the rigid system:
redundant (statically overdefined)
the basic element has to withstand the maximum possible impact without being able to transfer moments to the adjacent elements.
The material has to have high qualities and only little irregularities. Basically, the rigid system needs more material than the adaptable system, since it has to calculate any additional stresses that can come up through the dynamic behavior of the elements.
When the rigid systems reaches a critical size, it has to embed dilatation systems, which prevent the unwanted forces to accumulate to a degree where they can threaten the performance difficult to calculate the stresses in the material, since the material is dynamic and imperfect
hierarchical system
defined on a geometrical level

the adaptable system:
easily to be put in vibrations and low resistance against lateral impact, unless additional measures are being taken – like pretension
cannot to be used as a surface with dynamic loads – like a floor statically determined
Adaptable and rigid systems require less material and can cope with imperfections in the material, like anisotropic behavior. The system can compensate these irregularities.

The wrong way of optimization can make it rigid – if it loses its adaptability through materials which are too thick. The emphasis shifts from the element to the node, since the node is responsible for the equal distribution of the stresses to all elements. The optimization has to take place on the level of the entire system, the distribution has to be optimized - not so much the single element but the node.

The adaptable system is suitable for imperfect, non-homogeneous - cheap - materials. Yet it has to be carefully assembled, and the relationship between the basic unit and the overall structure has to be clearly defined. Adaptable systems are non-hierarchical systems, consisting out of an array of one basic configuration. The design starts with the basic configuration. After optimizing this one, it can be added until the overall buckling comes into play. But the development of size over weight and strength is different since the basic element does not need being scaled up.

The adaptable system is like a mechanical system, where the change of one element can change the entire geometry of the system.

Within this process of scaling, the necessity to change the basic unit within the bigger array can come up or basic changes on the entire concept can become necessary. One example for this is the big column, where the number of nodes and intersections grows to such an extent, that the friction of the pantographs becomes a defining force which keeps the column from equally expanding, and also the weight of the nodes exceeds the weight of the strips. Therefore the next step to think would be if the diagonal cables could not be replaced through horizontal springs with a progressive spring constant, which could be a system of distribution without cables and pulleys. The other way of thinking would be to replace the cables inside with an adaptable surface outside, which wraps around the column and does not need any nodes.

In contrast to the rigid construction, which is defined through geometry, distances and angles, the adaptable system is defined on a topological level (nodes more important than actual sizes and angles).

Since the optimization process for both systems is different, the result in the end can be different as well. In the example of the column, the rigid column has to be the thickest at the center, where it is at the biggest distance from the nodes, since only the
buckling position and axis can be determined but not the
direction, the column has to be secured in both/all directions
equally. The process of optimization of an adaptable system
starts from the basic element and then reaches only via addition
and scaling the overall shape. In the case of the column, the
center is actually the thinnest since this geometry makes the
shortest field lengths happen at the point where the uncontrolled
horizontal forces are the biggest.
In the same way, the adaptable system cannot be reinforced nor
braced like a rigid system, since every element has to keep the
gradual indirect character. Any direct or immediate force within
the structure makes the adjacent weak elements collapse.
The scaling behavior of the adaptable systems is different from
rigid systems. Whereas with a few elements, the strength of the
column increases since it has more nodes to distribute the
stresses over, the rigid column is being defined purely by its
buckling behavior.
Another feature to research would be the BIC of the adaptable
column in the process of scaling. The hypothesis after this
research is that the BIC does not increase at the same rate as the
size does. First, the skin should not have to scale precisely to
the degree the entire construction does, especially not in
thickness. Second, the distributive qualities of the interior cable
should improve within a bigger system, since the number of
nodes to distribute the loads to is increasing.
Scaling and slenderness: in the column, does the basic element
want to have the same properties, proportionally like the overall
column in terms of slenderness? Relative slenderness \( \lambda = s/F^{1/2} \).
With \( s = 100 \) cm and \( F = 400 \) N, the slenderness is \( \lambda = 5 \). In
case of 8 strips and the same slenderness, the required length
would be 25 cm.

In the adaptable structures the relationship between the single
element and the entire column is very important. The
parameters for the overall can be contradicting for the basic and
overall – the radius for example. A big radius of the column is
good for the overall performance against buckling, yet it causes
a very low degree of twisting on the stripe between two nodes.
this means that there is, depending on the context, a point of
optimal ratio.

Adaptability is related to absolute size. Bigger elements have a
lower ability to adapt since they need a higher stiffness to
support their own weight and since bending is much more
prominent feature. Addition might be the right approach for an
adaptable system, not scaling. Yet the problem of scaling in contrast is the number of joints required – this causes friction as well as weight. So the solution has to be a mixture of these two measures.

**nodes**

how does the continuity of the material influence the character of the node? Is there a way to have an even smaller buckling coefficient (Euler) than $\beta = 0.5$ (both connections fixed), when one assumes that the element is being pushed beyond the node in the direction which counteracts the bending?

so in the case of the buckling force:

$$ S_k = \pi^2 \times \text{min } I \times E / S_k^2 = \pi^2 \times \text{min } I \times E / (1 \times \beta)^2 $$

With

- $S_k$: buckling length
- $\text{min } I$: moment of inertia around weak axis
- $\beta$: Euler coefficient
- $E$: Young’s modulus

$\rightarrow$ the Euler coefficient can influence the result by max. $2^2$

if the material is not continuous, or cannot be for reasons of size, nodes have to secure the load transfer as well as the transfer of tensions. In analogy to topology, they are more important than the geometrical arrangement of the load bearing elements themselves. This means that the nodes have to have defined degrees of freedom as well as the mechanically working system. Not simply force fit or hinge, but different requirements in different directions, and maybe even with different resistances. The example of the nodes in the column shows different requirements and degrees of freedom in every dimension. The difference to a rigid system also is the fact that the nodes in an adaptable system have to be able to provide the possibility for real displacements – it is the layer of cables which keeps the construction from doing so. In the Z direction, the nodes have provide the pulley system to work with minimal friction, in the X/Y direction they have to secure the pantograph mechanism of the stripes to work well without compromising the force transfer between these two stripes in the Z-direction.
at the level of 11.50, the stairs divide and work like helixes
one leads to a room without continuation - the spatial
continuity interrupted
the density of circulation has the same impact as the
density of the structure – one can choose which one should
be the functionally relevant element.

cul-de-sac
cul-de-sac

The room is empty except for two posters of Buckminster Fuller’s project of a dome over Manhattan and Frei Otto’s dome for the city in the Antarctica. The civil engineer of the early 20th century still has the activist spirit of 19th century utopianism, fully confident in human progress, peace and wealth, through technology. The refusal to theorize and instead the wish for applied world making is a feature that can be found among many of the great engineers, be they Freyssinet, Nervi or Roebling. The technical solution is being seen as a generalizable construct and as a social tool. That can be applied without major modifications. It even has to applied, the engineer is fully responsible, he is “the incarnation and the representation at the same time” of the fact that humanity can be saved through progress.

The results, since structures are a limited field if it does not transform into architecture, are utopian projects close to the megastructures of the sixties, which deal with big scale, second skin, bad urban environments and the escape from them, they always create inside outside conditions and have a separating rather than integrating approach. The anti-urban and technocratic utopian are always quite close to each other.

The second interesting feature related to this is the relationship between engineering and nature – on the one hand, nature serves as a source of inspiration on the very technological level, and the arguments to protect nature fit into the agenda of the engineers (bigger need for economy in building in order to protect nature), when they try to make amends for the destruction and exploitation of nature in early modernism.

45
But to quote Francis Bacon: "the damages done by technology cannot be repaired but by a metatechnique. Our next dialogue with nature will therefore have to have a supra-constructivist character." 13

Modernism provides a rich history of abuse. Curtain wall, free façade, modular systems, prefabrication are the most prominent examples where the technical and architectural measure with the goal to improve a spatial or even social situation, was in the end only used to heighten its efficiency, through lowering construction costs or heightening revenue, at the expense of the qualities which were meant to be gained.

It seems that the metatechnique Bacon talks about has to do something with the specific and the context, with the development of individual solutions for places. Nearly all of those places have already undergone treatment, have had users and abusers, and cannot be dealt with as if they were innocent.

It takes a step back from general solutions and from toolmaking. This is where architecture comes into play, as an approach, not as building. Architecture consists of different fields, with different modes of operating and different modes of assessment (hard sciences and soft sciences). Good architecture is a compromise between these fields and never the pure optimization of a single field. The specialist almost necessarily must be disappointed.

For the architect, detachment and the ability to deconstruct are crucial abilities in dealing with special fields within architecture. The distance has to be kept, so that one is protected against overemphasis and still can shift the focus, be ironical.

The history of engineering in the 20th century is asking for consequences, and the first consequence I see is the need for the context to be held up. There is no use in writing
decontextualized guidebooks. There is enough specialists busy doing this. This is even more true today as the degree of specialization and the splitting of tasks and knowledge reach new extremes.

Tools and guidebooks are by nature general, they reduce the specificity as far down as possible, in order to serve the biggest number of possible applications.

With all admiration, there is a pathetic element within the architect-engineers of the 20th century, Frei Otto, Fuller, Le Ricolais, Jean Prouve, in their global views in combination with the specialized research, in the unclear relationship between architecture and the special field, in the attempted reconciliation with nature, expressed in the direct formal analogies of their architectural translations.

There is a virtue in non-specialization, which is about intellectual flexibility, cross-linking between different fields of knowledge, and the ability of making compromises, of admitting subjectivity rather than hiding behind a cloak of scientific objectivity, and, most important, in cultivating the art of improvising, the opposite of the use of ready-made tools.
towards the top of the building, one floor is completely consecrated to the library. This floor serves as a platform for the top floor which is completely free as well as a distributing surface for the rooms below.
“nature builds for a degree of adaptability, humans build for a degree of rigidity” (Le Ricolais)

The problems of dynamic loads, of vibrations, of missing lateral resistance are crucial and pose a big problem to the use of adaptable systems in architecture. Pure adaptable systems as they can be found in nature have to be excluded in architecture. But it is different with hybrids - the combination of adaptable and rigid can make a system where the two different parts contribute their advantages. They result from functional requirements, like the fact that a floor can’t be really spanned (the allowed sag for a floor is 1/250).

In an abstract way, this system can work in two ways: either a tensile structure is being spanned between two rigid elements. In this (well known) case none of the tensile surfaces cannot be used neither as a floor nor as any other element that requires a minimum of lateral stiffness.

The second option, for which this structural model stands, is to make an adaptable surface with a certain lateral stability and to use this as a network for the positioning of local rigid members, which fulfill the functional requirements. Additionally, their qualities, like stability, are distributed over the entire construction of the adaptable surface.

The basic problem about the idea of addition of weak elements on the architectural scale is, that in architecture, local failure is not possible - each element that is in contact with the user has to be stable in itself.

The question of hybrids is directly related to the question of the joint, which has been dealt with already in this text. As was mentioned, the node has to be able to transfer the forces from the one system to the other, but it always can be only as strong as the weak element allows. They have to mediate between the indirect system of stress transfer of the adaptable system and the direct load transfer of the rigid system. A too direct impact can compromise the weak system.
Rigidity is being gained through the size of sections (the stiffness of the members), through triangular arrangements, and through moment connections.

The hybrids are a way to mediate between the natural advantages and the human requirements. This can take place in a way that both take advantage of each others strengths. Ricolais' models are a good example for that. It is the most efficient to put the rigid element to the center of the construction and to move the adaptable as far to the outside as possible, but one can also imagine the rigid to be on the outside being pretensioned through interior cables.

The notion of time and context becomes important when thinking about hybrids: we face a big amount of rigid structures already in our surrounding and one could think about combining those with adaptable constructions which rely on the strength of the rigid elements. This is partly already being done in construction techniques, like the FRP (fiber reinforced polymer) technology, where sheets of carbon or glassfiber are being used to reinforce concrete columns. These additional sheets, although not adding any substantial mass, can increase the strength of the column by up to four times, because they keep it from buckling.

In the example of the column, one can detect different degrees of rigidity, depending on the use of either horizontal or circumferential cables.
roofspace no material no structure just thoughts
The parameters developed out of the structural research have all at least double meaning and thus not only structural, but spatial, programmatic and social relevance as well. These oppositions are the essence of this research on structures which tried to understand structures as just one field within building, and which tried to understand structural means as never self-referential but always open for multiple interpretation.

| Continuous | assembled |
| Gradual          | immediate  |
| Figure            | ground     |
| Texture           | shape      |
| Inhabit           | express    |
| Straight          | synclastic/anticlastic |
| Surface           | line       |
| Specific          | generic    |
| Weave             | lattice    |
| Scaling           | array      |
| Geometry          | material   |
| Geometry          | topology   |
| High tech         | low tech   |
| Thick skin        | thin skin  |
| Surface/sheet     | lattice    |
| Redundancy        | direct control |

today's context – or the context itself - is a way to employ weak structures, to accept a given situation and to deal to find the richest interpretation of this situation, in the best case one that adds another layer. Recycling in this sense becomes an abstract mindset, a way of reinterpreting, reusing and stimulating a given situation.

The idea of the weak structures can be understood in the end just a way to discipline the structural approach – which is to strive for the highest degree of interaction between the elements – the notion of synergetics. Even if Le Ricolais is highly suspicious about Buckminster Fuller's activities, they both share the idea of a far sighted structural economy, an understanding of the flow of forces, not only in the structural meaning. If it is being taken literally, it is in danger of a direct transfer of a structural idea into a context where it does not really fit. Any of the structural features which have been examined during this testing, have been done without context and therefore have only limited validity for direct application, but have much more...
validity as an intellectual challenge without any formal relevance to stimulate different solutions. This is the same for the “composite” approach thinking, which is the combination of the rigid and the distributive as well as the combination of the old heavy with the new light.

I understand good architecture as the optimal compromise or rather as one of the optimal compromises, in which the single system necessarily is being corrupted. It is the translation of ideal, non physical constructs, of constructs without thickness, which come from geometry, from computation, from imagination, into something physical. The built manifestation of this has necessarily all constraints and chances which are attached to the body. Time seems to be the main feature, it makes the body dynamic and embedded in a bigger constantly moving system. Ageing, patina, vibrations, thermal reaction, imprecision are just some of the features attached to the notion of time.

I would like to finish with a quotation of Robert Le Ricolais “finalism, which means a final aim for an observed phenomenon, has plagued our scientific systems and theories for centuries. This naïve anthropomorphic attitude has been at the root of the so-called ‘human architecture’, or architecture for human beings.”

Therefore I argue for the architectural approach and for recognizing the potential in the collaboration between architects and engineers, since the architect is by profession responsible for putting up the frame work. The purely structural approach will make the borders between structurally economical approach and post-structuralizing blur, since in both cases, structures are the point of focus.

I search structure accepting imprecision, structure acting like a music instrument that has an acoustic space and a vibrating skin, that takes full advantage of the space’s and the skin’s properties.
1) introduction to the notion of form, unpublished article, from the archives at the University of Pennsylvania

2) L’Art de l’ingénieur, p. 326

3) IL 23, p. 54

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5) unpublished articles by Robert Le Ricolais, U Penn archives

6) IL 23, p. 17

7) L’Art de l’ingénieur, p. 476 (Joerg Schlaich)

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12) L’Art de l’ingénieur, p. 526

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