

Building (as) Performance: A Material Approach to Adaptive Architecture

by

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B. Sc. Arch. McGill University, 2006

Submitted to the Department of Architecture in partial fulfillment
of the requirements for the degree of

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ABSTRACT

One measure of performance in adaptive architecture is its ability to respond effectively to the environment and evolving program. As architects strive to create designs that respond to external change, more and more literally and actively, they are inevitably faced with the challenge of merging the kinetic with what is inherently an “immovable”.

Yet traditional mechanic devices allowing freedom of movement to an assembly have proven to be very expensive and often unreliable. This is in part due to their incompatibility with a building's use and lifespan. Thus, they are either implemented permanently at great expense or are confined to the temporary and architecturally limited realm of installations.

We can thus witness a trend in architecture moving away from the mechanic and towards the use of material behavior and deformation as a cheaper and more durable architectural solution to responsiveness. Responsive materials such as shape memory alloys (SMA's) and electroactive polymers offer new possibilities for architecture. Furthermore, an understanding of the difference between kinetics in architecture and kinetics in mechanical objects has led to investigations into evolving interplays of rigidity and flexibility within structures.

This thesis tries to advance the discourse by investigating the limits of elastic material deformation, and framing a niche where it is possible and fruitful for architecture to use material properties to produce adaptable space. The work instantiates these notions into a program of informal performance and exhibition space to test how performance criteria such as acoustical absorption, transmission and reflection, visual transparency and media proliferation at an architectural scale can be mediated by this approach.

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INTRODUCTION :: PERFORMANCE ARCHITECTURE

Material limitations in kinetics and scaling

One measure of performance in adaptive architecture is its ability to respond effectively to the environment and evolving program. As architects strive to create designs that respond to external change, more and more literally and actively, they are inevitably faced with the challenge of merging the kinetic with what is inherently an “immovable”.

Yet traditional mechanic devices allowing freedom of movement to an assembly have proven to be very expensive and often unreliable. This is in part due to their incompatibility with a building's use and lifespan. Thus, they are either implemented permanently at great expense or are confined to the temporary and architecturally limited realm of installations.

::responsive

The field of material science has, for a long time, investigated adaptability on a micro ($< 1\text{cm}$) scale. Innovations in responsive materials have opened up new possibilities contributing to architecture such as self cleaning glass, acoustical textiles and flexible photovoltaics. Yet, only recently have materials been considered as candidates for a macro ($> 10\text{cm}$) scale adaptability in architecture, a niche reserved to the mechanical. This underlines a trend in architecture moving away from the mechanic and towards the use of material behavior and deformation as a cheaper and more durable architectural solution to responsiveness.



Turning the place over, Richard Wilson, 2007

::actuator

This is in part due to the reinvention of the actuator itself. In addition to standard rotary and linear devices (motors or pneumatics), we see more and more the use of sheet materials (building surface materials) as the drivers of kinetic movement. Responsive materials such as shape memory alloys (SMA's) and electroactive polymers offer new possibilities for architecture. Novel textiles can also be seen in applications for light-weight high performance axial actuators in the robotics and manufacturing industry. Festo FG's Fluidic Muscles, for example, offer an alternative to the oil based pneumatics in use today. Yet the use of materials in kinetics is heavily constrained by durability and the often impractical nature of their control strategy. Shape memory alloys and thermal expansion materials are dependent on temperature. Although temperature can be controlled by electrical resistance, it can only be effective at a small scale and becomes inefficient when subjected to the environmental conditions affecting architectural applications. Furthermore, SMA's become weaker after repeated use, as the thermo mechanical treatment leaves them with a very low fatigue limit. Electroactive polymers on the other hand are composites and use an electrical field to deform and elastomer sandwiched between two layers of electrodes. Voltage can be adjusted for a progressive form change but the current needs to be relatively high and constant to produce a substantial force. The constant energy input required becomes the limiting factor in the proliferation of these actuators in long term/ slow cycle response.

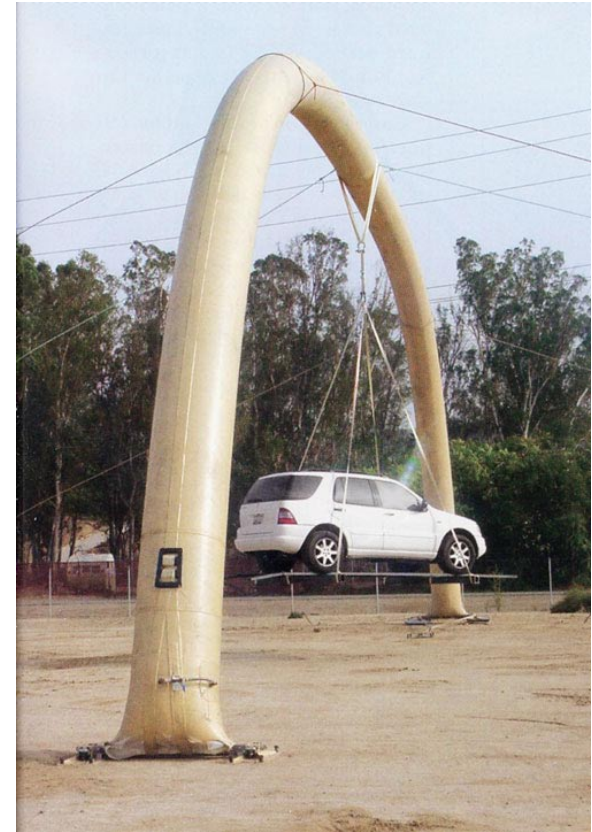


[Norman, Golabchi, Seffen, Guest, 2008]

::rigidize

The main hurdle of the use of material deformation in architectural applications is the issue of scale. The scaling of bent structures is not linear, as the influence of member depth grows faster than that of member length. The scaling of stiffness when playing with the elastic limits of members is further complicated by the relationship of formal forces (the internal sum of forces giving a stable shape) and the external forces to be resisted (gravity, wind, etc.). In smaller scales, the internal forces (from boundary conditions and induced by actuators) deforming materials are much greater than the external ones. Thus, considering the unpredictability of the latter, the overall formal instability remains minimal. At bigger scales, the external forces grow to the same order of magnitude as the formal ones, thus a random variation (ex.: from wind gusts) will have a major impact on form. Relying purely on forced deformation limits greatly the scale of such strategies. Rigidity must be found through other means.

An understanding of the difference between kinetics in architecture and kinetics in mechanical objects has led to investigations into evolving interplays of rigidity and flexibility within structures. The emergent field of rigidizing structures using textiles tries to reconcile these notions of temporary stability and the kinetic. Vertigo' AirBeam uses a flexible polymer matrix to create an airtight surface when inflated. The pressurized air acts as a compressive element within the tensile surface enclosure. Inversely, vacuum can also become the actuator for some materials. The Peanut Bridge project at Delft shows how an amorphous collection of particles (in this case plastic balls) can be organized within a sealed bag. The vacuum compresses the particles and adds shear resistance through the induced

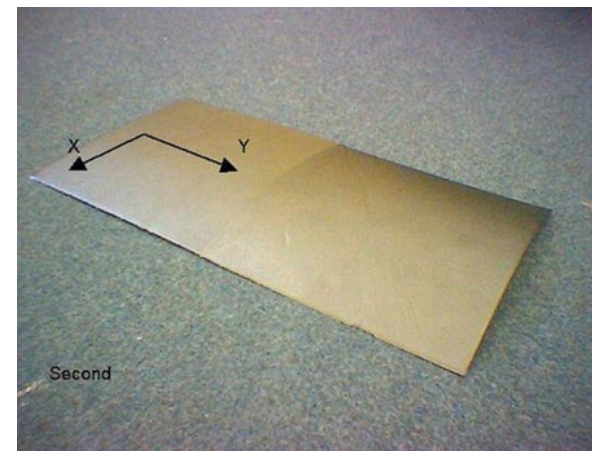
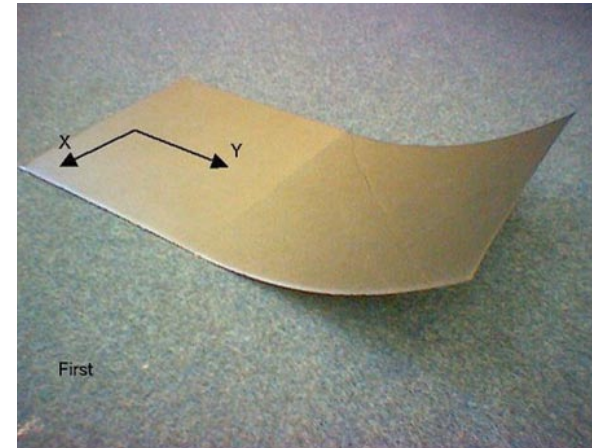


AirBeam from Vertigo, 2004

friction, a jig is used during the process to create the shape. Other matrix materials, such as ILC Dover's fiberglass textiles use epoxy for permanent rigidity or SMA's to morph the fabric between rigid and flexible. All of these approaches have the disadvantage of a binary system as only one given rigid shape can be produced.

A synthesis might be found in the use of materials in bending as switchable forms of stable states of energy, as continuous supply of energy (electrical or pneumatic) becomes impractical in architectural applications. Bi-stable composites can offer some new possibilities by combining them with responsive materials producing a temporary force that will switch a material from one stable state to another.. The summation of local integer switches could also allow for a gradient of variation in form at a larger scale keeping in mind that the relationship of external and internal forces will still be the main constraint.

This thesis tries to advance the discourse by investigating where that scalar limit is, and framing a niche where it is possible and fruitful for architecture to use material properties to produce adaptable space. The author first provides a descriptions the physical properties of some standard construction materials in sheet and red form pertinent to the discussion. This will serve as a base for establishing the limits of these strategies as assemblies. The work then instantiates these notions into a program of informal performance and exhibition space to test how performance criteria such as acoustical absorption, transmission and reflection, visual transparency and media proliferation at an architectural scale can be mediated by this approach.



[Mattioni, Weaver, Potter, Friswell, 2007]

CHAPTER 1 :: MATERIAL PROPERTIES

Physical properties of sheet materials in bending

Movement in assemblies can be achieved by mechanical connections with a set number of degrees of freedom. Alternatively, it can be produced by deforming the materials themselves. This deformation is dependent on stiffness, geometry and force applied. By keeping the internal stresses below the yield limit, a bent member can regain its shape when the load is taken away. Repeating this action can however create micro fissures in the material, and weaken it substantially. The fatigue limit (*Fig.1.1*) is the maximum stress that can be applied over many cycles while keeping the deformations purely elastic. Some materials do not exhibit such a limit and will continue to deteriorate as the repetitions increase. As a measure, an effective fatigue limit is defined as the maximum allowable stress over 50 million cycles.

Movement in assemblies through bending can be induced from axial loading, moment loading or directional loading out of axis. As a start, the behavior of various materials under axial loading will be examined.

The critical load for buckling will be used as a comparative unit of force to assess various bending states. Critical buckling axial load is defined as:

$$F_{cr} = \frac{\pi^2 EI}{(kl)^2}$$

Where k is a coefficient related to the support conditions. As a base value, this value will be set to 1.

Past this critical point, the stress in the material is dependent on the stress distribution across the section and on the maximum curvature along the length of the member.

$$\sigma_{\max} = \frac{My_{\max}}{I}$$
$$r = \frac{EI}{M}$$

Thus, the maximum stress is related to the radius of curvature as follows.

$$r = \frac{Ey_{\max}}{\sigma_{\max}}$$
$$\sigma_{\max} = \frac{Ey_{\max}}{r}$$

So, the properties of interest when selecting materials are the fatigue limit and the modulus of elasticity (*Annex 1*).

Given a uniform stiffness distribution and a support condition, the geometrical shape of deformations is scaleless. However, if we map the shapes of two benchmark support conditions (*Fig.1.2, Fig.1.3*) onto various material thicknesses (*Fig.1.4*), we find the exponential effect of scale on the loading applied and the minimal allowable curvature.

Fig. 1.1 :: Fatigue limit of elastic materials
Ref.: [Dowling, Norman E., 2007]

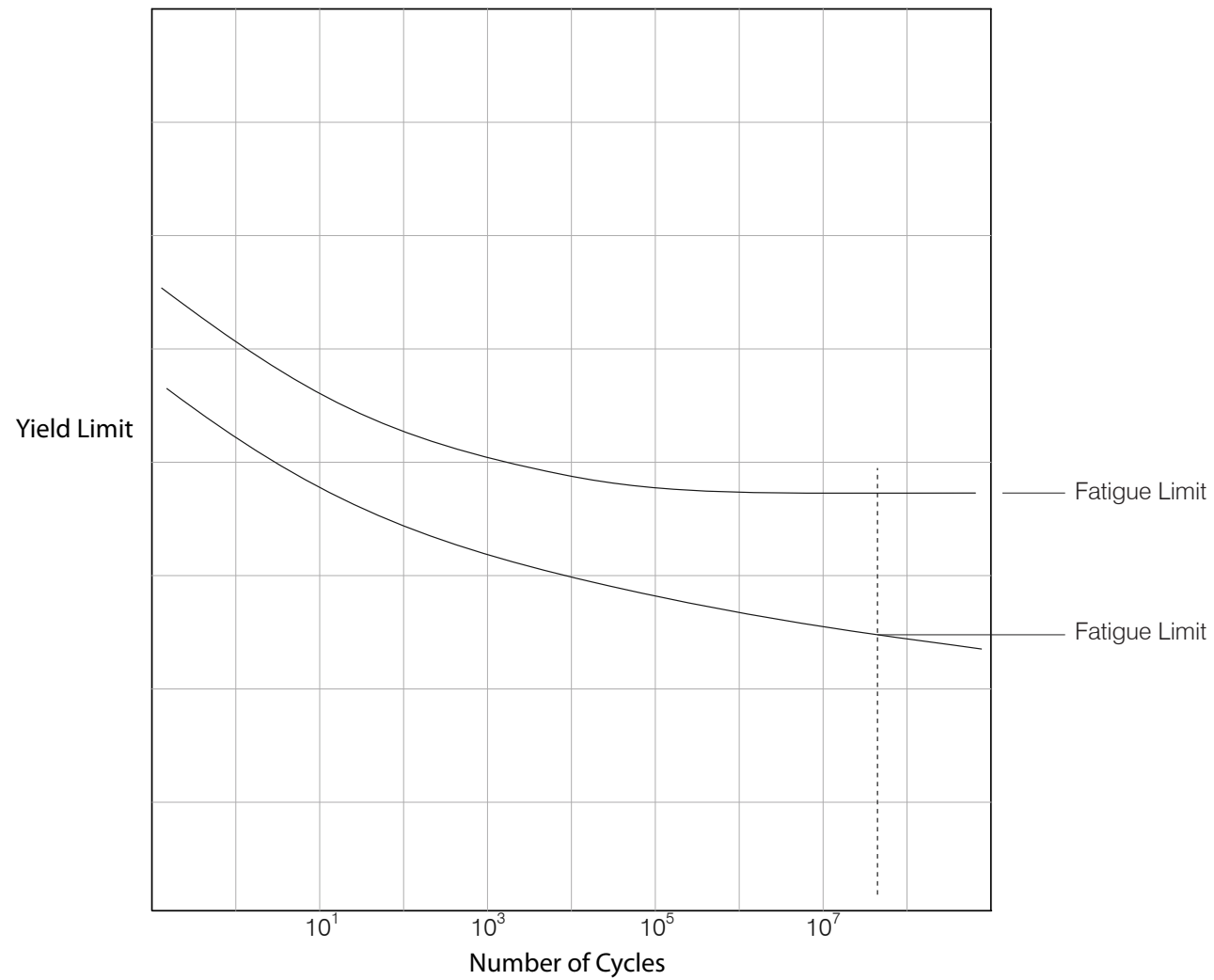


Fig. 1.2 :: [A] Shape and maximum local curvature of simply a supported sheet under axial loading
Ref.: [Goss, V. G. A, 2003]

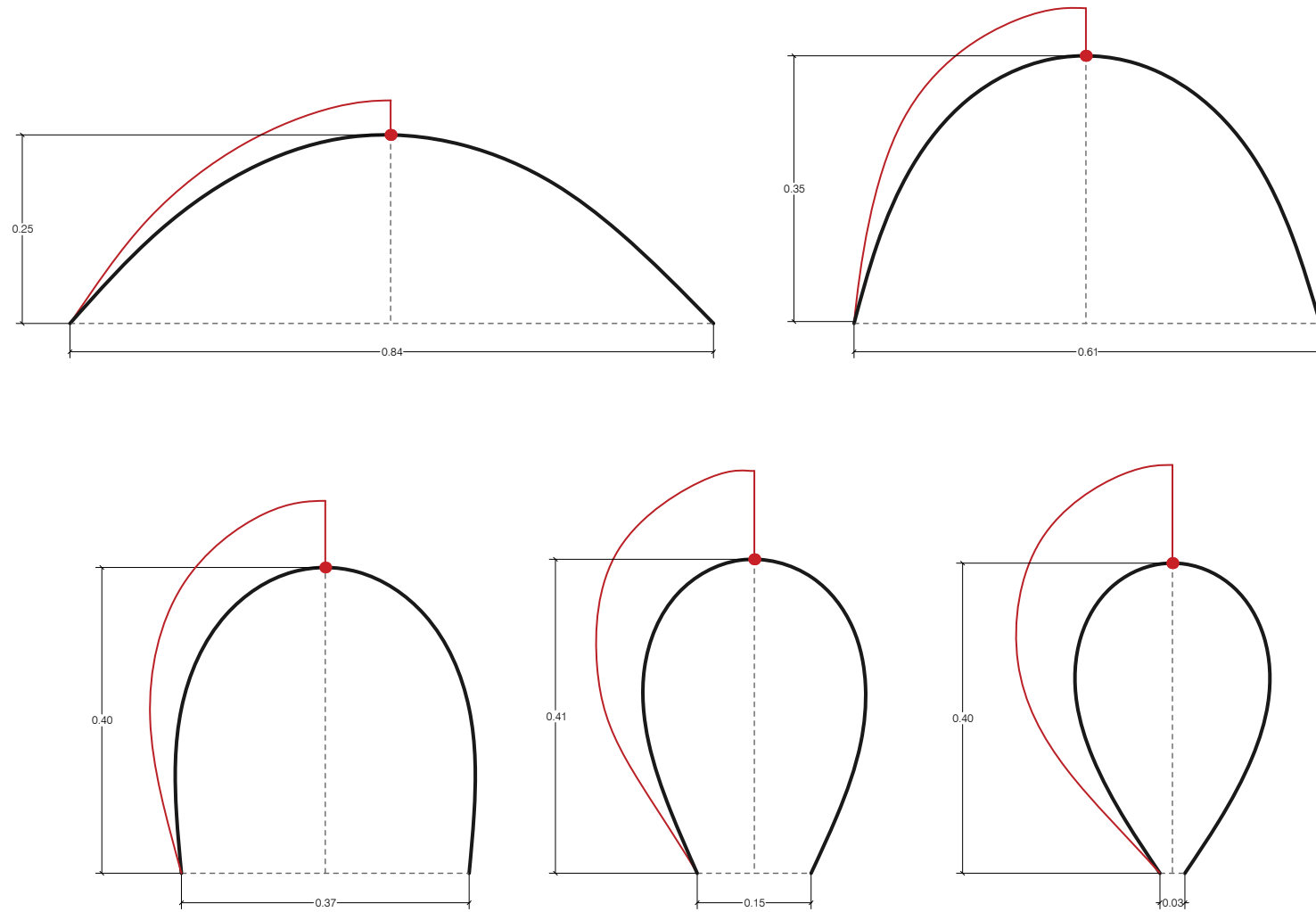


Fig. 1.3 :: [B] Shape and maximum local curvature of embedded (moment resistant) sheet under axial loading
Ref.: [Goss, V. G. A, 2003]

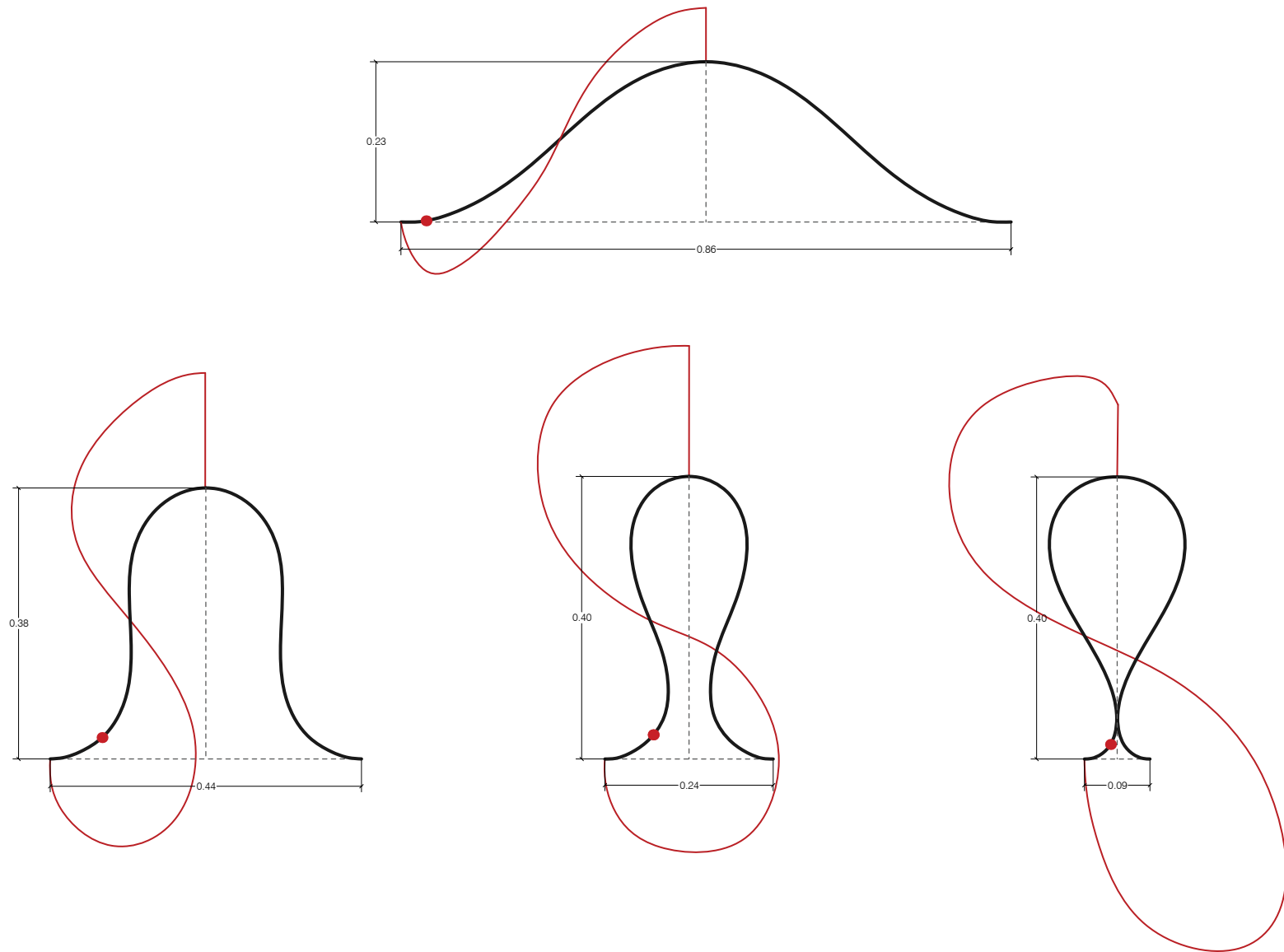


Fig. 1.4.1 : Maximum allowable deformation under fatigue limit and required axial loading for different material thicknesses

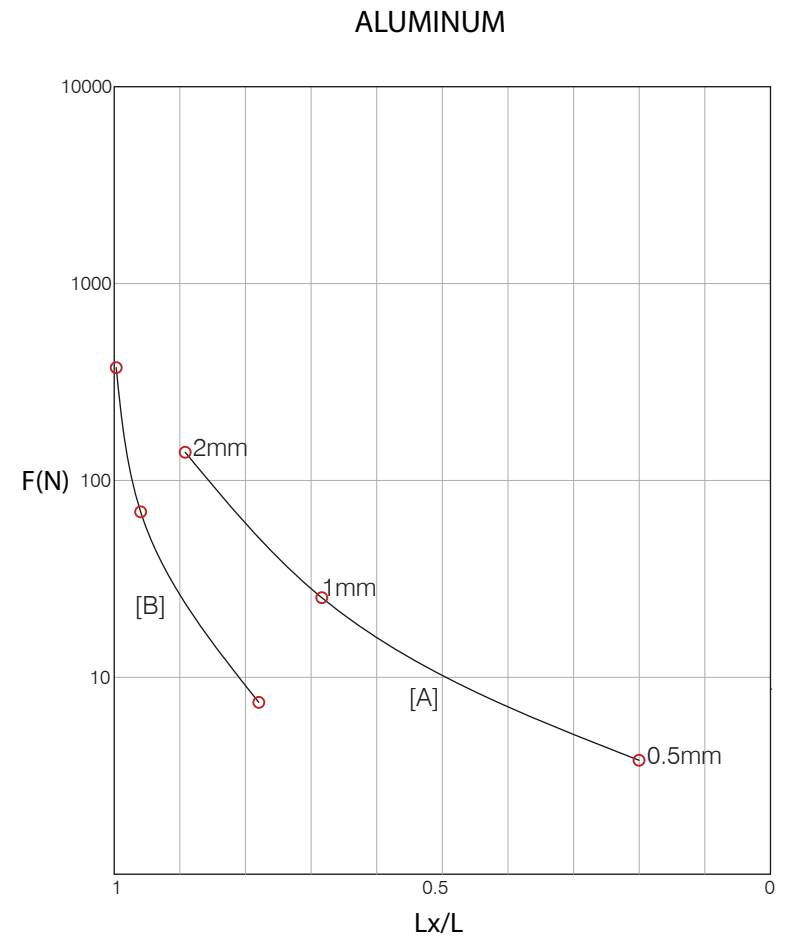
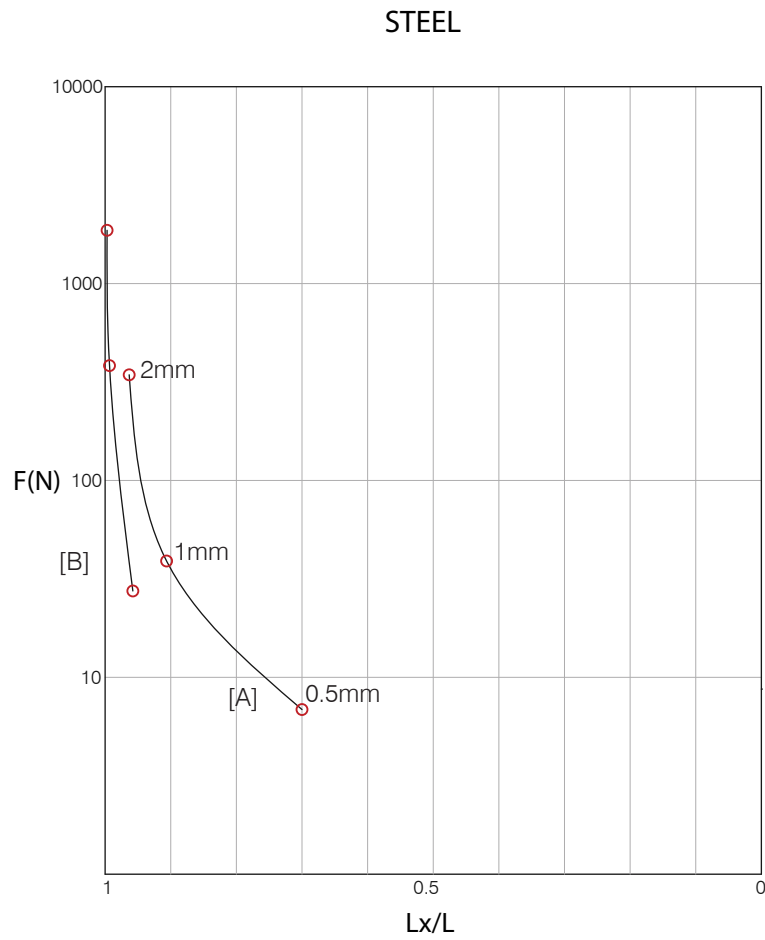
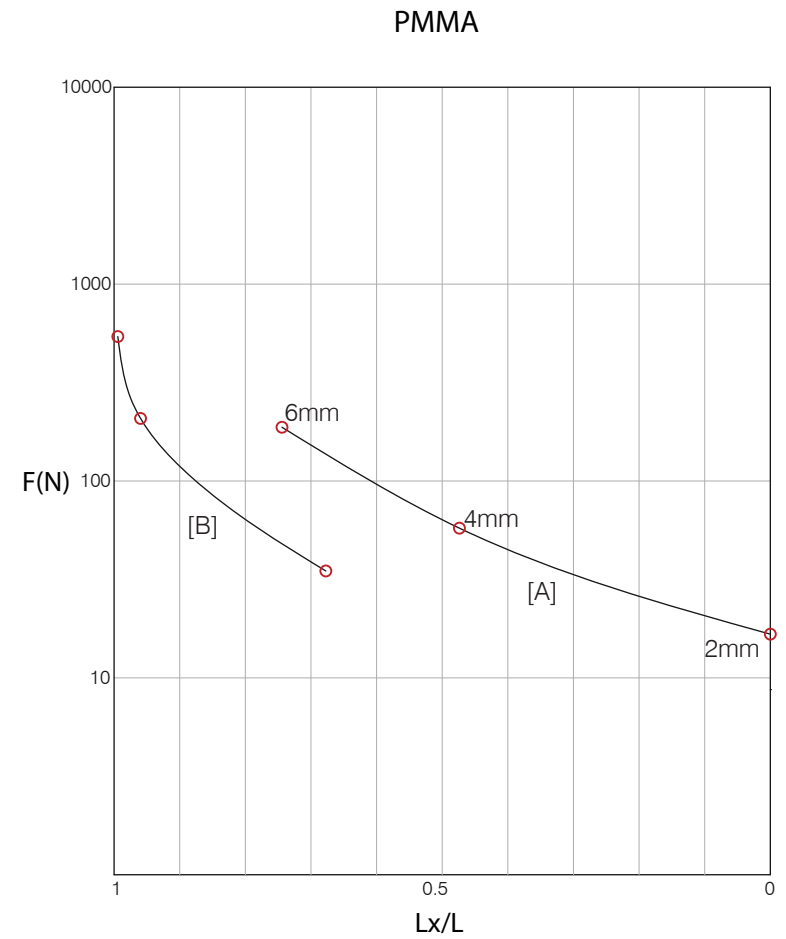
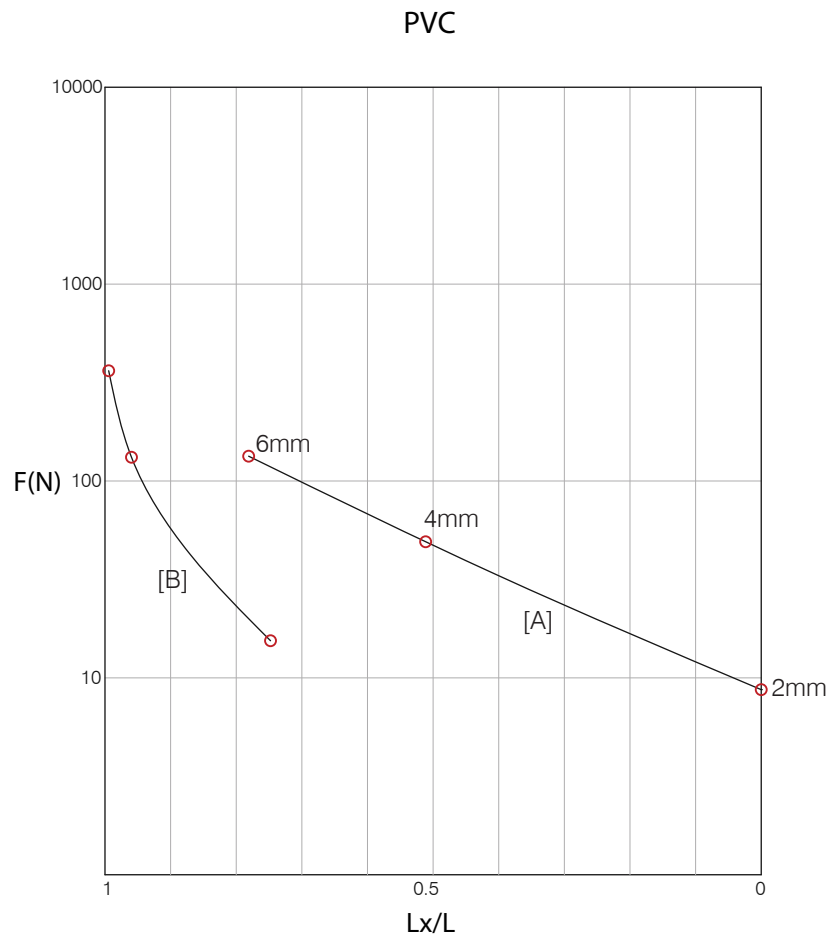


Fig. 1.4.2 :: Maximum allowable deformation under fatigue limit and required axial loading for different material thicknesses



CHAPTER 1 :: MATERIAL PROPERTIES

Physical properties of sheet materials in bending

As a two dimensional sheet, a variation in the support geometry can have important implications for the induced three dimensional shape. As the supports are pushed together the eccentricity into the third dimension is $0.3/L$ for the first $0.1/L$ and becomes less significant further on (*Fig.1.5*). The implications on loading and curvature can be seen in *Annex 2*. Significant eccentricities can also be produced when pulling apart supports, as illustrated in the following diamond shaped sheet assembly (*Fig.1.6*).

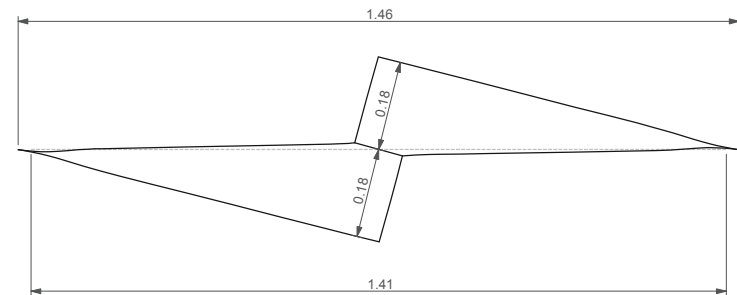
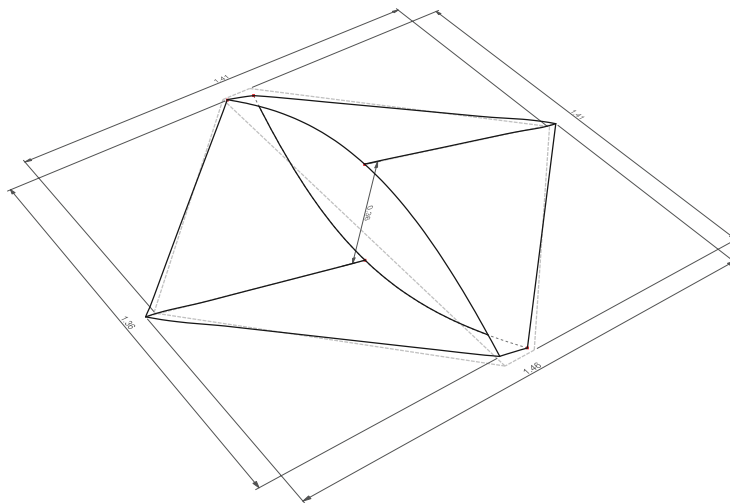
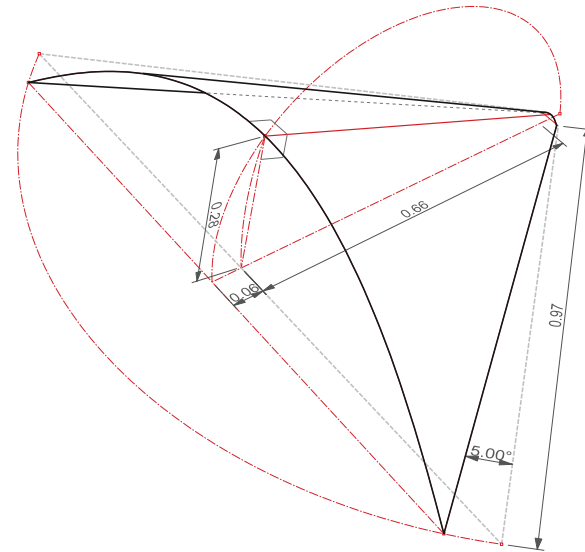


Fig. 1.5 :: Maximum eccentricity of sheet deformation in relation to length

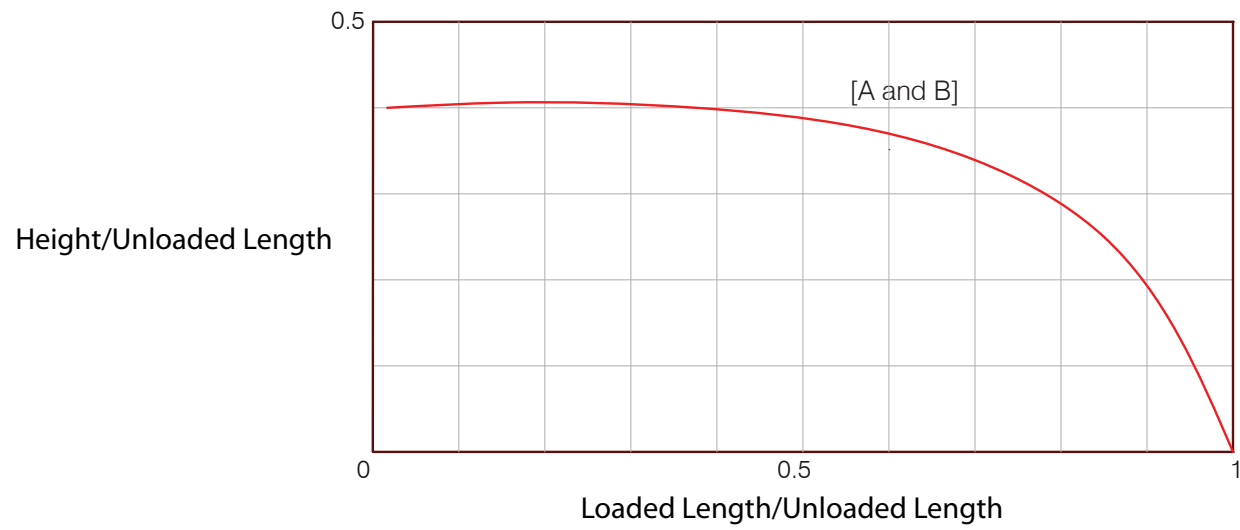
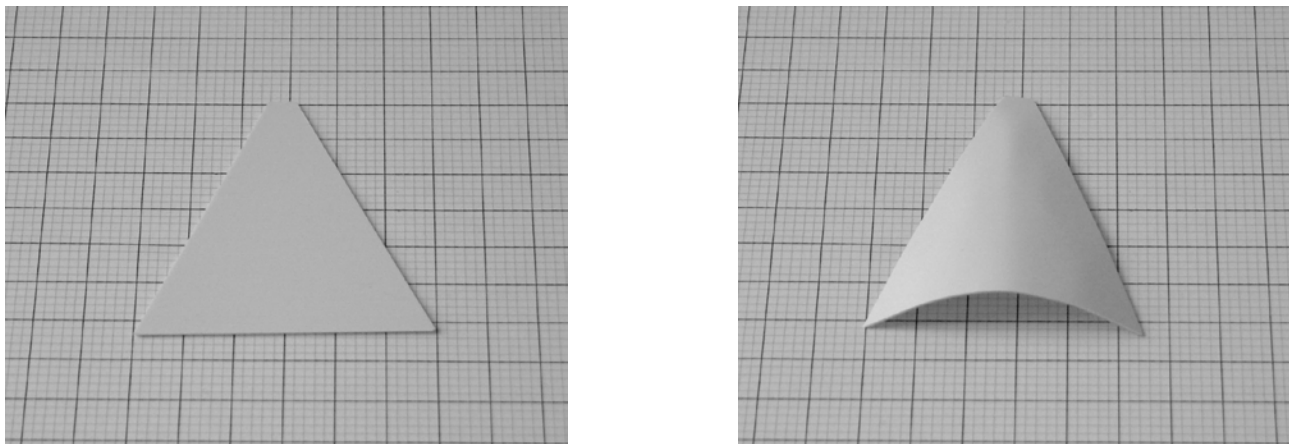


Fig. 1.6 :: Maximum eccentricity of sheet deformation in relation to length



CHAPTER 1 :: MATERIAL PROPERTIES

Physical properties of rods in bending

Unlike sheets, rods have a radial moment of inertia, which can result in a bending out of plane as the material deforms along the path of lowest energy. To illustrate this, we can compare the curves of a sheet [B] and a rod [C] under axial loading with moment connections (*Fig. 1.7*). Both exhibit the same curvature in plane at the beginning, but after a certain deformation, the minimal curvature solution will be a bifurcation out of plane. Further deformation will cause the rod to twist on itself and rejoin the first curvature plane. At that point, the rod reverses its reaction and will start pulling slightly on the supports.

This bending out of plane creates formal possibilities calling for actuators with much lower force magnitudes that required to deform the rod in a singular folding plane. By manipulating this planes locally (*Fig. 1.7*), a gradient of global morphology can be achieved (*Fig. 1.8*).

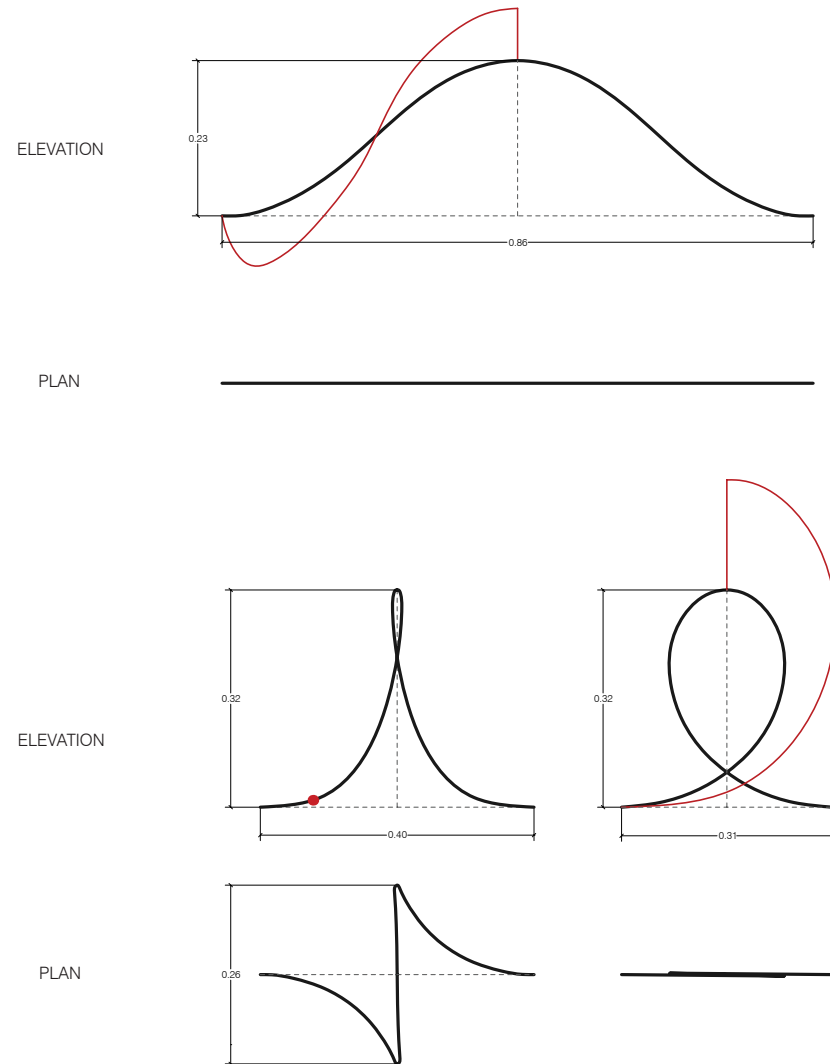


Fig. 1.7 Loading in relation to displacement of supports

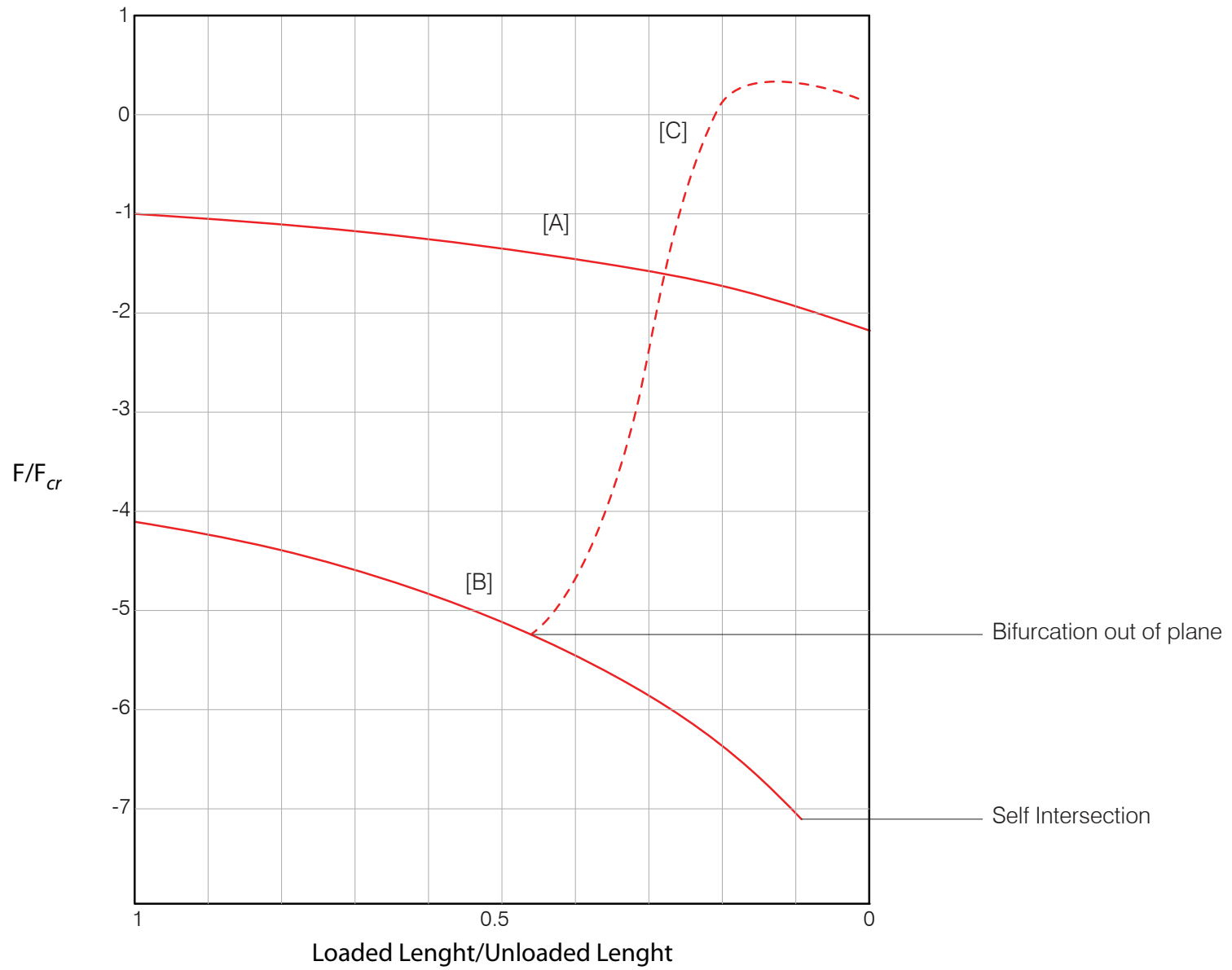


Fig. 1.7 ■ Local manipulation of the folding plane

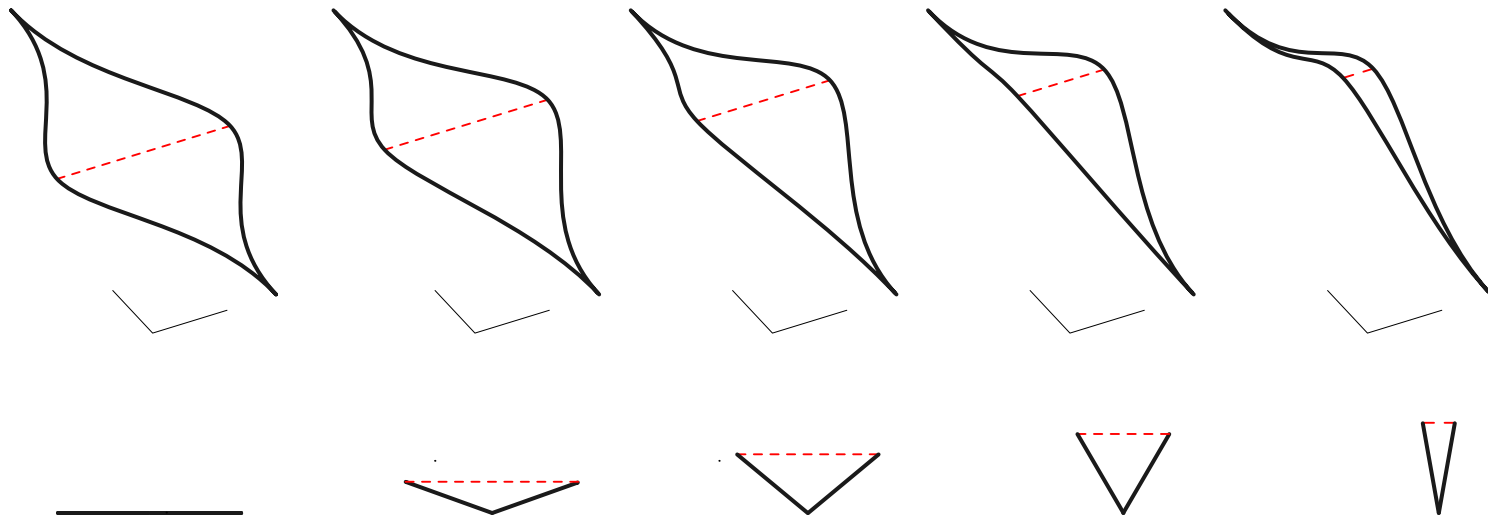


Fig. 1.8.1 ■ Physical model

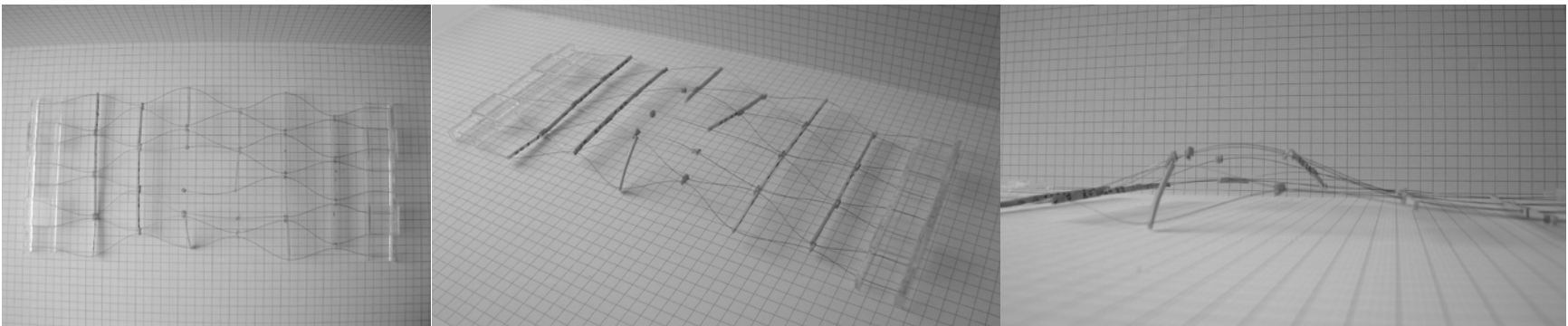
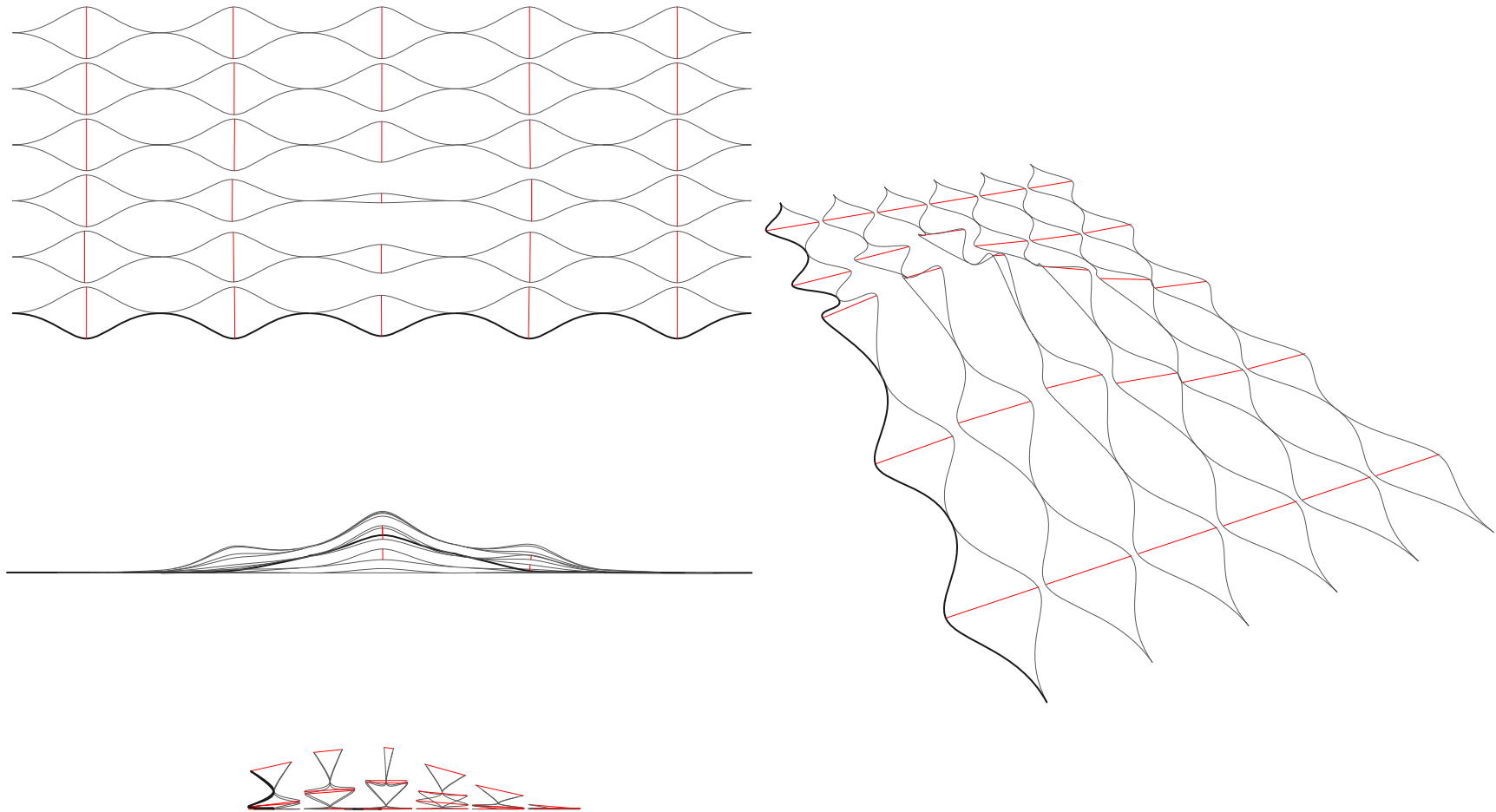


Fig. 1.8.2 ■ Global morphology



CHAPTER 1 :: MATERIAL PROPERTIES

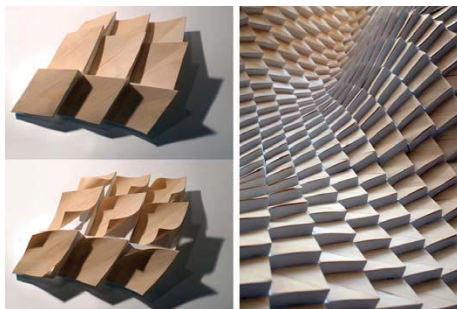
Composites and thermal expansion

When dealing with composite assemblies with different materials, the coefficient of thermal expansion becomes a relevant property to consider (*Annex 1*). Considering the elongation,

$$\alpha = \frac{\Delta L}{L \cdot \Delta T}$$

it follows that combining two thin materials with significantly different coefficients can produce a substantial curvature as the external temperature varies.

This behavior can be applied as a continuous deformation or a binary switch. In environmental applications a switch is most desirable as an opening would only be desirable within a specific window of temperature (*Annex 4*). In that case, there are considerable internal stresses gathered before the switch. This window is possible because the energy required to switch stable states is greater than the new stable state (*Fig.2.1*).



[Steffen Reichert, 2006]

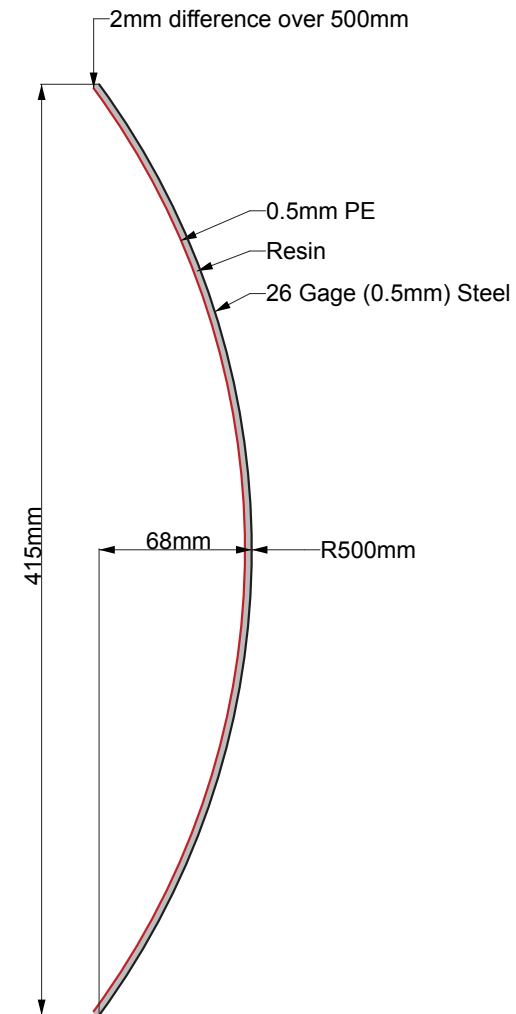
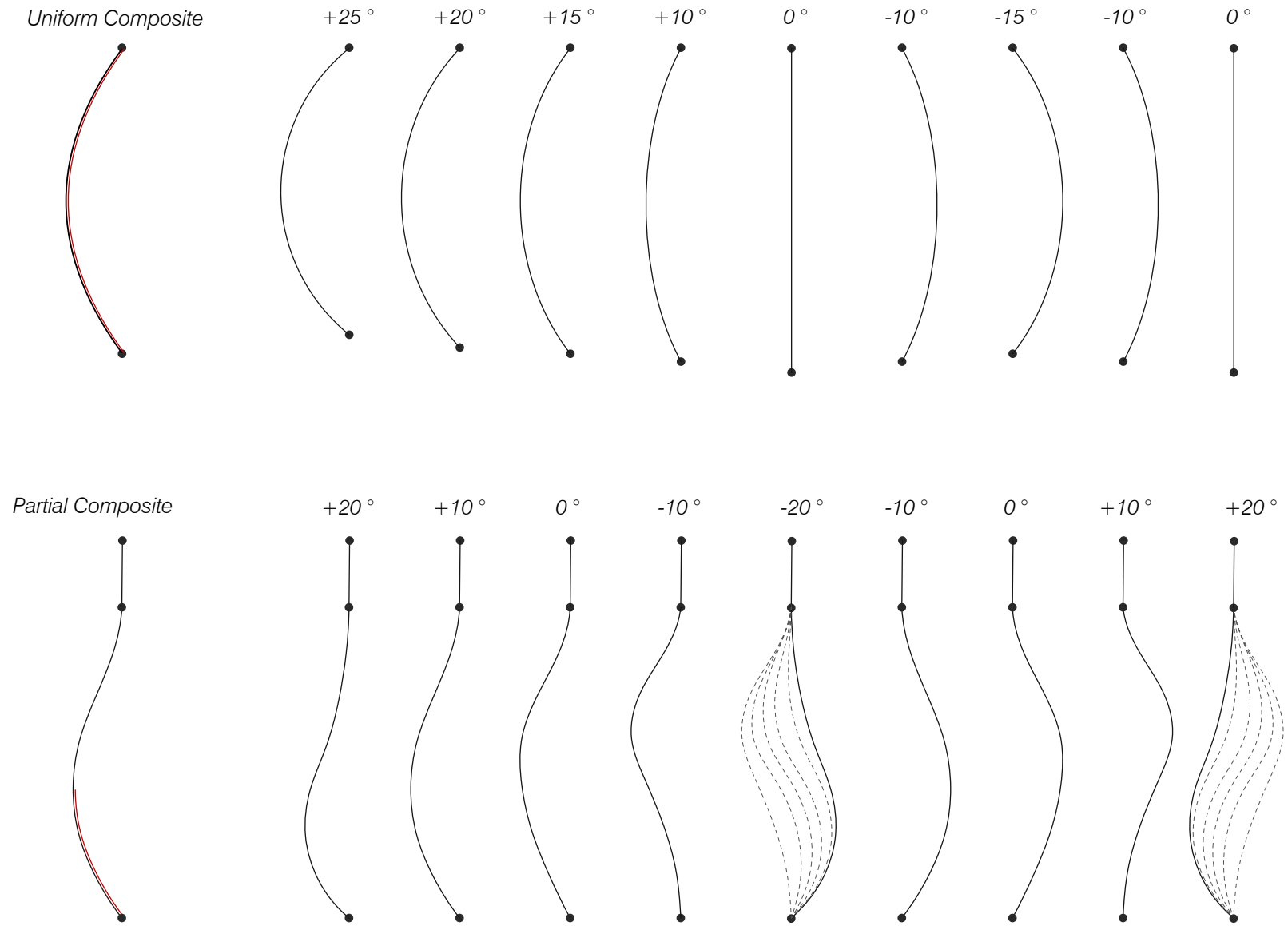


Fig. 1.9 ■ Loading in relation to displacement of supports



CHAPTER 1 :: MATERIAL PROPERTIES

Sheet materials with initial curvature

So far, it has been assumed that the initial unloaded state of the construction material is flat. A further investigation is required to find if new possibilities arise from starting with already plastically deformed members with local curvature. This becomes specially important when designing support details.

The generic relationship of stress to radius of curvature in a beam subject to bending is:

$$\varepsilon = \frac{-y}{r} \quad \sigma = \frac{-y}{r} E$$

If we expand this definition to a member with an initial local curvature, the relationship becomes (Annex 3):

$$\varepsilon = 1 - \frac{(r' - y)r}{(r - y)r'} \quad \sigma = 1 - \frac{(r' - y)r}{(r - y)r'} E$$

After plotting these variables, it becomes apparent that, by itself, no considerable difference in behavior can be noticed in curvatures bigger than 100mm. In smaller curvatures, the initial shape reduces the added curvature the member can take before reaching its fatigue limit. As a general rule, it can be concluded that small local curvatures, or creases, are to be avoided as these zones will be subject to the highest stresses with little addition to the overall range of movement of the pre-bent member (Fig. 1.10 and Fig. 1.11).

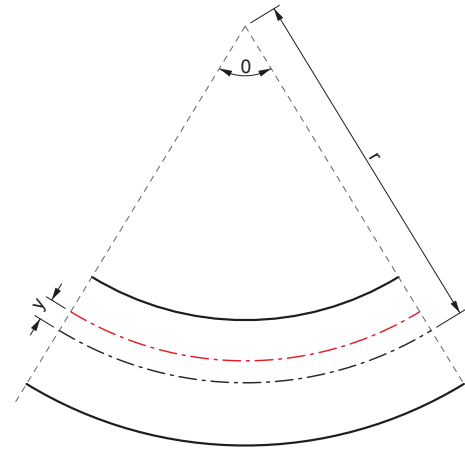


Fig.A.1 Ref:[Mattioni, Weaver, Potter, Friswell, 2007]

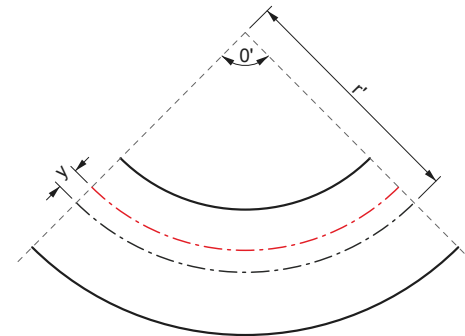


Fig.A.2

Fig. 1.10 ■ Loading in relation to displacement of supports

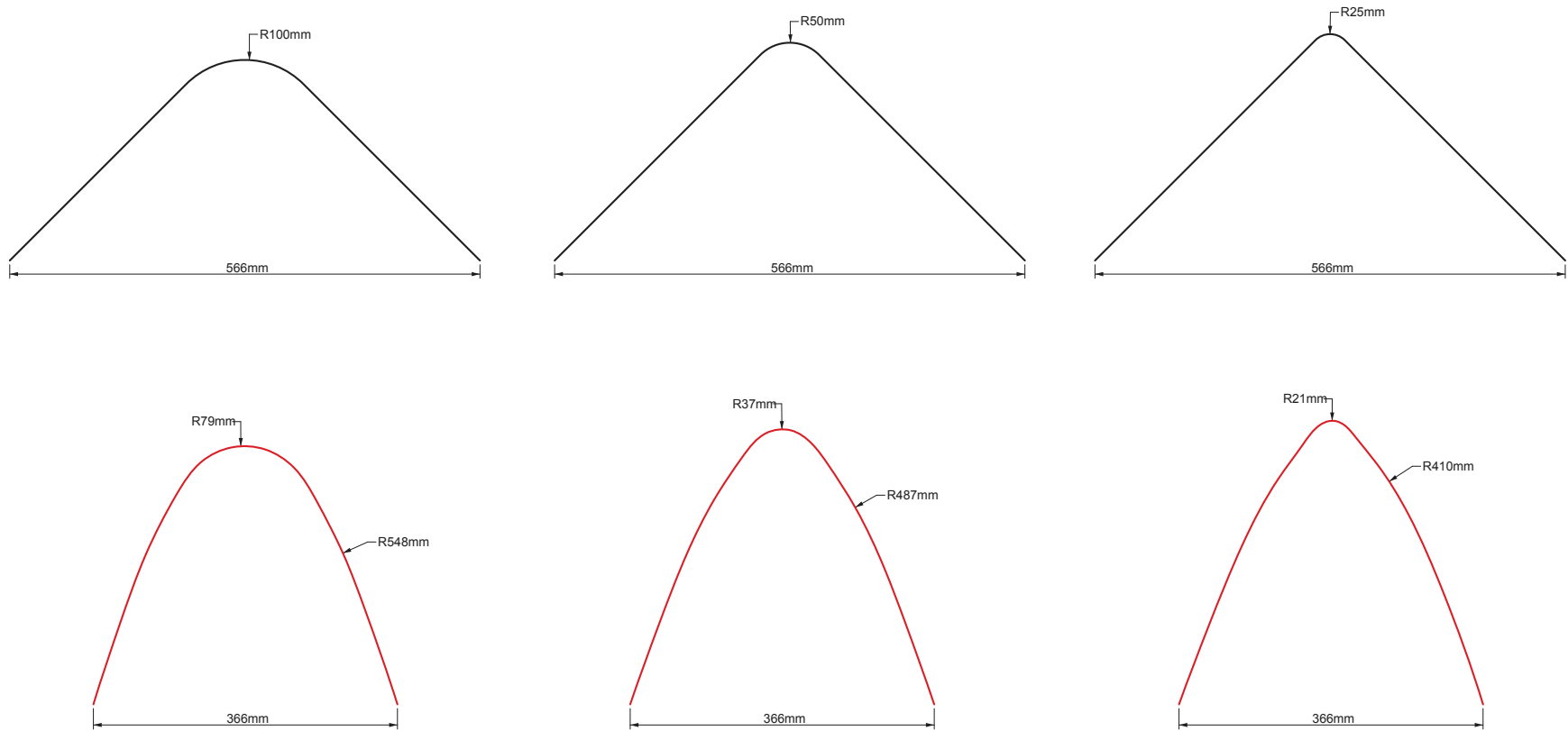
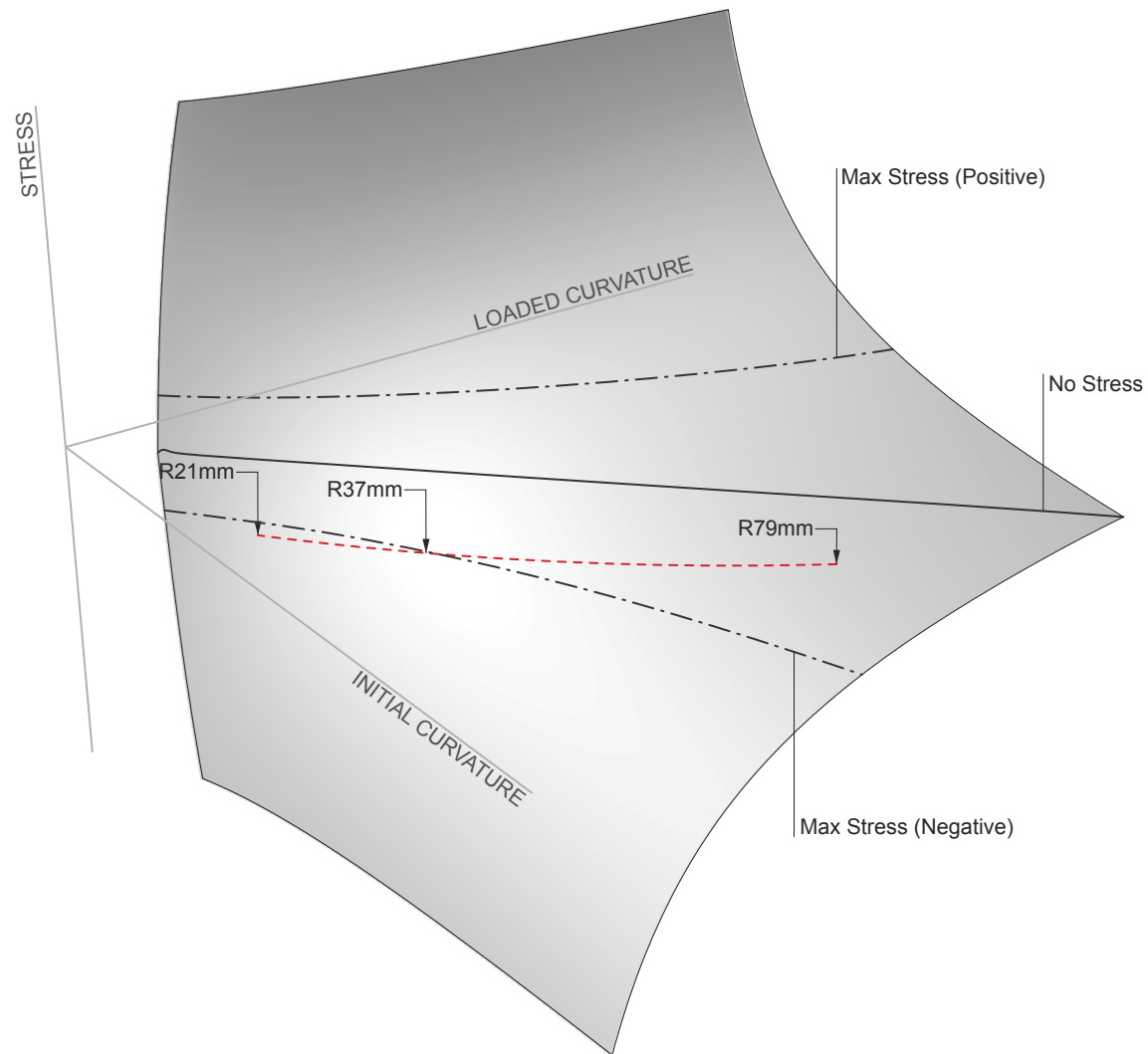


Fig. 1.11 :: Maximum stress in plastically curved members in relation to maximum allowable stress



CHAPTER 2 :: KINETIC MOVEMENT USING MATERIAL BEHAVIOR

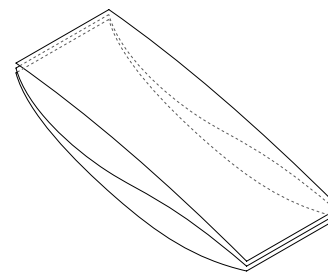
Fundamental degrees of freedom

With the development of new materials, a trend in kinetic structures moving away from mechanics and towards material behavior can be traced. Mechanical joints are still the most expensive and often unreliable elements in architectural projects; using continuous deformable materials offers an opportunity to reduce cost and increase longevity of kinetic architecture.

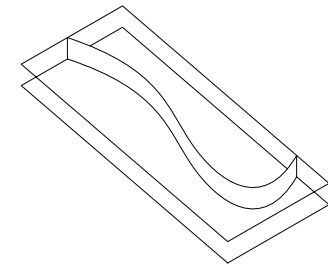
There are two fundamental mechanical actions: translation and rotation. All mechanical degrees of freedom are one or a combination of these actions. When a material deformation is used to give an assembly a degree of freedom, three actions need to be addressed:

Assembly strategies using sheet materials to create a variable response in these three actions can take two forms:

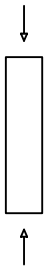
Layering in a single folding plane



Layering in perpendicular folding planes

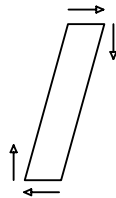


Translation



Axial Rigidity

Translation/Rotation

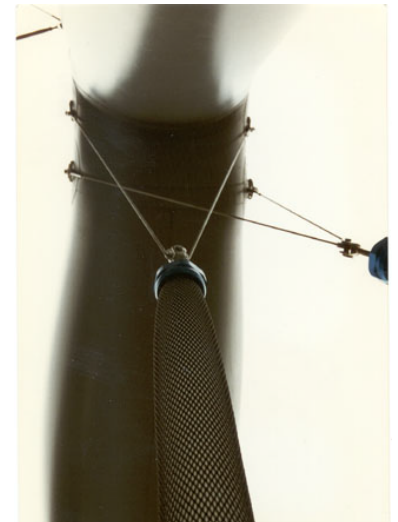
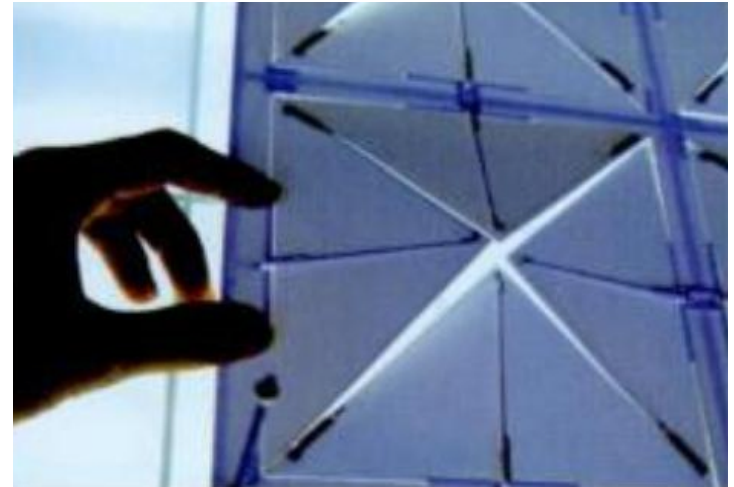
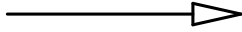
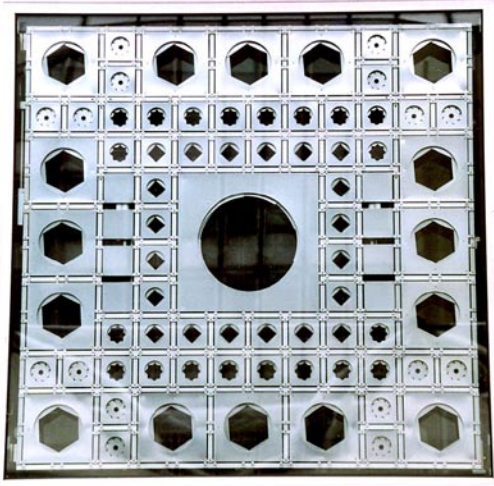


Shear Rigidity

Rotation



Bending Rigidity



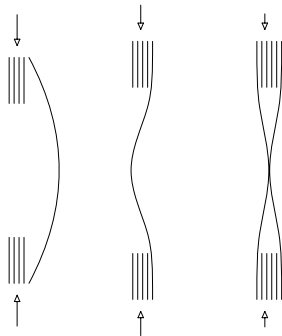
CHAPTER 2 :: KINETIC MOVEMENT USING MATERIAL BEHAVIOR

Layering in a single plane

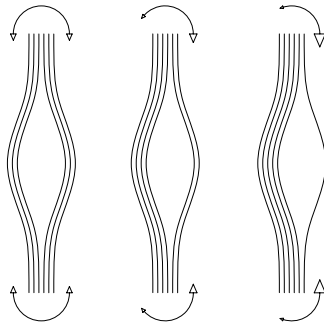
Layering in a single folding plane takes advantage of the multiple stable energy states within a material. The multiple solutions to an Elastica problem with given boundary condition can provide variations in assembly rigidity with low energy switches (*Fig.2.1*). Switching and boundary strategies can add control and local rigidity.

Yet, switching between stable conditions can be induced by a change in boundary conditions as well as an external loading. This becomes problematic in failure conditions. When a force that the assembly resists goes beyond the prescribed limit, the change in the support geometry can induce a switch and modify the rigidity of the assembly in the wrong direction.

Switching states and axial rigidity



Switching states and bending rigidity



Switching by deformation

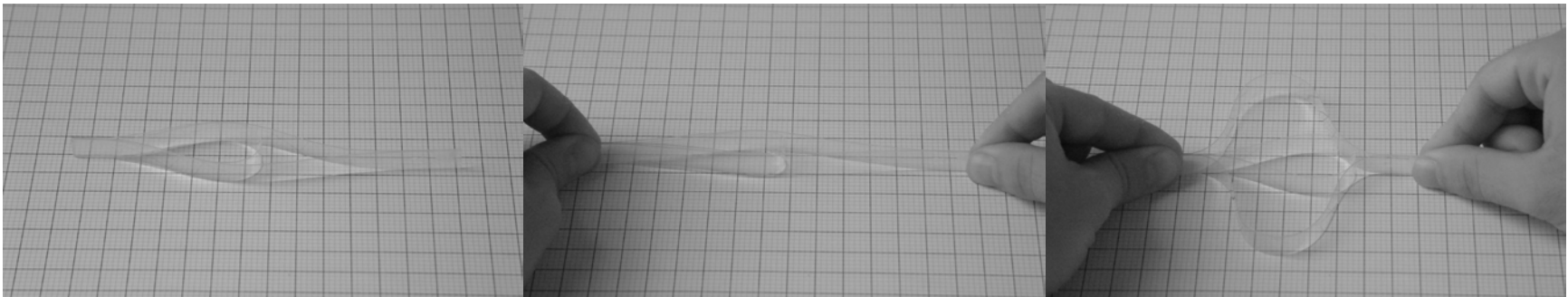
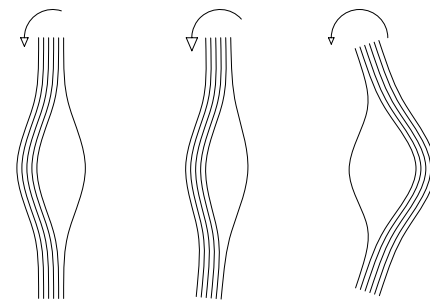
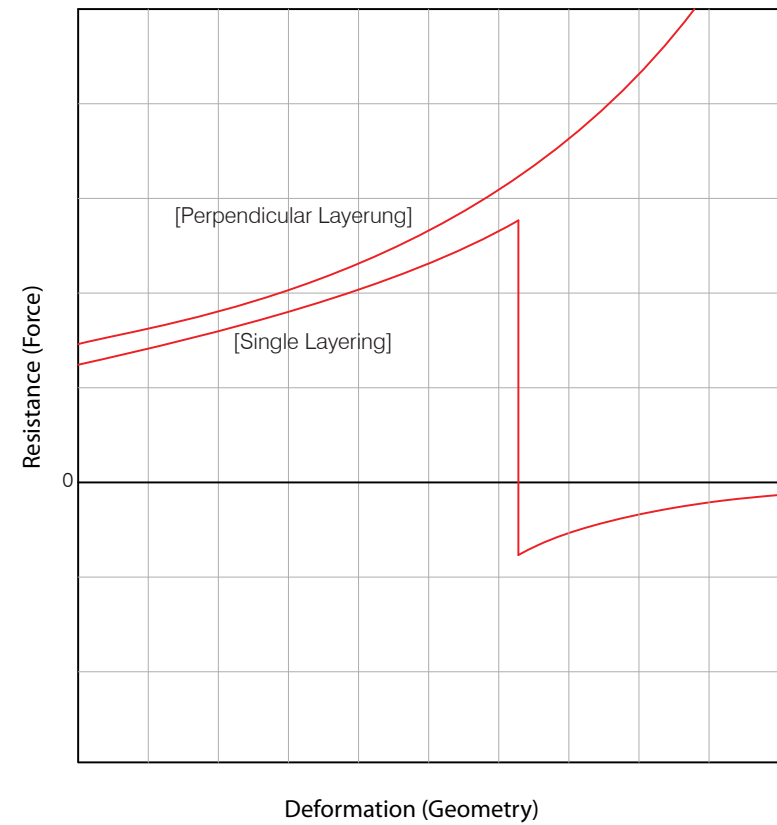
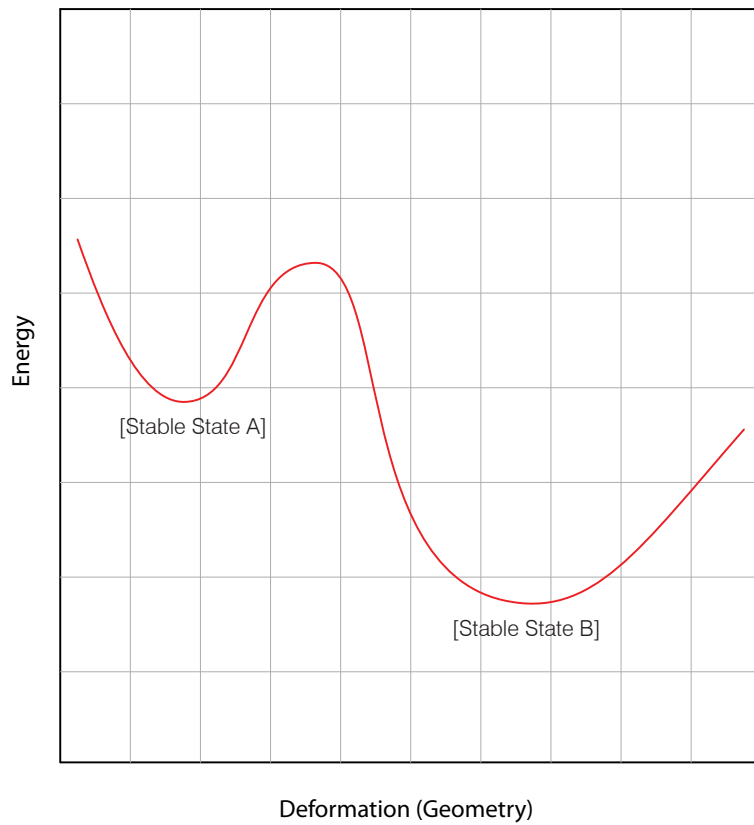
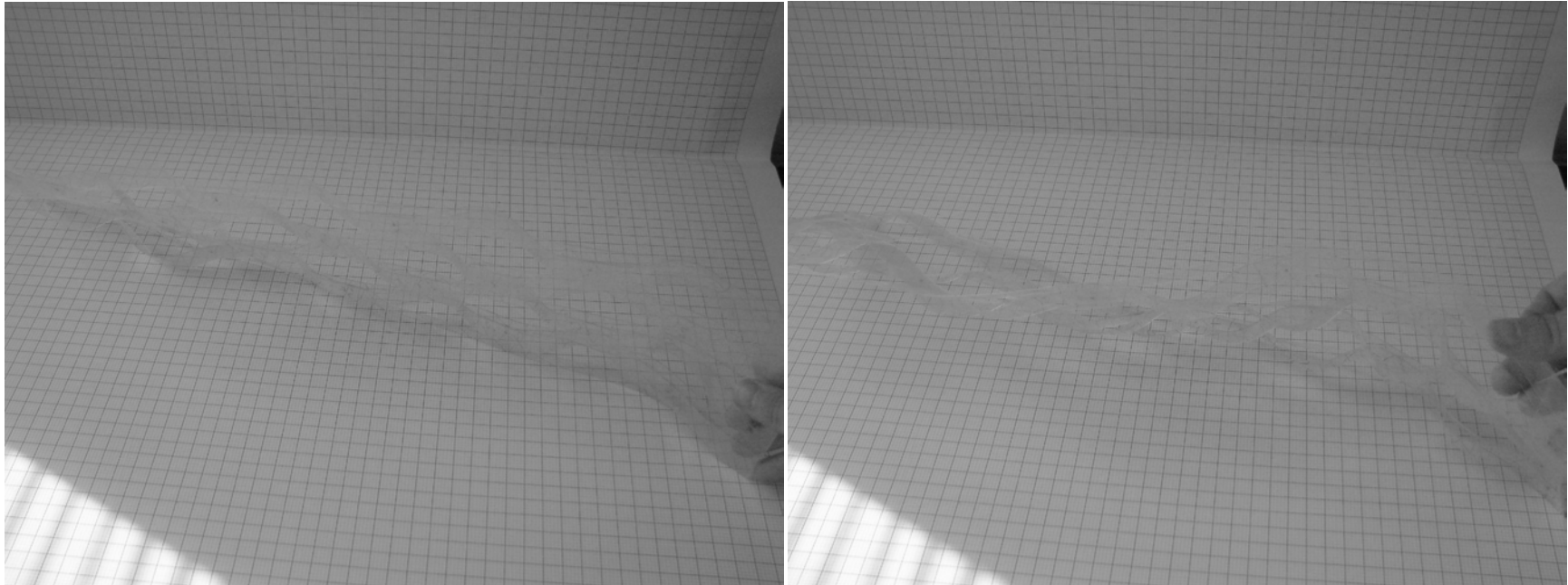


Fig. 2.1 ▣ Energy levels in stable states and switching

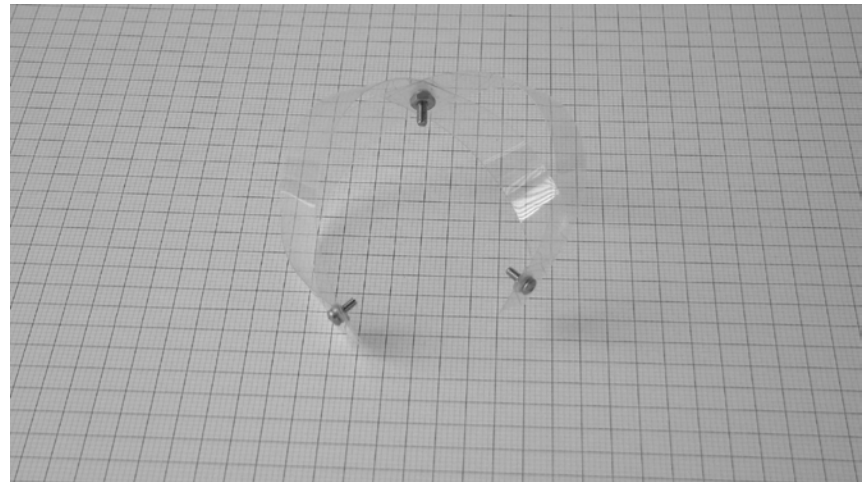
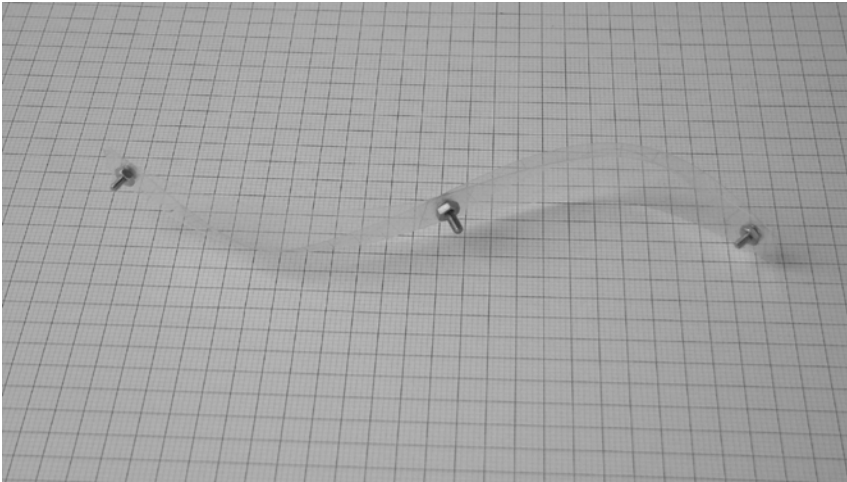
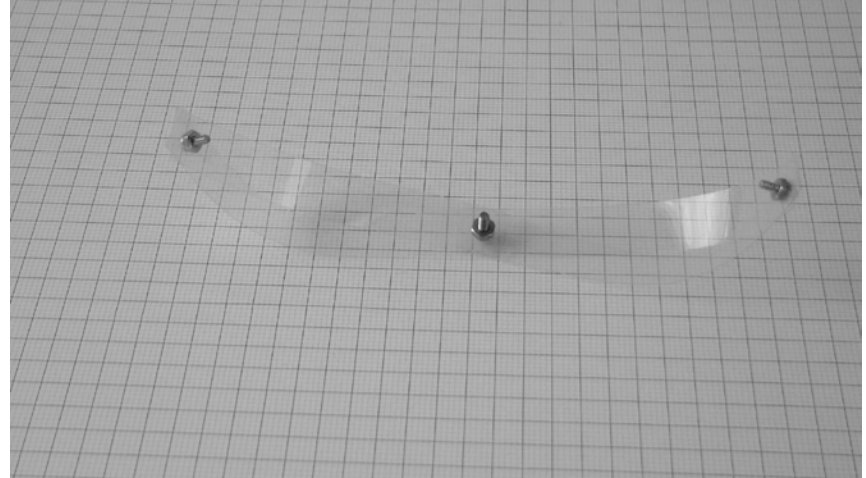
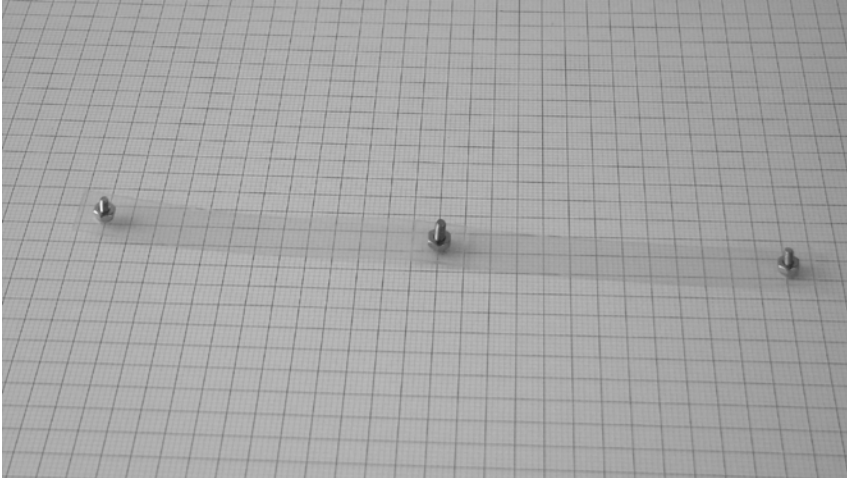


CHAPTER 2 :: KINETIC MOVEMENT USING MATERIAL BEHAVIOR
Accumulation of local switches creating a global deformation



CHAPTER 2 :: KINETIC MOVEMENT USING MATERIAL BEHAVIOR

Rotation resulting in out of plane bending

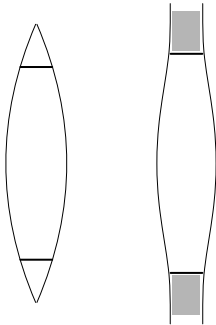


CHAPTER 2 :: KINETIC MOVEMENT USING MATERIAL BEHAVIOR

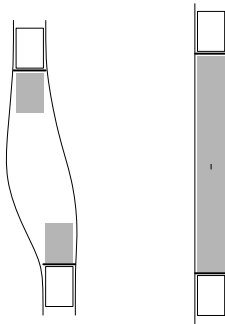
Perpendicular assemblies

Layering in perpendicular folding planes allows for a transfer of forces into the width of a sheet material, drastically affecting rigidity. However, this approach is most effective as a binary switch and becomes problematic for large scale gradual responsiveness (Fig.2.2).

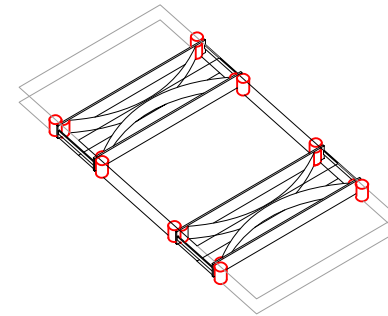
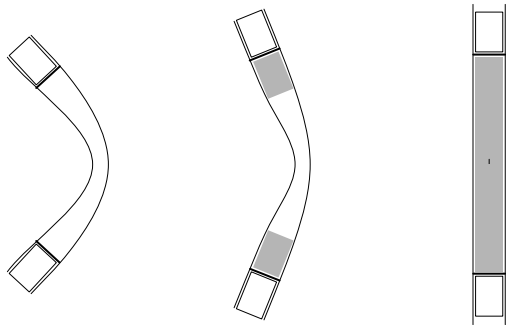
Increasing axial rigidity



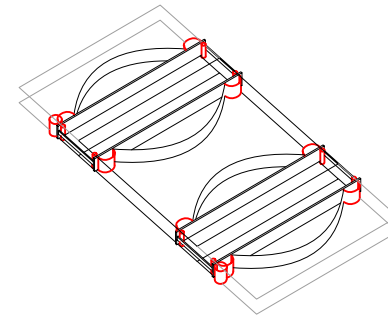
Increasing shear rigidity



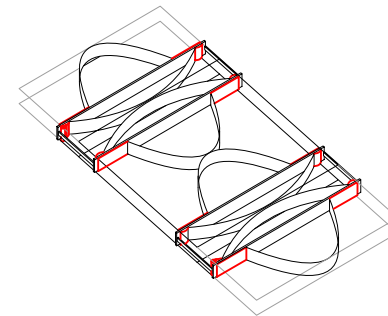
Increasing bending rigidity



Increasing axial rigidity

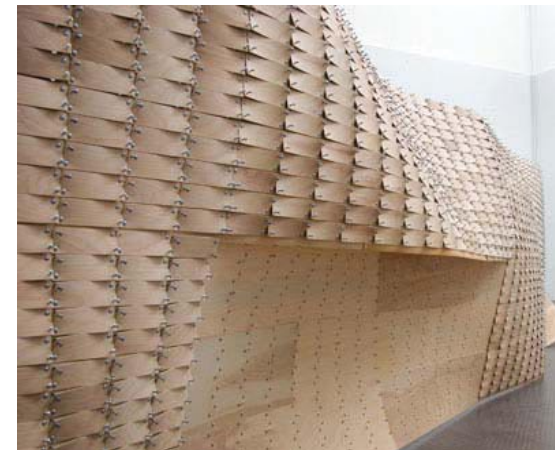
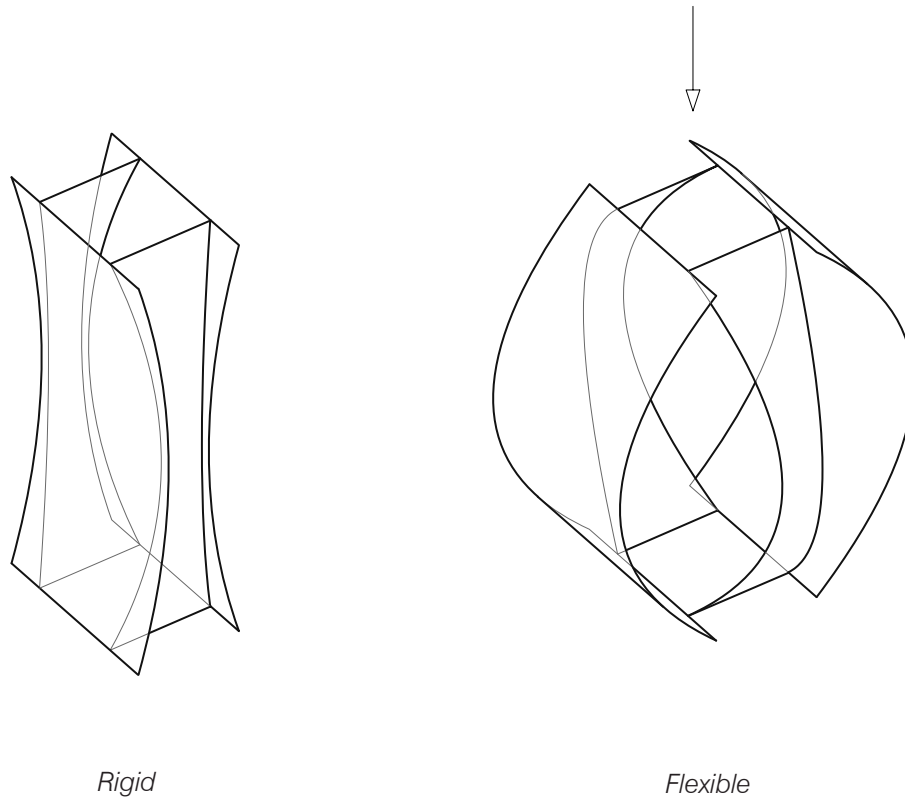


Increasing bending rigidity



Increasing bending, axial, and shear rigidity

Fig. 2.2 ▣ Local binary switching and possible global gradient



[Kellner, Newton, 2004]

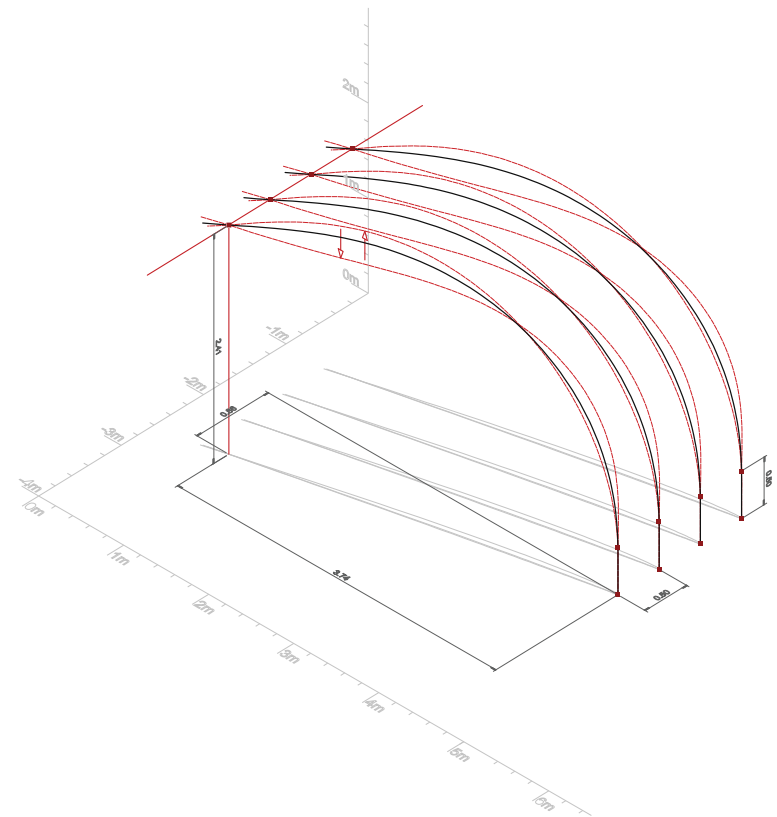
CHAPTER 2 :: KINETIC MOVEMENT USING MATERIAL BEHAVIOR

Limitations of deformation in scale

A study of the limitations of an elastic bending strategy showed the success of adaptable cladding and the failure of larger scale adaptable structure.

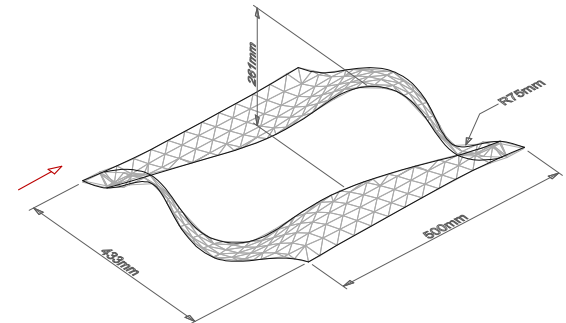
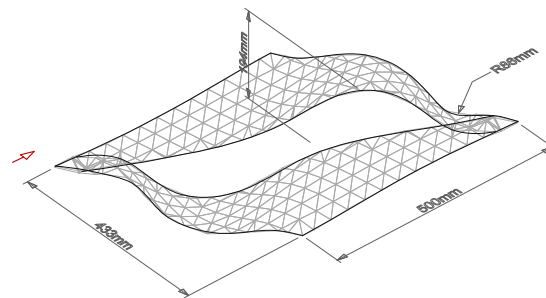
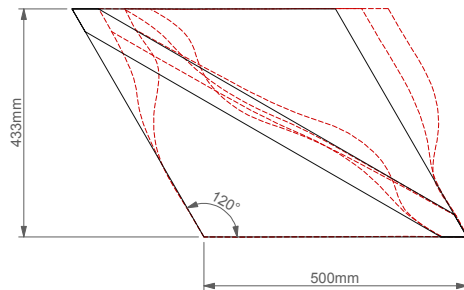
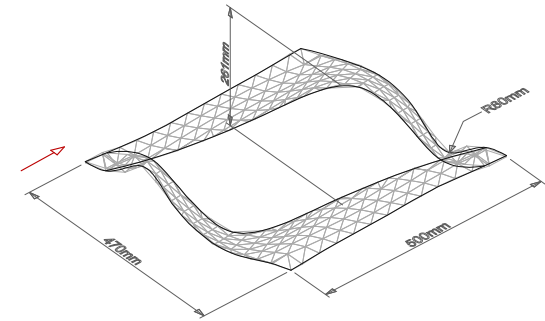
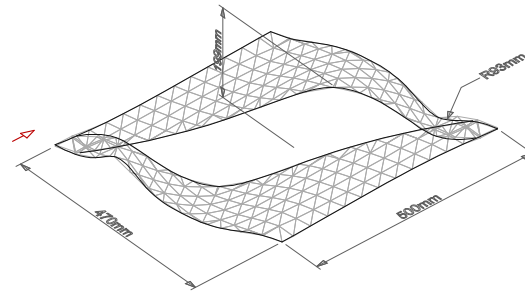
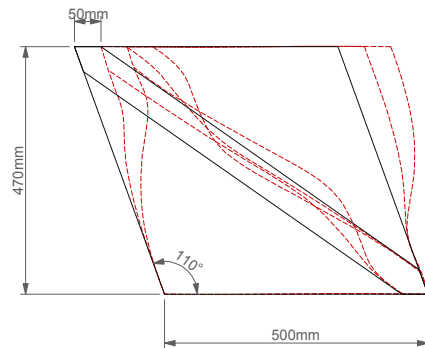
The experiment consisted of a deformable structure supporting sheet modules. These would react to the relative displacement between structural members. As scale models do not show an accurate reaction due to stiffness, simulations using modified Maya Cloth and spring particle systems allowed some predictions of the behavior of these two systems (*Annex 5*).

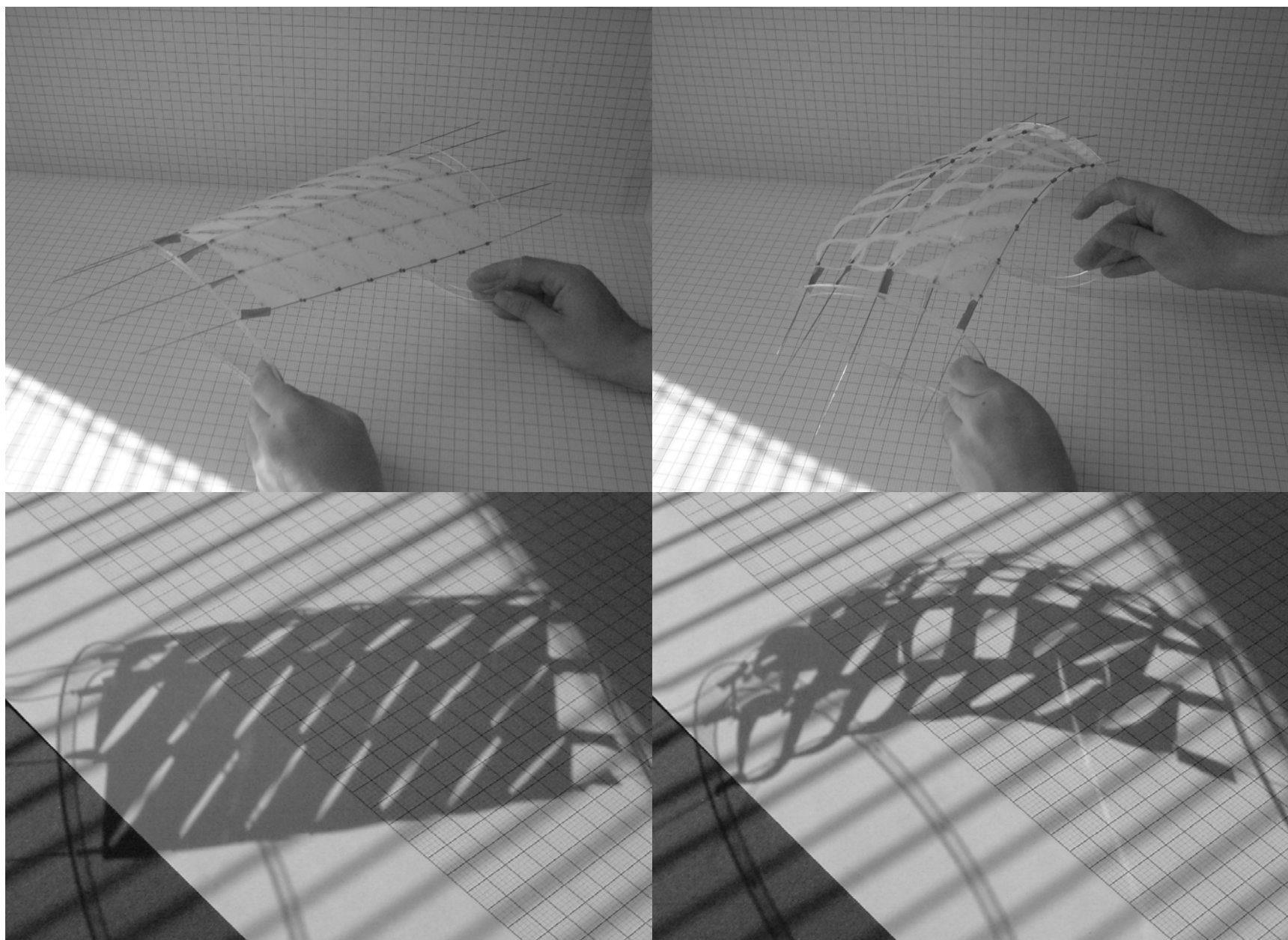
It was concluded that an application larger than 2m starts to exhibit problematic deformation and insatiably due to its susceptibility to wind and snow load.

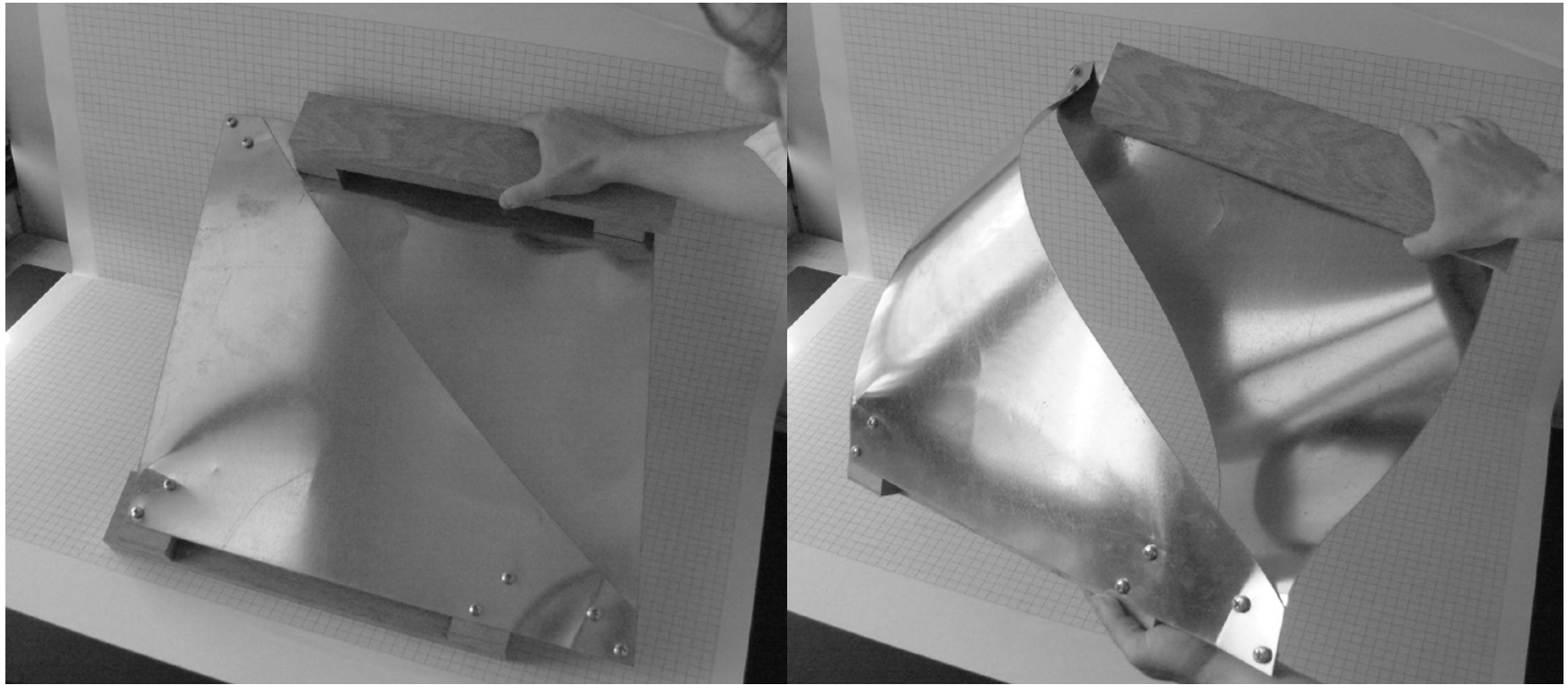


CHAPTER 2 :: KINETIC MOVEMENT USING MATERIAL BEHAVIOR

Limitations of deformation in scale







CHAPTER 3 :: BUILDING (AS) PERFORMANCE

A permanent pavilion for Montreal's Quartier des Spectacles

PROGRAM :: QUARTIER DES SPACTACLES

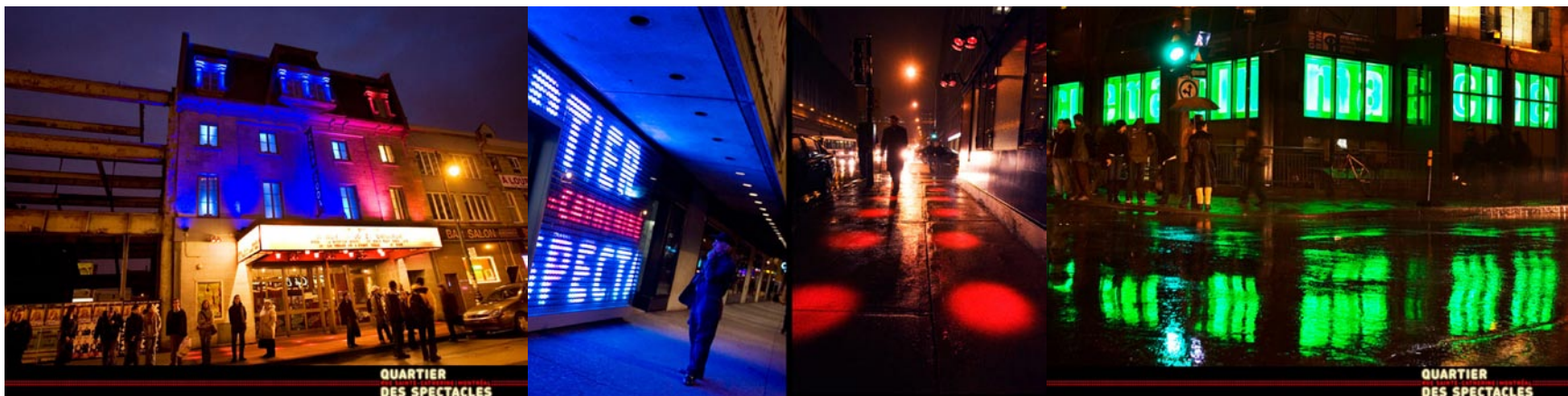
The district

Quartier des Spectacles is Montreal's main district. The neighborhood contains more than 30 private performance venues and hosts a dozen festivals throughout the year. Each venue has its own distinct visual identity, yet contributes to the unified visual lining that defines the area.

The intersection of St-Catherine street and St-Laurent street is its geographical and transitory center. During major public events such as the Just for Laughs festival and the International Jazz festival, these become pedestrian streets linking the established indoor venues with outdoor performance spaces and both ends of the neighborhood. The public path thus created is animated by street performers and vendors. Yet during the rest of the year, that center disappears.

The project proposes a ticketing booth and exhibition pavilion to be built on that site, defining the cultural network and serving as a resource and reference point to montrealers and visitors alike.

The pavilion will have to deal with the evolving program that surrounds it, transforming from a exhibition and information center, to a performance facilitator merging into the festival network.



SITE :: QUARTIER DES SPACTACLES
Performance venues and main street axis



SITE :: FESTIVAL JUST FOR LAUGHS
Performance venues and exterior public spaces



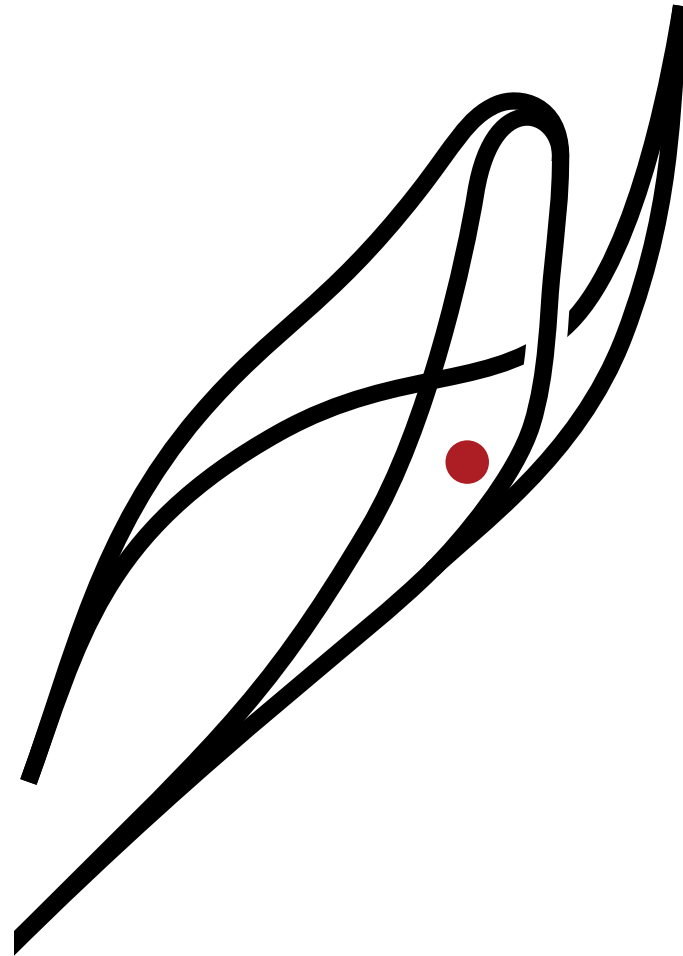
SITE :: INTERNATIONAL JAZZ FESTIVAL
Performance venues and exterior public spaces



PROGRAM :: DUAL IDENTITIES

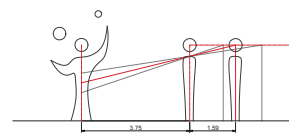
Circulation in context of temporary and permanent program

The ticketing booth program is in itself very small. The main area of the pavilion is used as exhibition space and exterior public space. A series of circulation paths lead the observer through the galleries and closer to the ticketing booth at the center. During festivals, these pathways draw the activity from the three adjacent streets into specialized zones for informal performance. The ticketing booth is still operational and the circulation is still free flowing, but the accumulation of crowds is controlled by subtle level changes, acoustical qualities and visual boundaries.



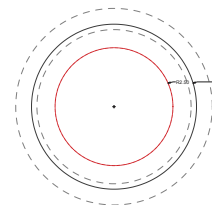
PROGRAM :: STREET ART

Spatial requirements as defined by crowd accumulation

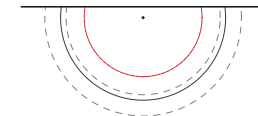


Condition A - Flat plane

Crowd Accumulation



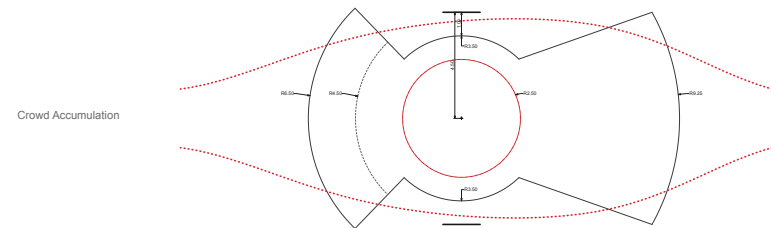
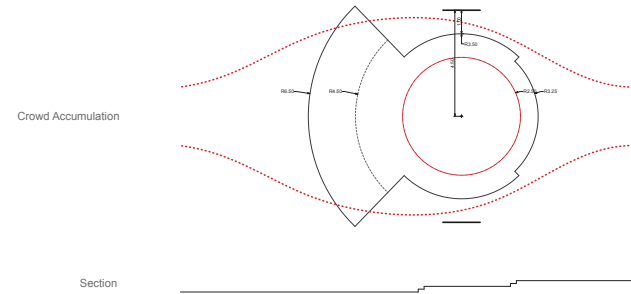
Street Art



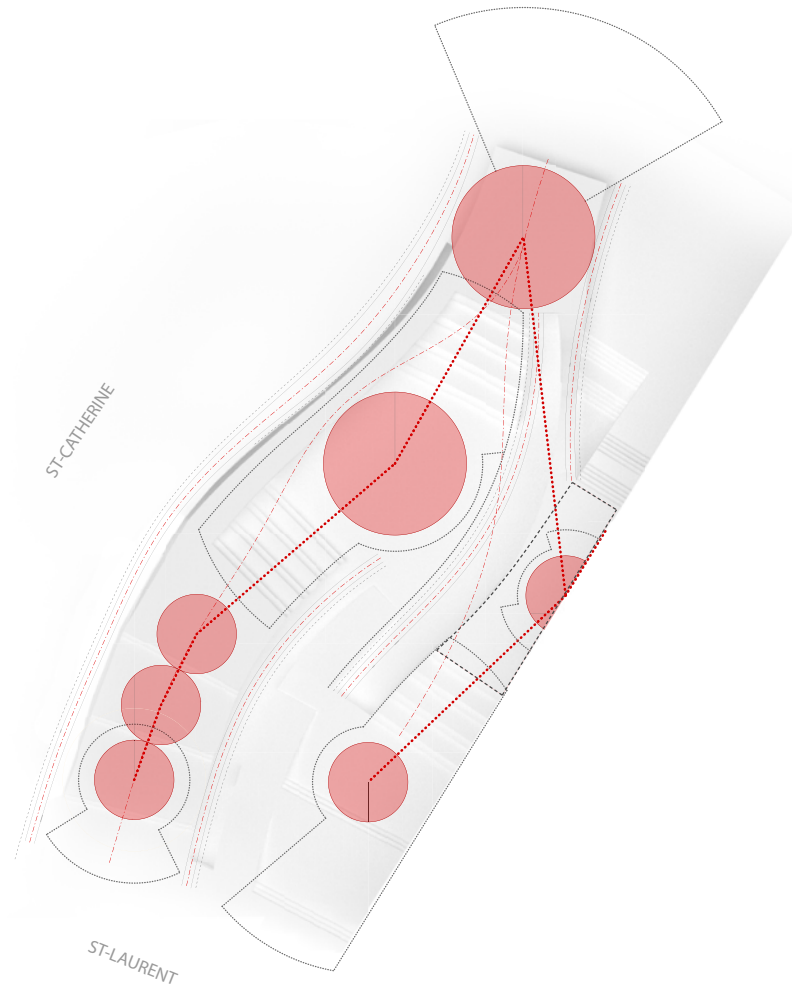
Musical Performance

PROGRAM :: STREET ART

Audience morphology: variability in crowd accumulation



PLAN :: PROGRAMMATIC DISTRIBUTION
Diagramed performance layout and plan



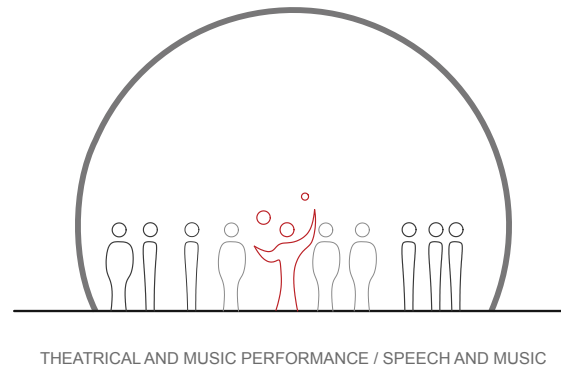
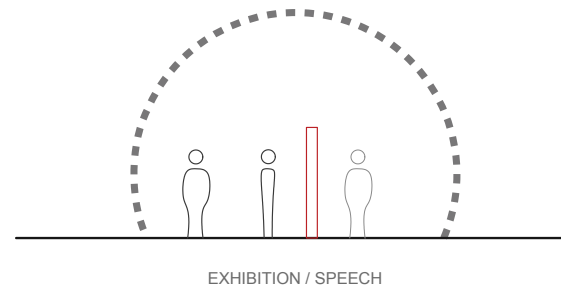
PROGRAM :: DUAL PROGRAMMATIC CONDITIONS

Performance criteria for exhibition and performance

The pavilion space is mainly a passageway. Many venues will add installations featuring a taste of the upcoming cultural and artistic events. Acoustically, this space needs to be designed for speech. This means a low reverberation time and acoustical transparency. Inversely, during performances, the reverberation time increases, the acoustical separation between street noise and interior is accentuated and the immediate enclosure acts as an amplifier for the performer as well as the crowd's reaction. This enables a condition of temporary internal privacy with a broadcast of activity to the outside to draw people in.

Visually, a similar transformation is called for. The exhibition program is not only internal but also emissive. The skin that surrounds it projects the internal lighting choreography as broadcast media. As a performance space, on the other hand, the lighting needs to be controlled and confined to an internal experience. This shift between opacity, surface transparency, and volume transparency adds to the intrigue that brings and ephemeral audience into the space.

As a result, the tunnel like space will deform locally during a performance to increase in volume (and reverberation time proportionately), force its skin to close up becoming acoustically and visually reflective and opaque.



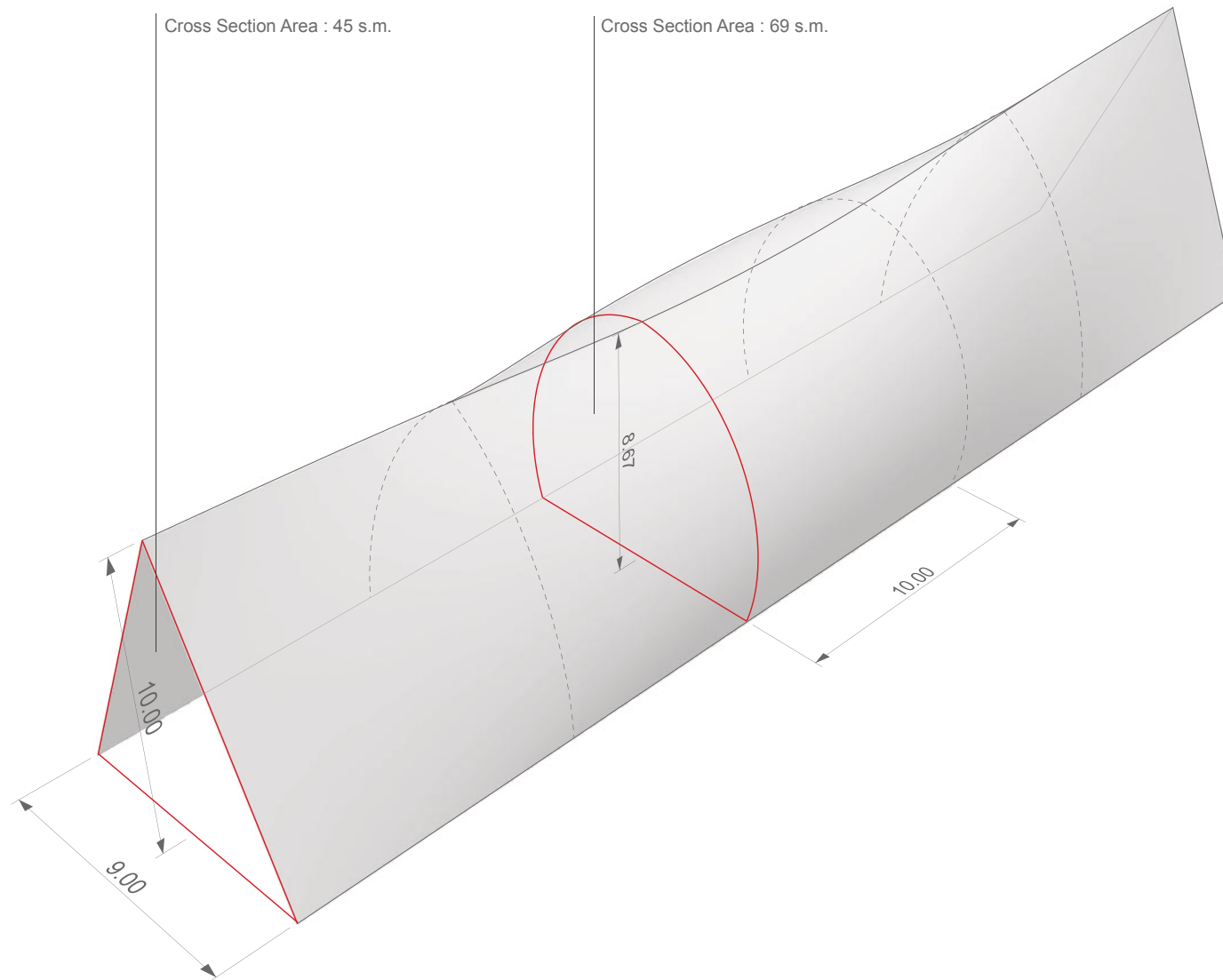


Fig. 3.1 :: Sound level absorption and transmission goals
Ref.: [Egan, 2007]

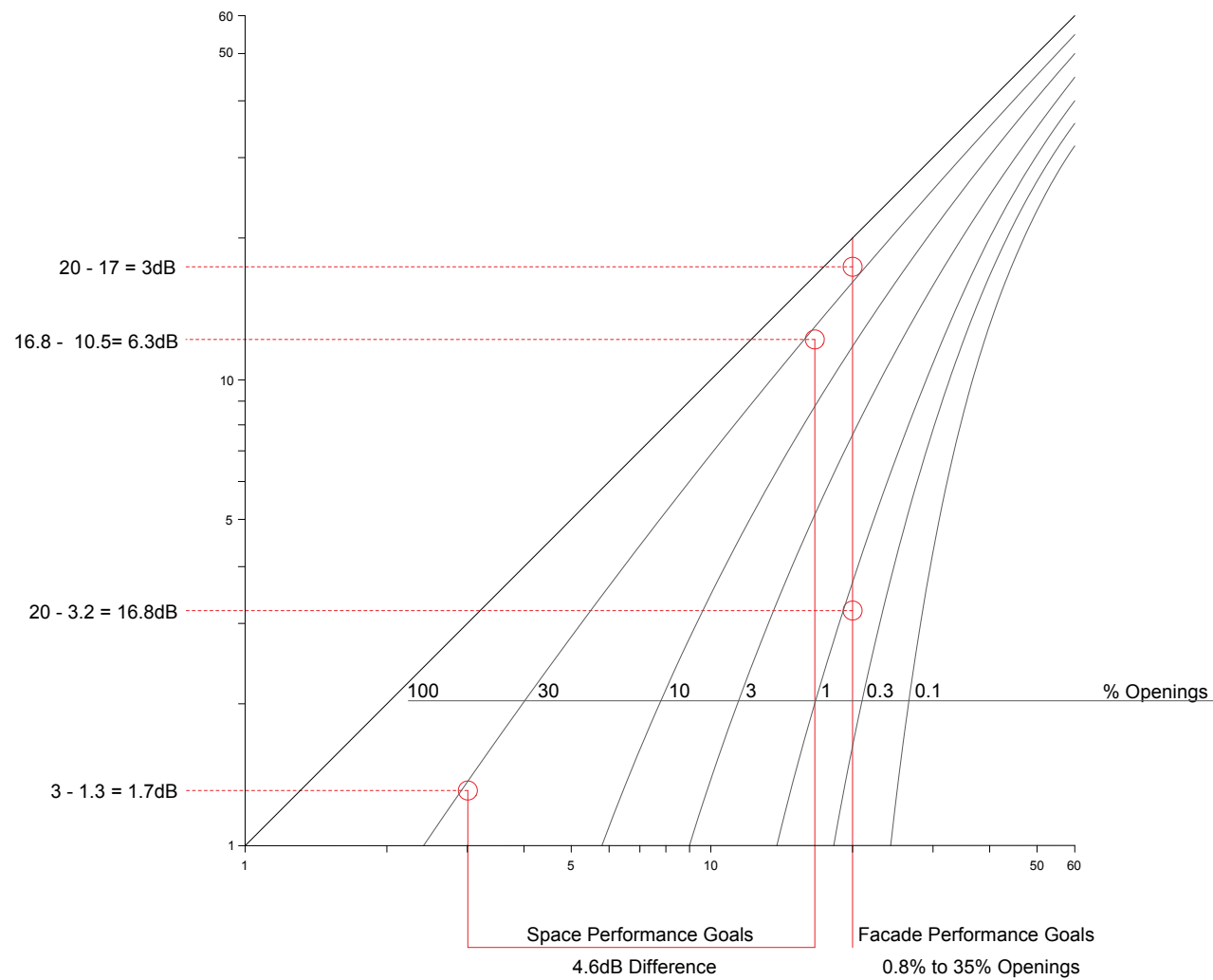
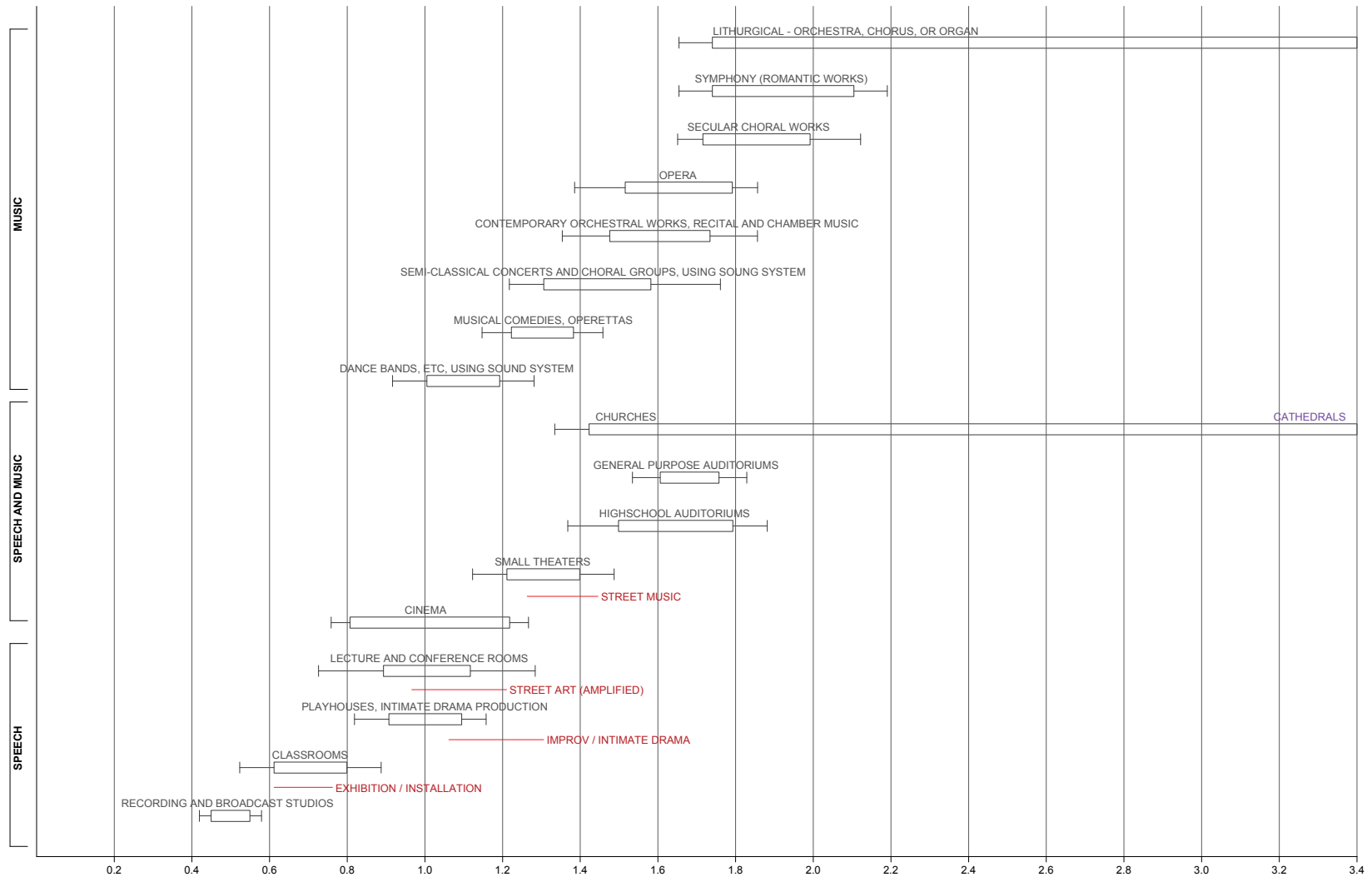
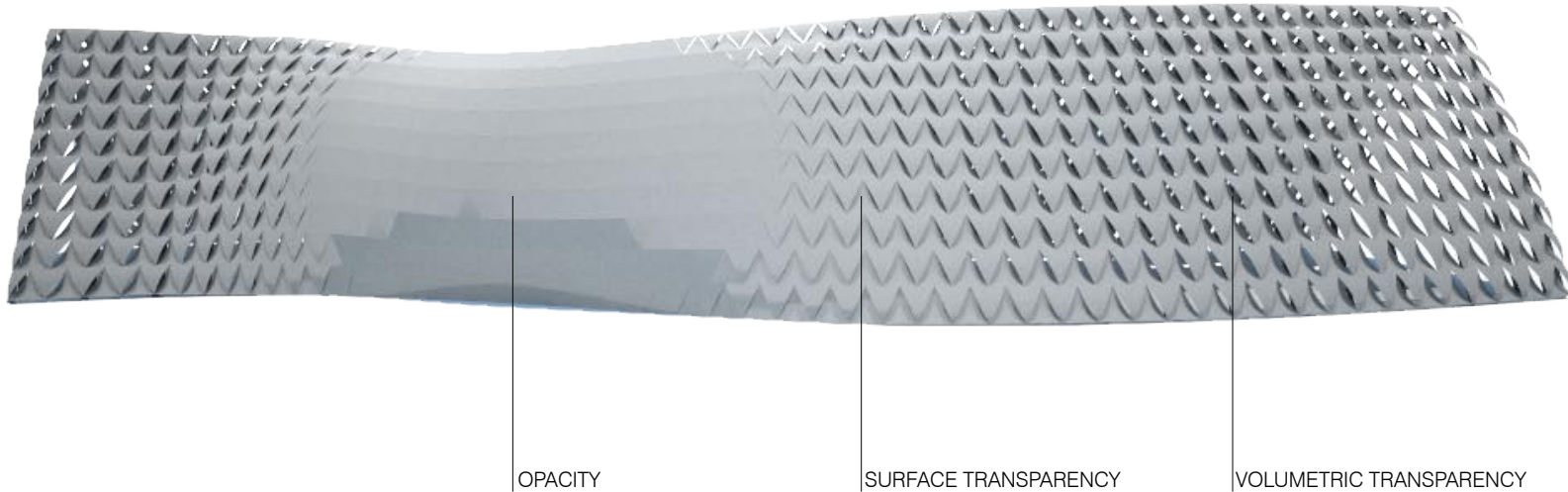


Fig. 3.2 :: Reverberation times for given program types (in seconds)
 Ref.: [Egan, 2007]

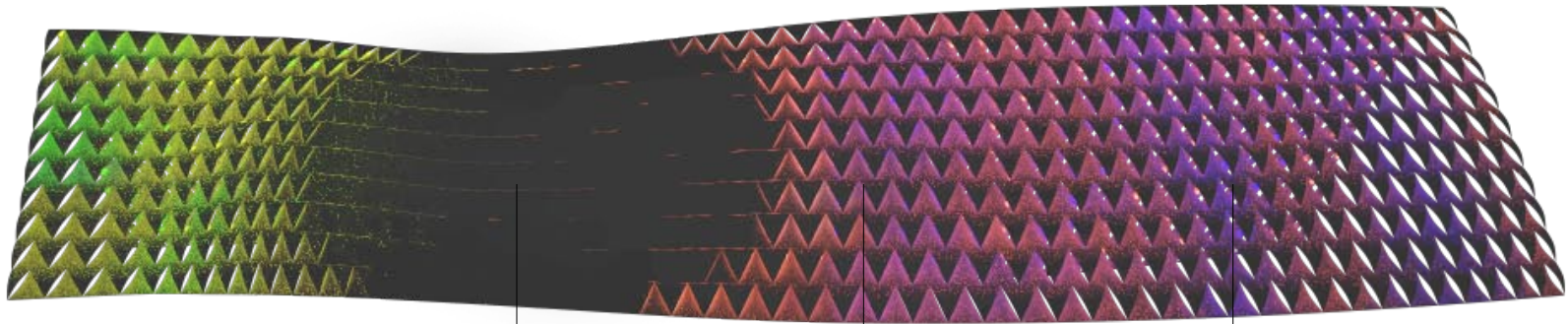


SKIN :: ADAPTIVE SURFACE
Local variability



SKIN :: ADAPTIVE SURFACE
Mediascape

EXTERIOR

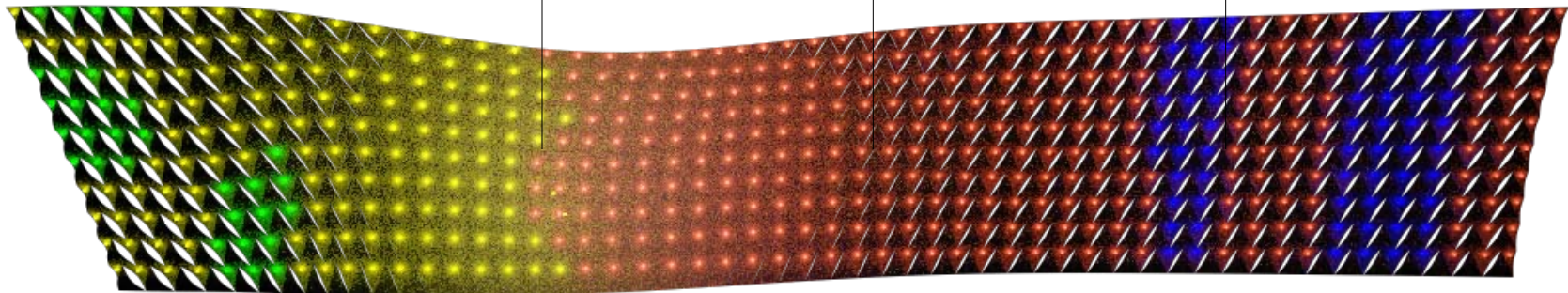


OPACITY

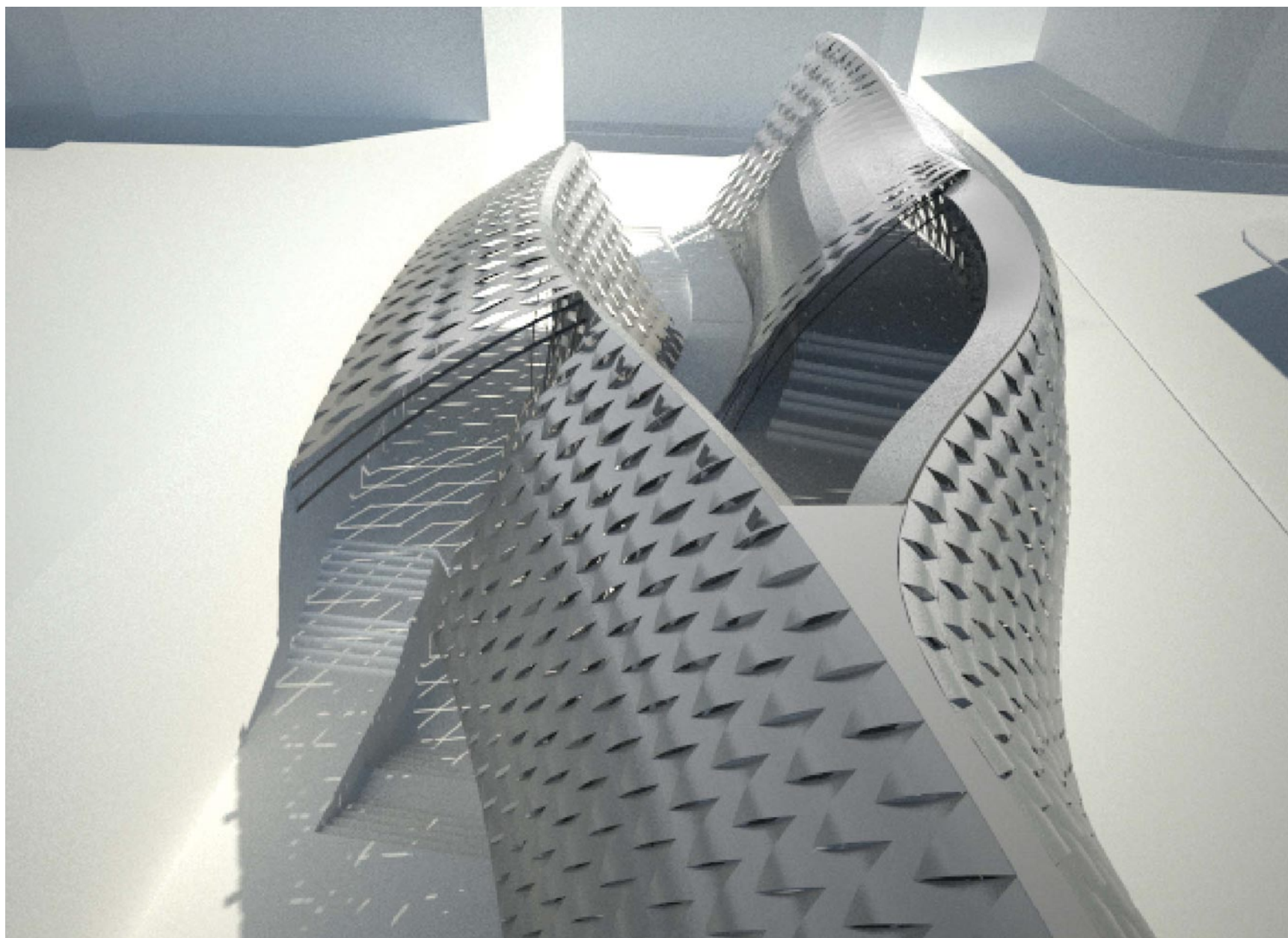
SURFACE TRANSPARENCY

VOLUMETRIC TRANSPARENCY

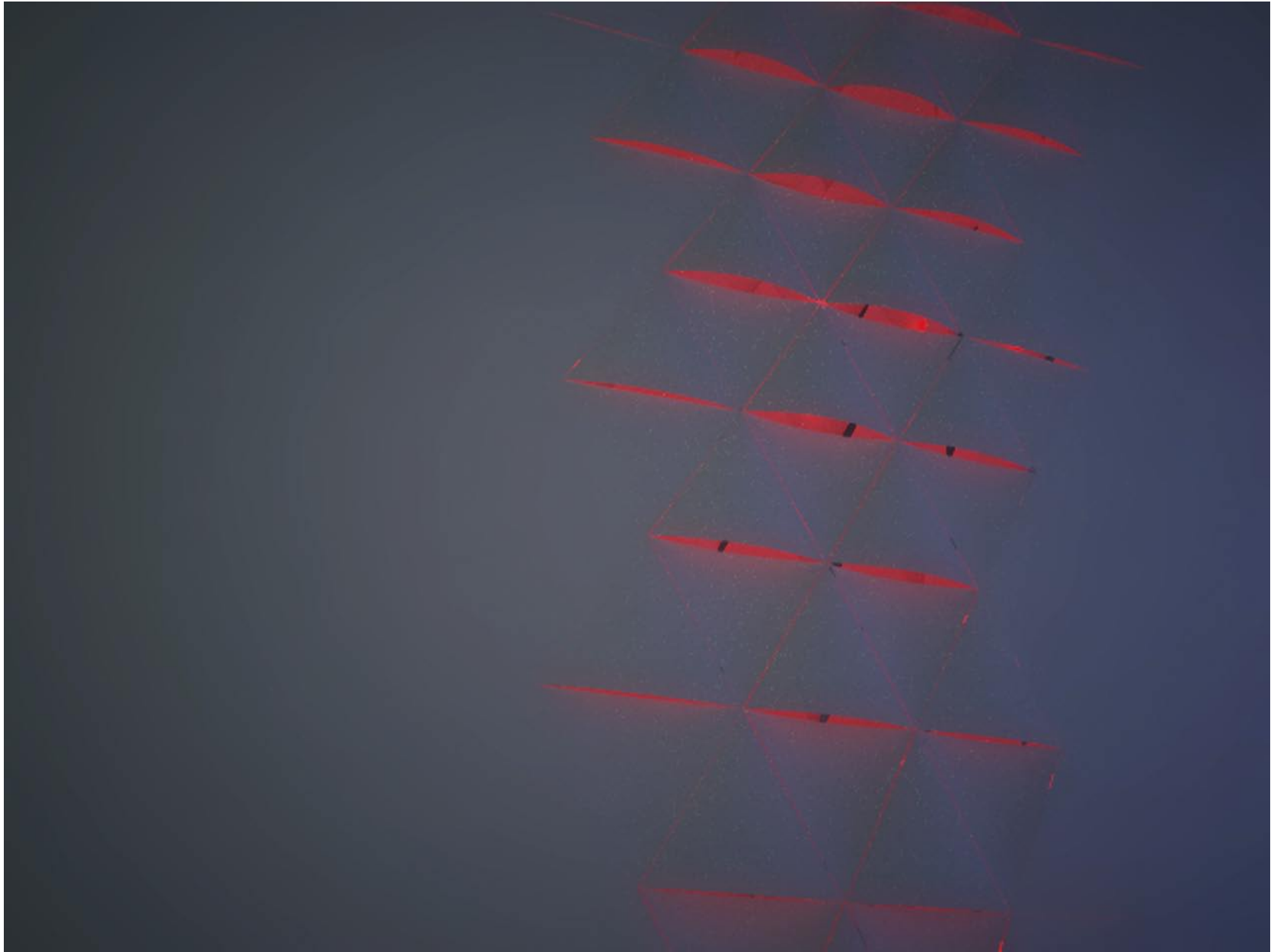
INTERIOR



SKIN :: ADAPTIVE SURFACE
Spatial intersections

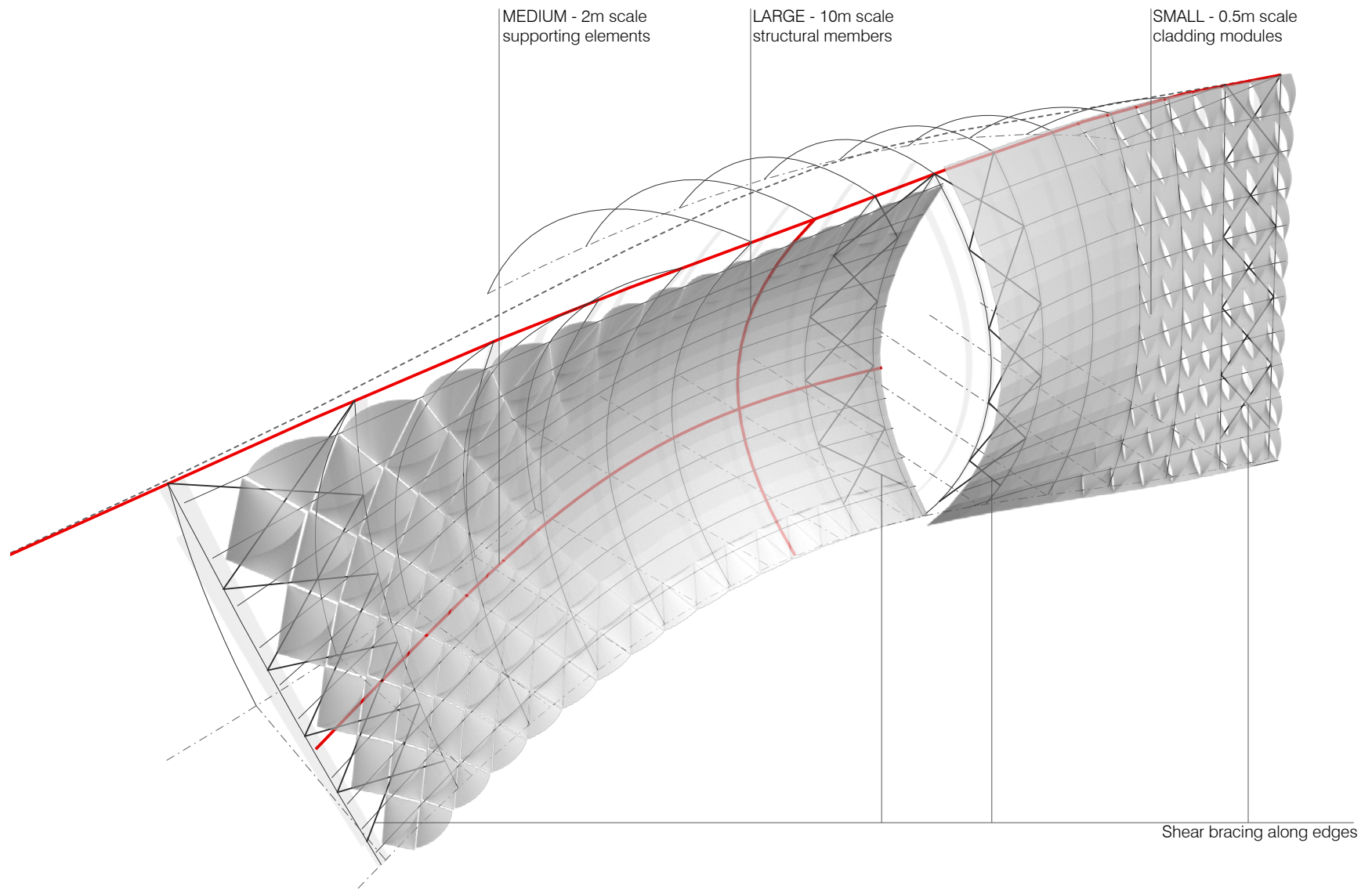


SKIN :: ADAPTIVE SURFACE
Building as performance



TECTONICS :: ADAPTABLE SURFACE

Three scales of flexibility using materials in bending



TECTONICS :: ADAPTABLE SURFACE

Large scale structural adaptability

From theory and simulations (*Annex 5*), it can be concluded that, for large scale structural members, bending as a singular strategy is unpractical. The internal forces required for morphological freedom become of the same magnitude as the external forces to be resisted. This implies major instability due to the volatility of wind, snow and earthquake loads. To achieve temporary rigidity without a continuous input of energy and without sacrificing gradual movement, some mechanical elements must be introduced.

Bending however helps in minimizing this addition as well as minimizing the actuator force needed to drive the movement.

The problem of movement at that scale becomes that of maintaining a stiff truss at every point within the range of deformation. To achieve this, a displacement needs to be introduced in the truss geometry. Focusing on the central neutral axis allows for minimal actuator force as well as minimal stress on the mechanical elements.

By producing a controlled displacement in shear, the form of the overall member can be modified (*Fig.3.3*). Also, this displacement can be linear if the shape remains the similar and only the magnitude changes. Most pertinent to this project is the circular shape and a variability from a 5m curvature radius to a straight line.

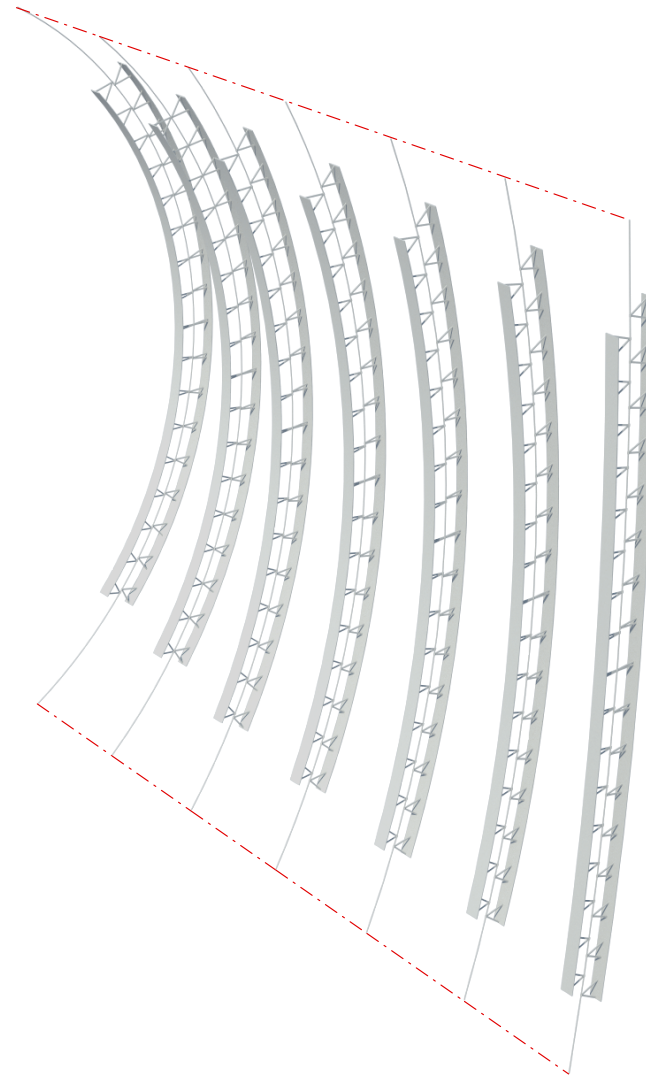
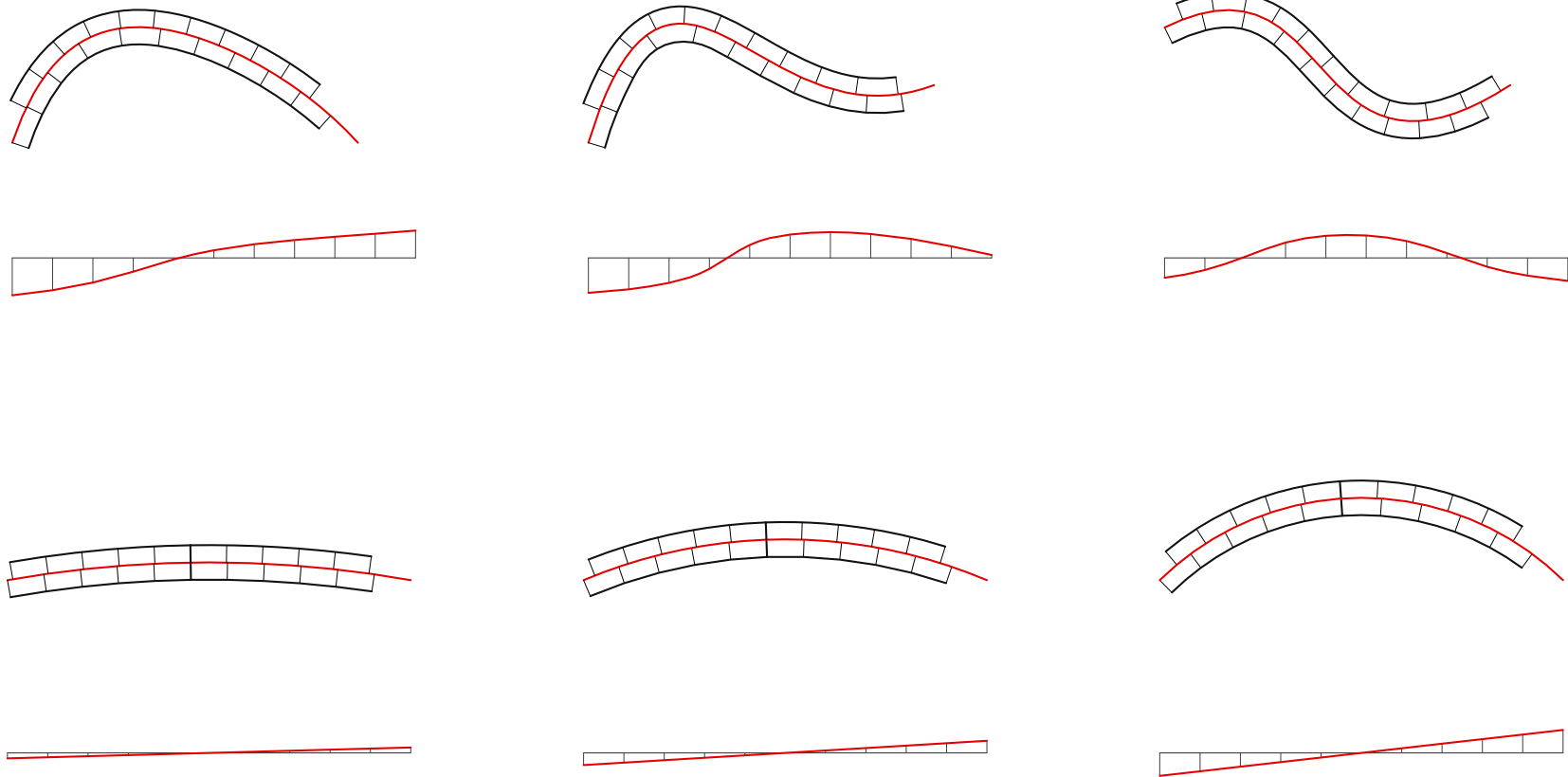


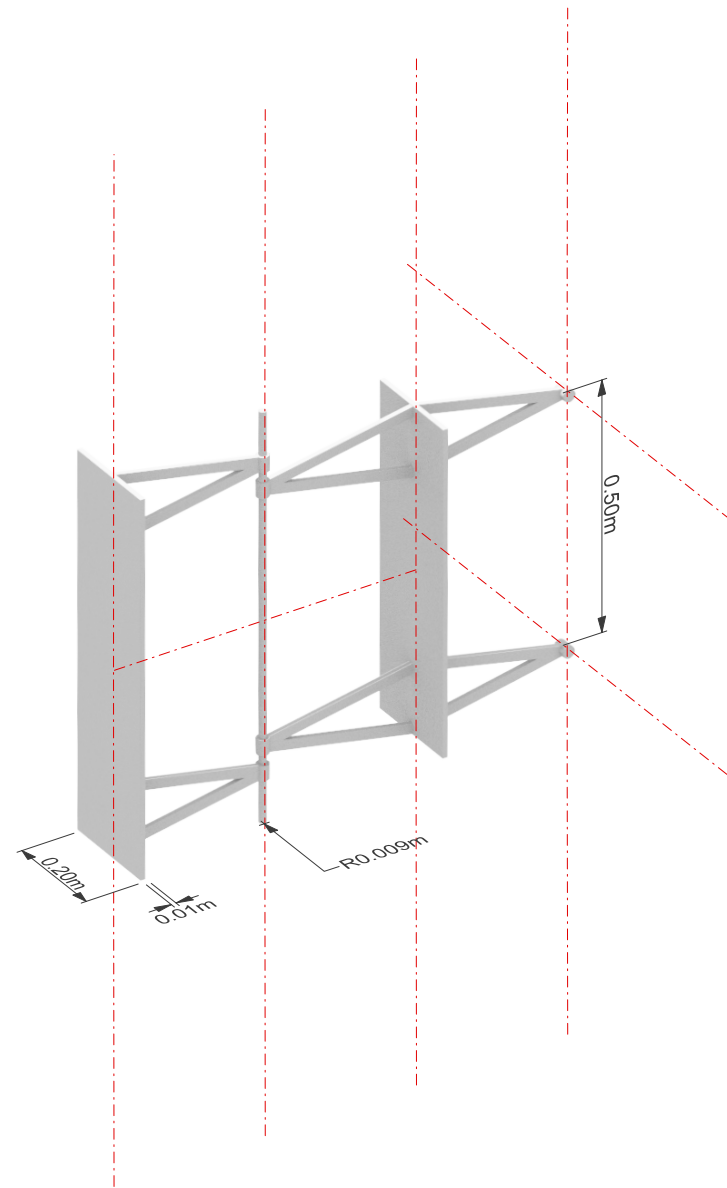
Fig. 3.3 ■ Shear displacement at neutral axis and implications on form



TECTONICS :: LARGE

Deformable truss

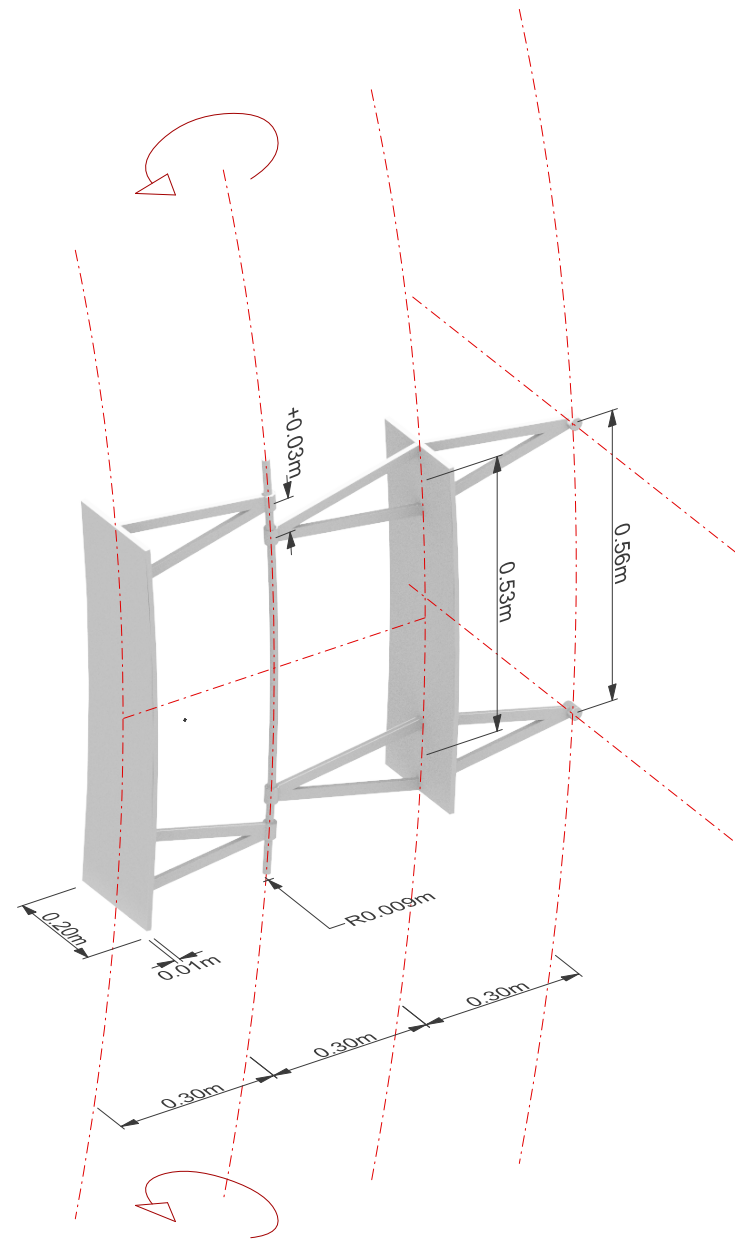
A 10m vertical truss is mainly loaded by the wind. From bending alone this force exerts a maximum load of 65kN in compression and tension at the edges of a 600mm wide truss. The maximum shear on the other hand is a quarter of the magnitude and highest at the edges. From Finite Element Analysis (*Annex 6*), the thickness and geometry of the individual members can be determined as to allow for minimal deformation from the rigid form.



TECTONICS :: LARGE

Deformable truss

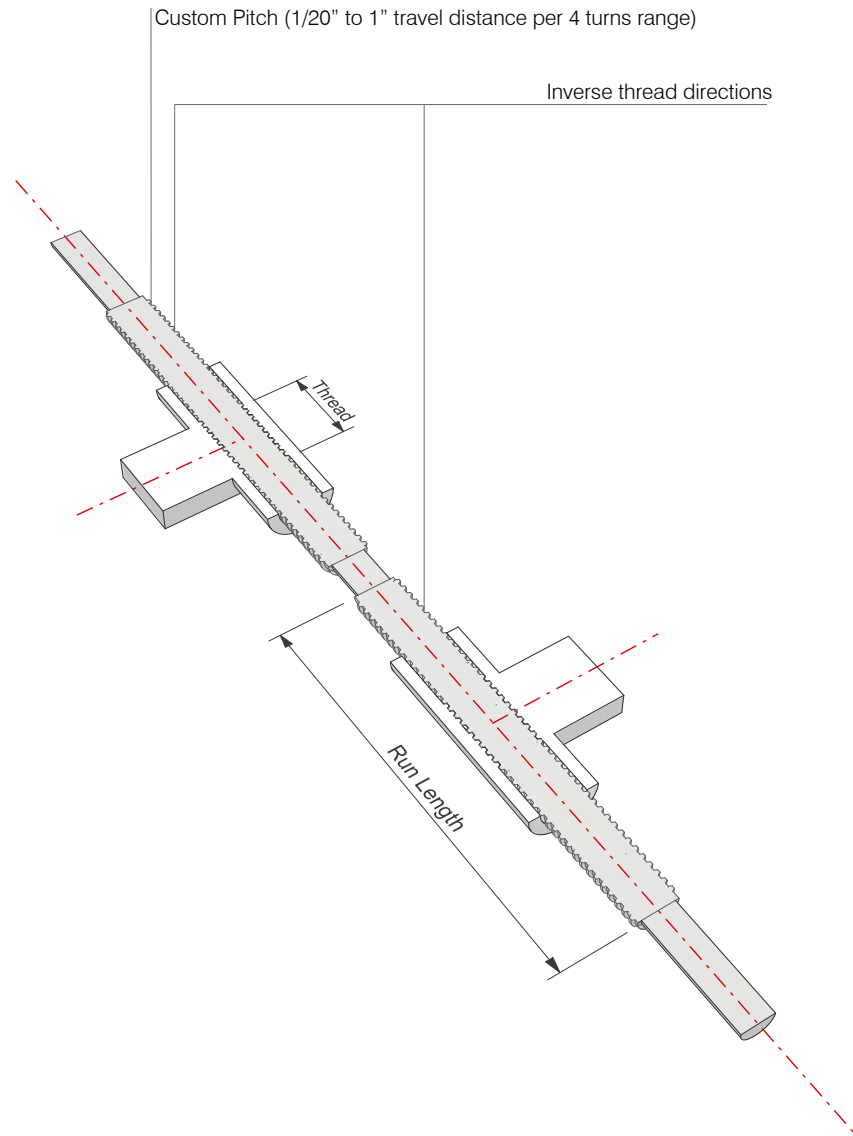
A continuous threaded rod at the center turns to generate a displacement that is translated through material deformation into a minimal radius of curvature of 5m. Because the horizontal support axis for the cladding is offset from the main structure, this curvature implies a change in the vertical spacing of the supports.



TECTONICS :: LARGE

Mechanical detail

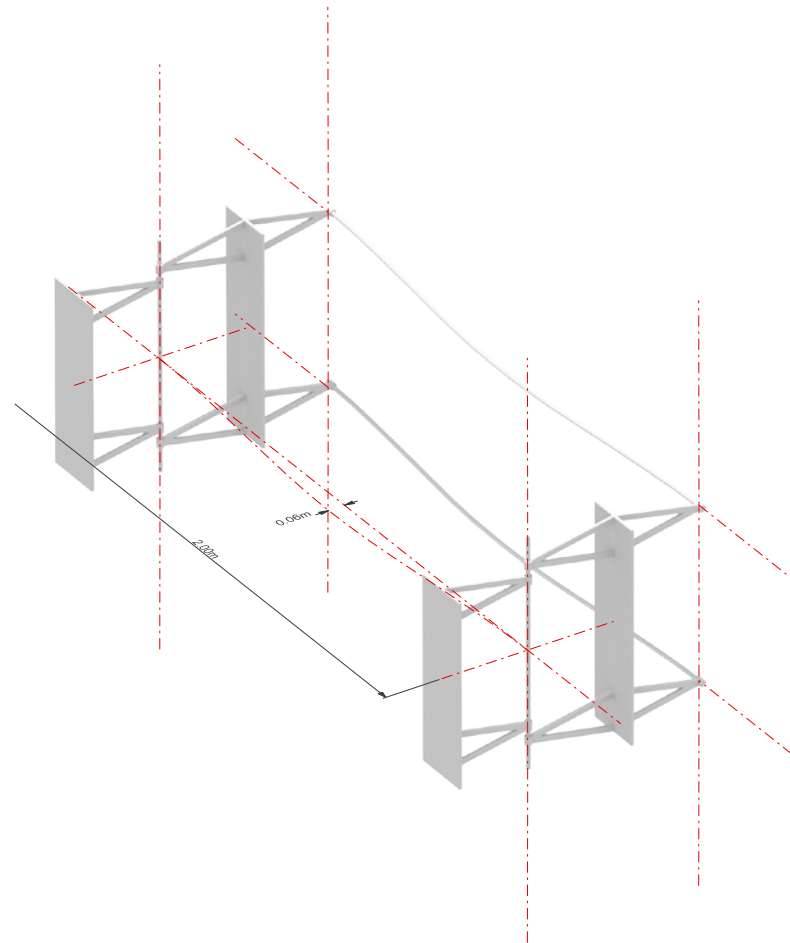
The threaded rod is the only custom CNC element. As shear displacement on the neutral axis is additive, the local runs grow as one moves from the center to the edges. The requirement of a continuous rod turning at a uniform rate results in a variable thread pitch: from a travel distance of $1/20''$ at the center to $1''$ at the edges.



TECTONICS :: MEDIUM

Supporting members

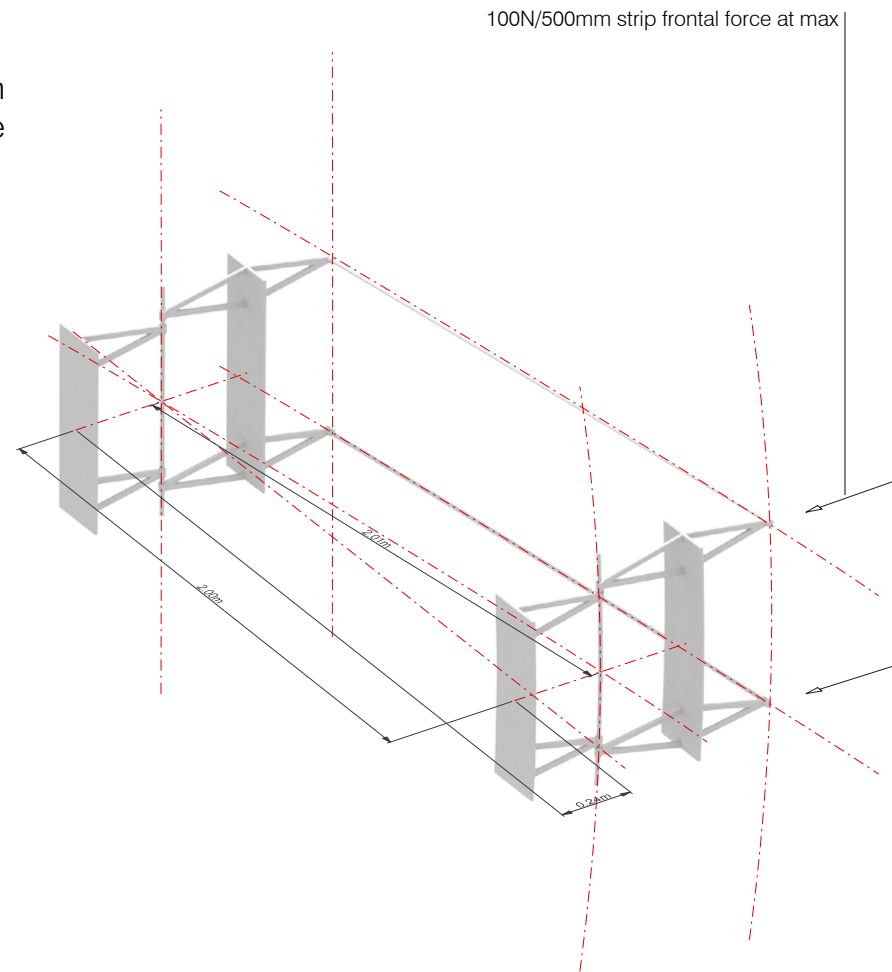
At the medium scale (2m), a controlled deformation of the horizontal support elements allows for an effective elongation needed if the overall surface is to morph smoothly, without mechanical joints. This added internal pressure has a minimal effect on the assembly's rigidity (*Annex 6*).



TECTONICS :: MEDIUM

Supporting members

The added force transferred to the structure by the deformation of the horizontal supports accounts for 1/20 of the magnitude of the wind load.

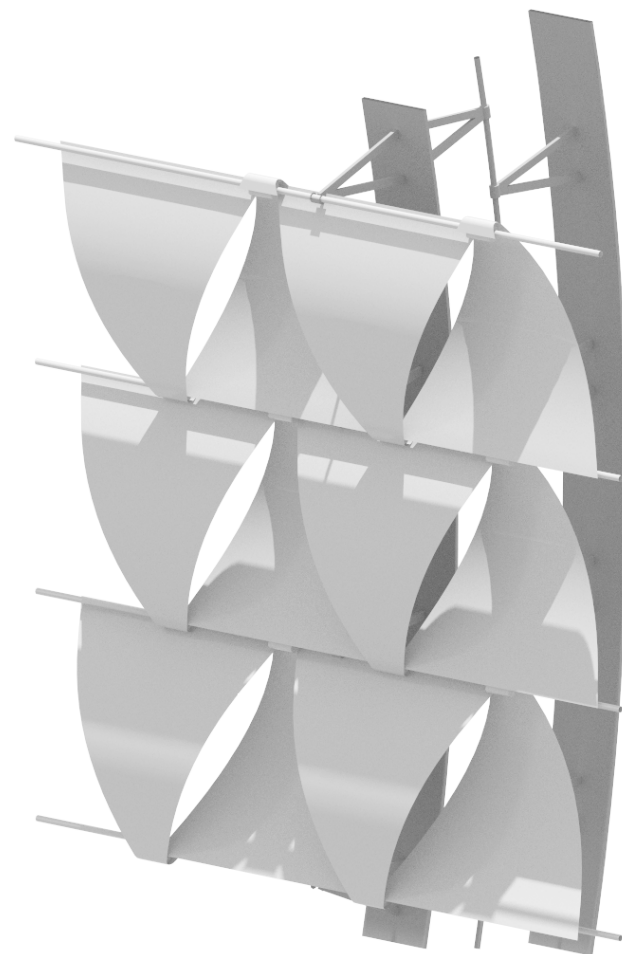
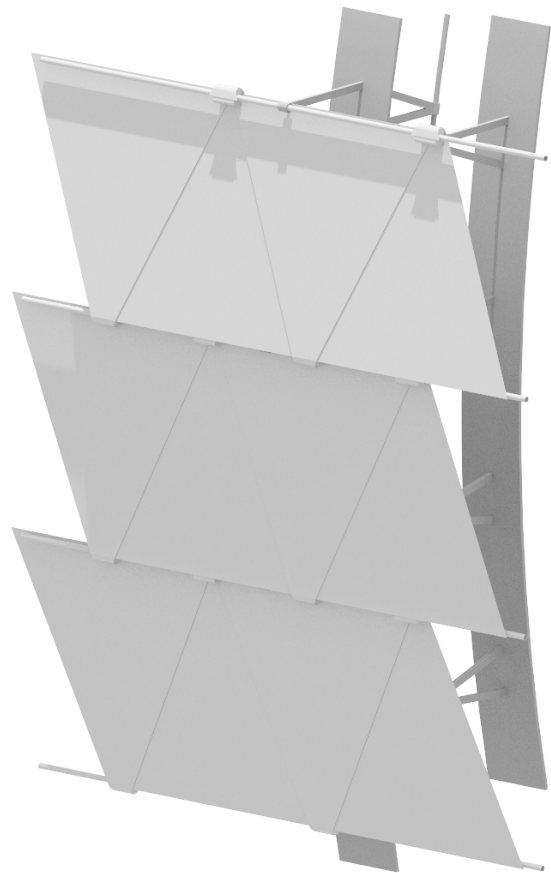


TECTONICS :: SMALL

Adaptive cladding

At the small scale ($< 1\text{m}$), bending of sheet materials becomes most feasible. Driven by the variation in curvature of the structural members and thus the change in spacing between horizontal supports, the cladding can be designed to respond in a desired way. Two systems were developed.

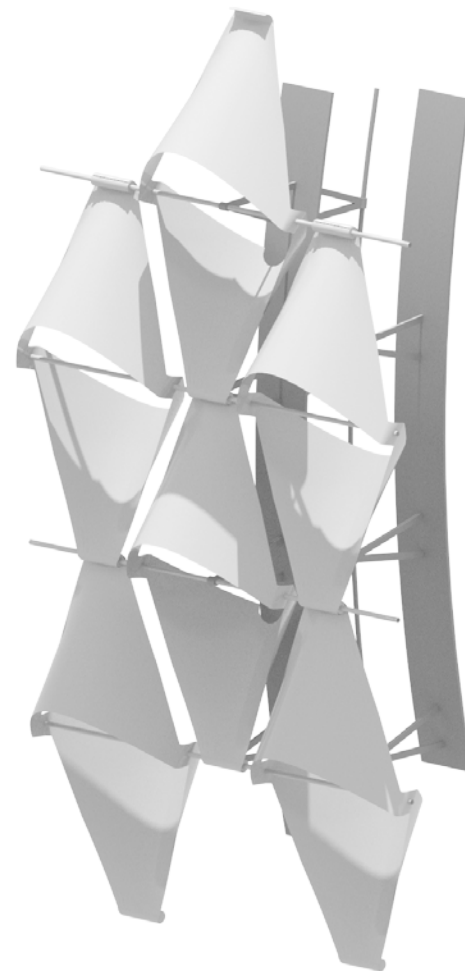
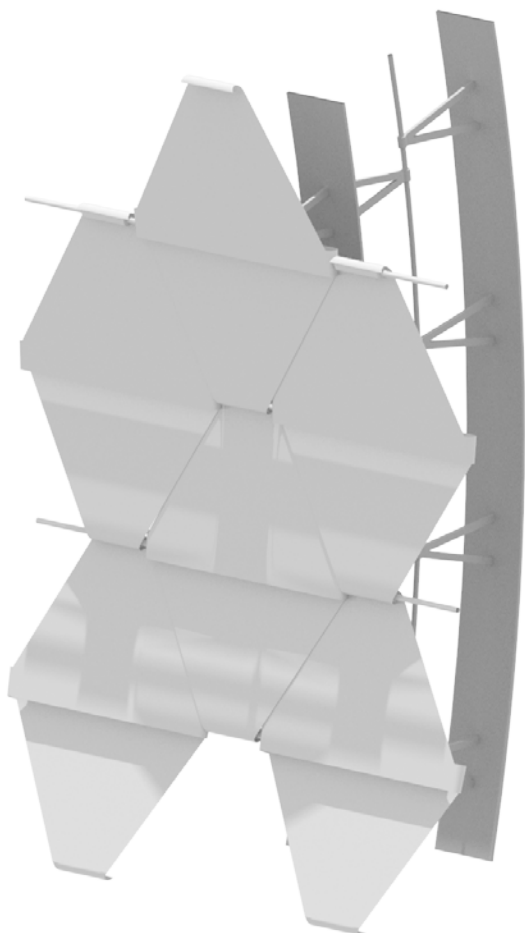
The first is closed and opaque when the curvature is directed outward and the internal volume is increased. The addition of LED lighting to the interior facing side of every downward triangle allows for a transmission of pixelated media to the outside through the reflectivity of the material.



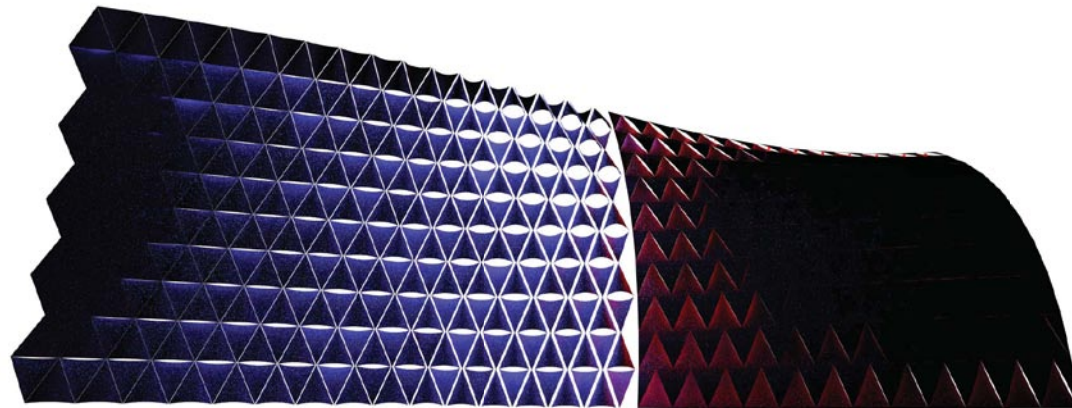
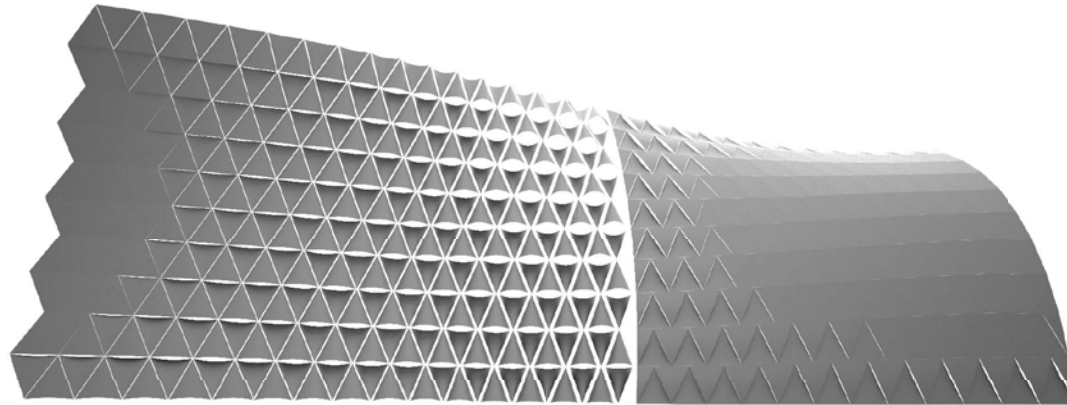
TECTONICS :: SMALL

Adaptive cladding

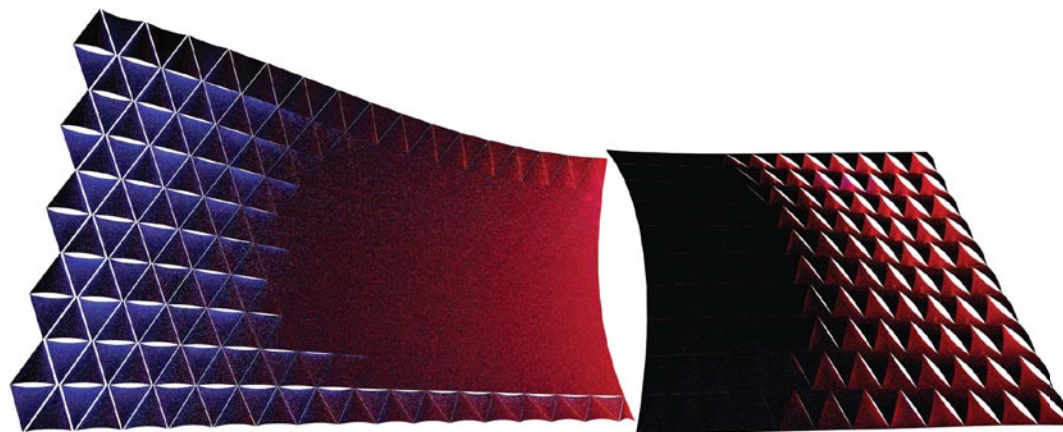
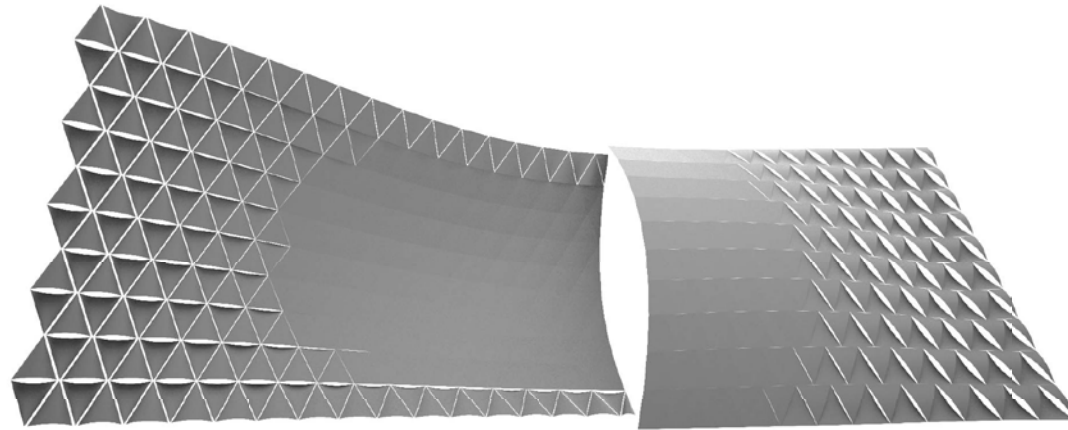
Inversely, the second is closed and opaque when the curvature is directed inward and the internal volume is decreased. This property allows for an acoustical amplification to an exterior adjacent space. The addition of LED lighting to the interior facing side of every upward triangle allows for a transmission of pixilated media to the outside through the reflectivity of the material.



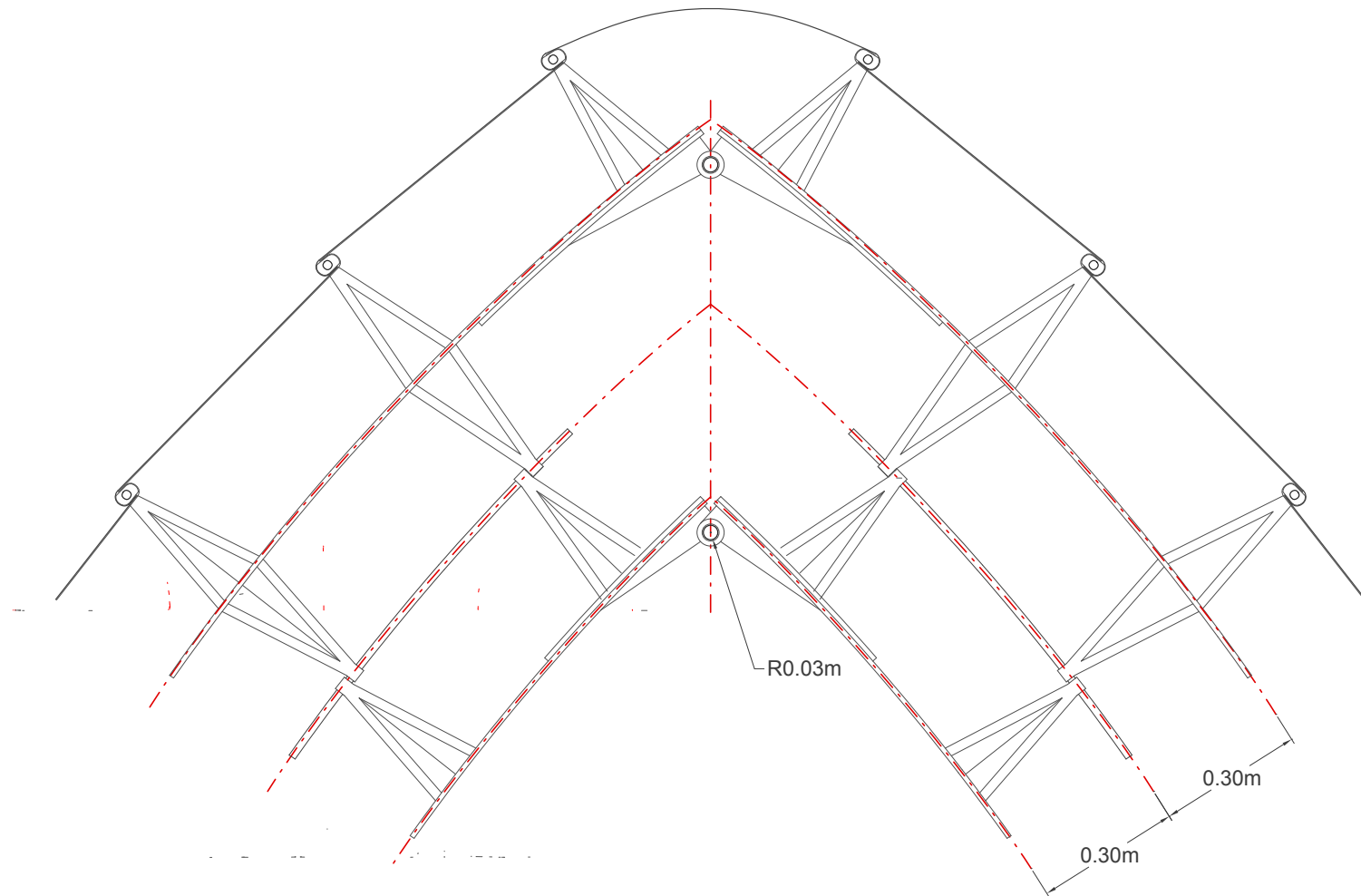
TECTONICS :: SYSTEM
Interplay of the two strategies



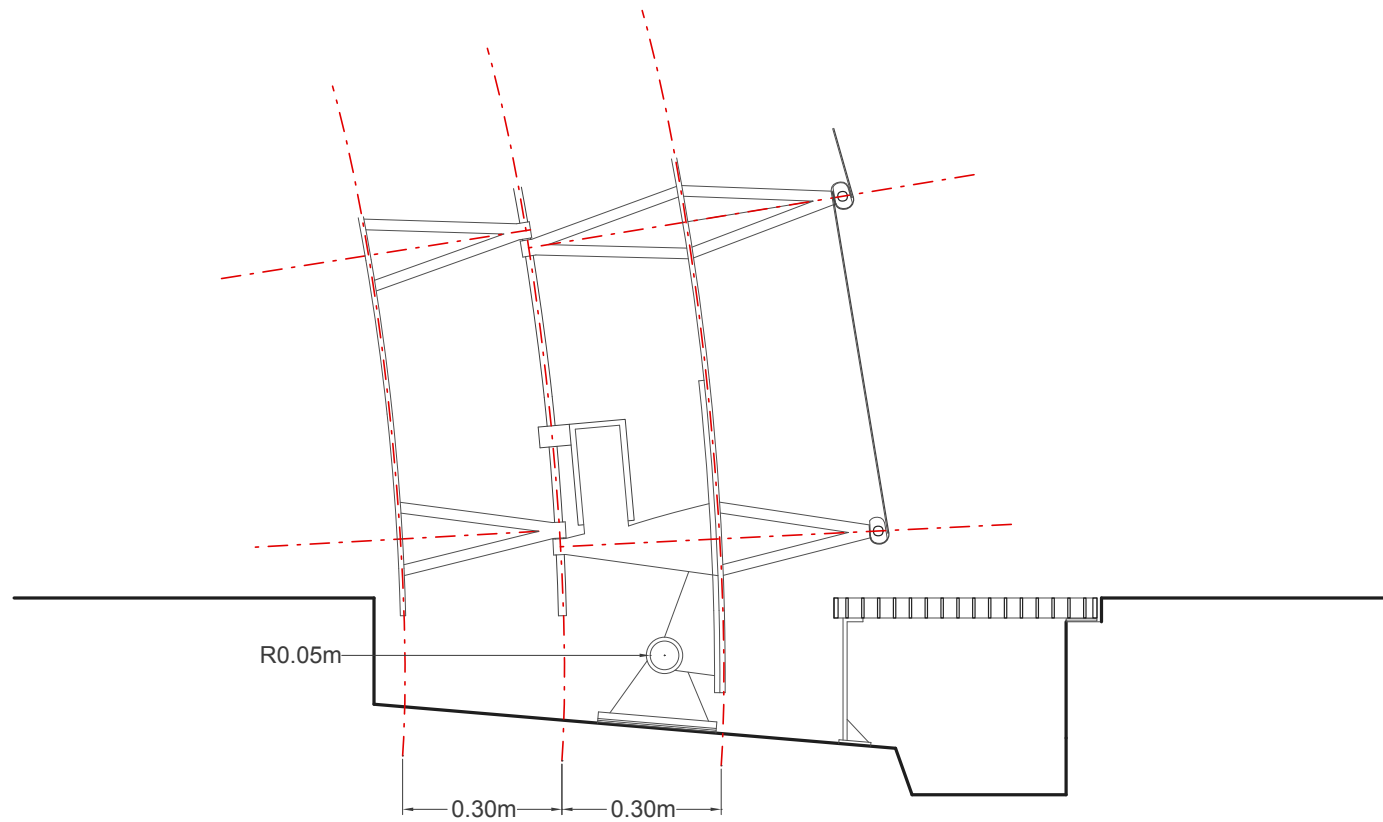
TECTONICS :: SYSTEM
Interplay of the two strategies



TECTONICS :: SYSTEM
Top detail



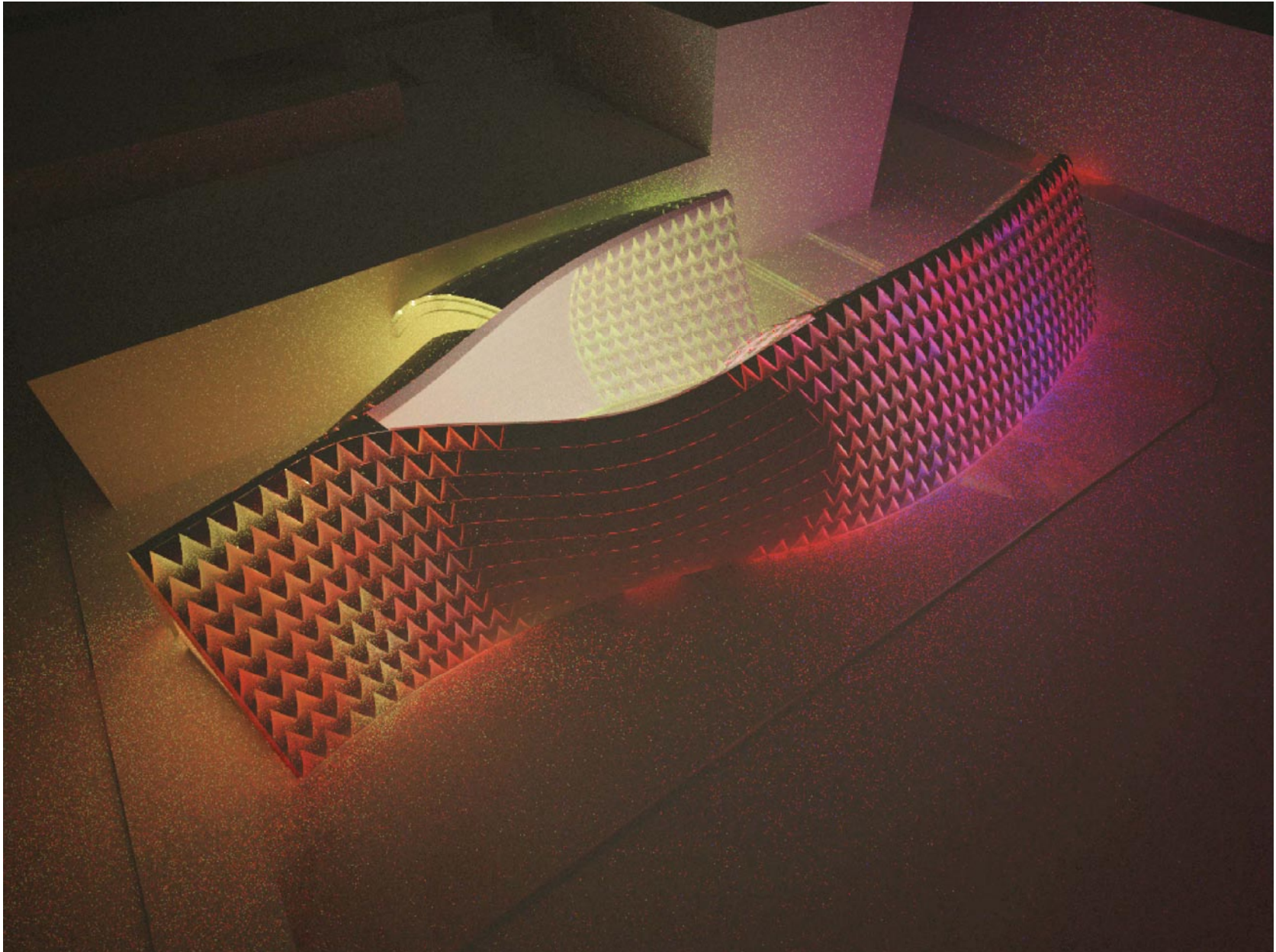
TECTONICS :: SYSTEM
Bottom detail

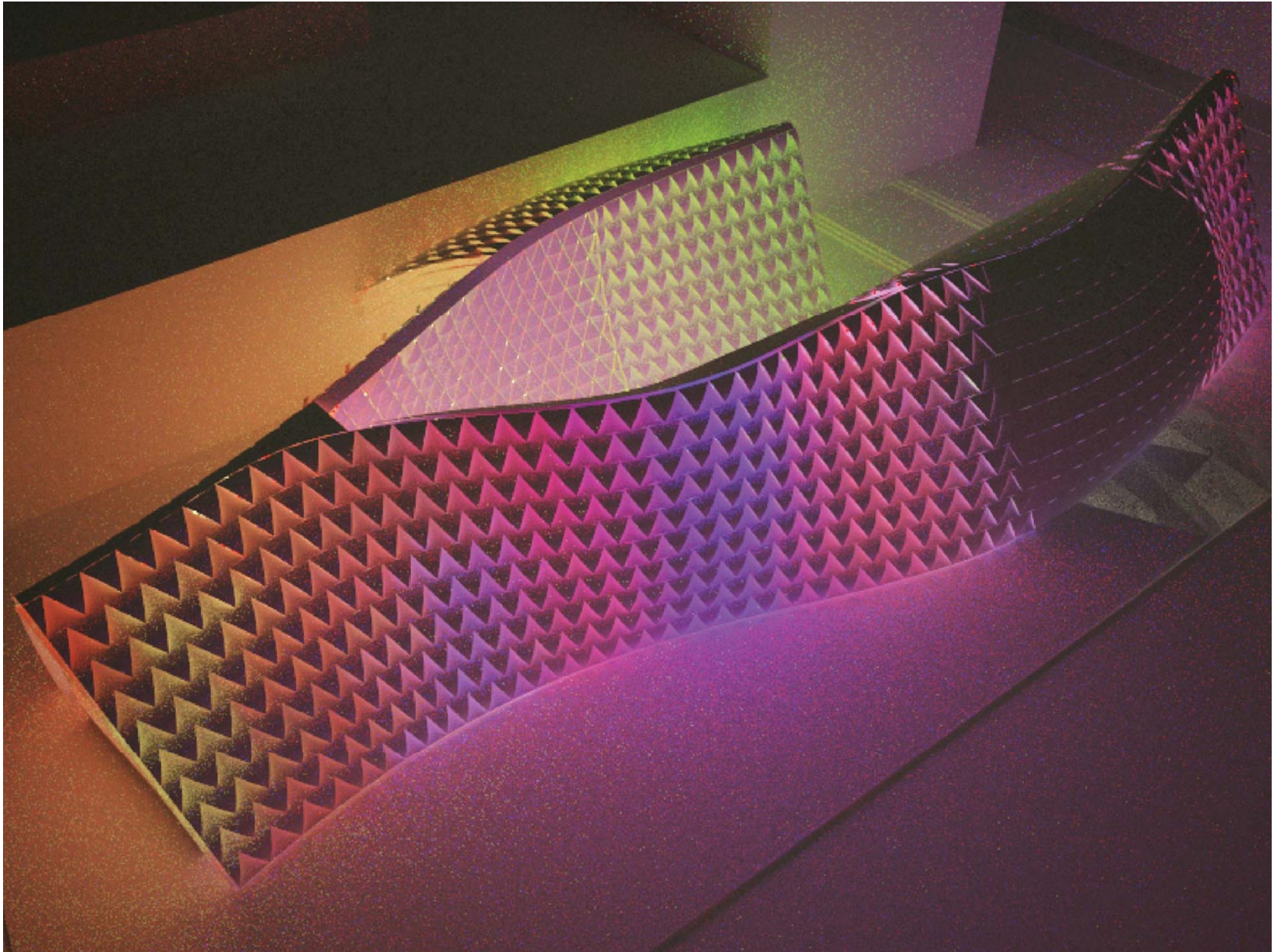


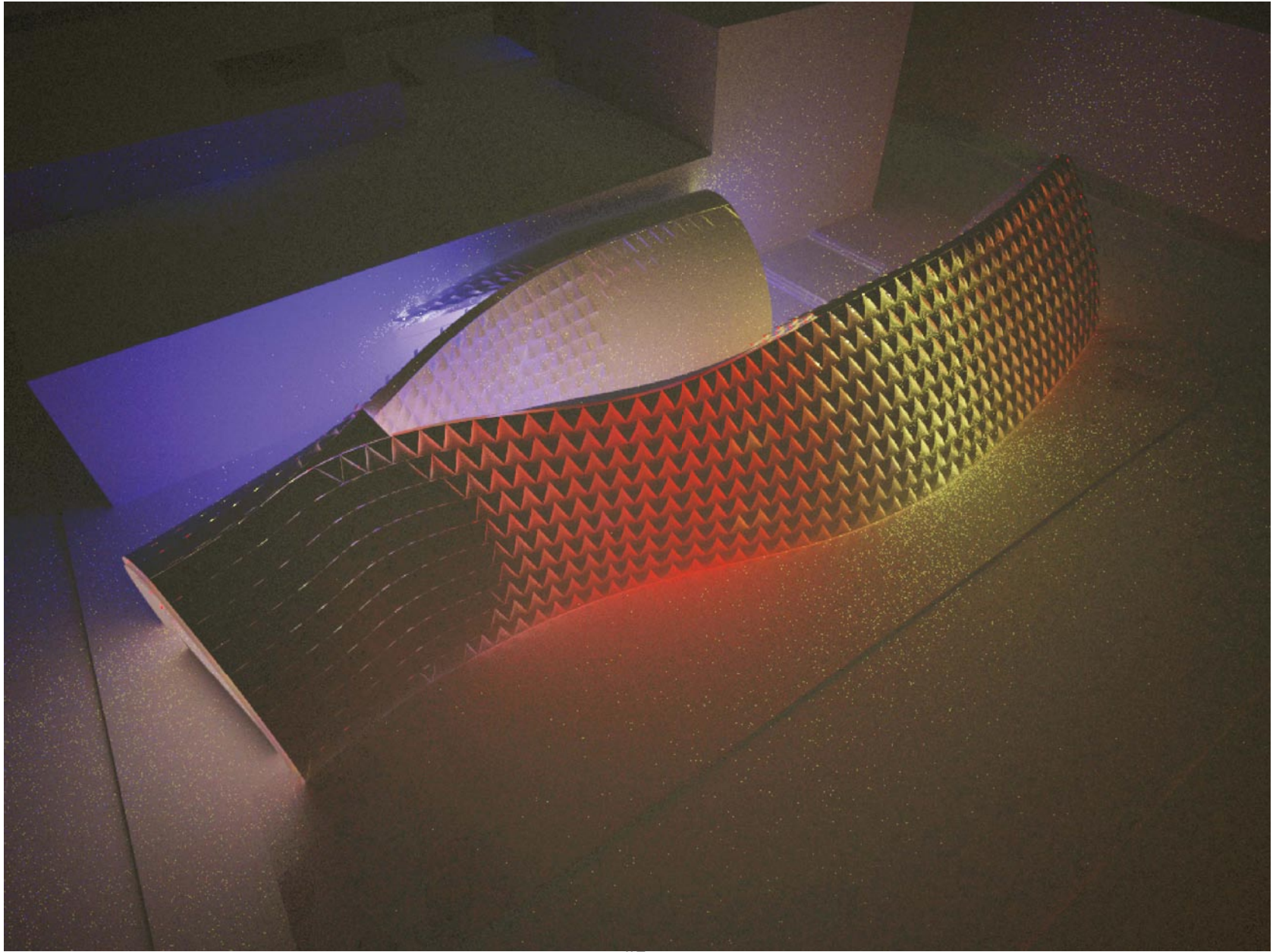
EXPERIENCE :: INTERIOR PERFORMANCE AND ACCUMULATION



EXPERIENCE :: EXTERIOR PERFORMANCE AND MEDIASCAPE

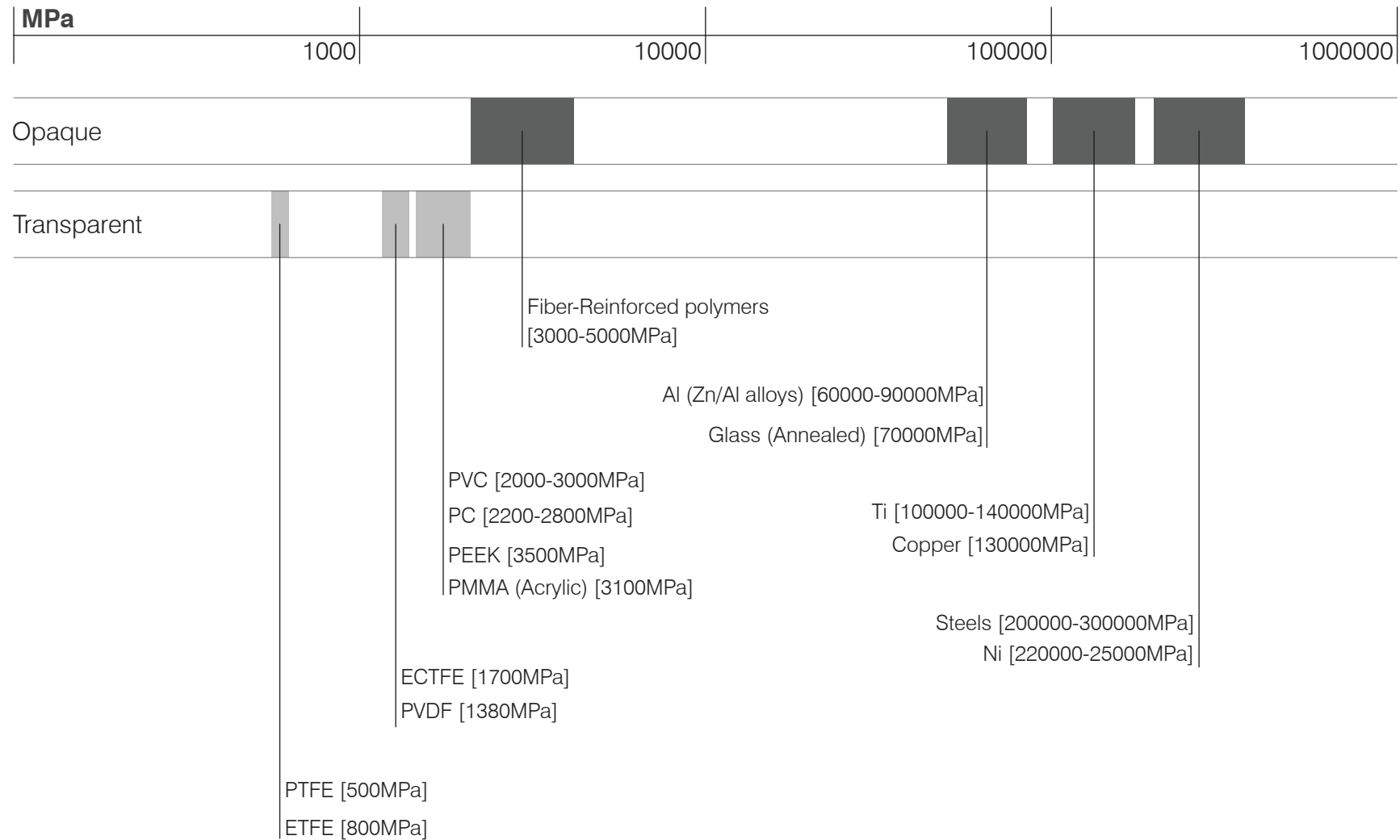






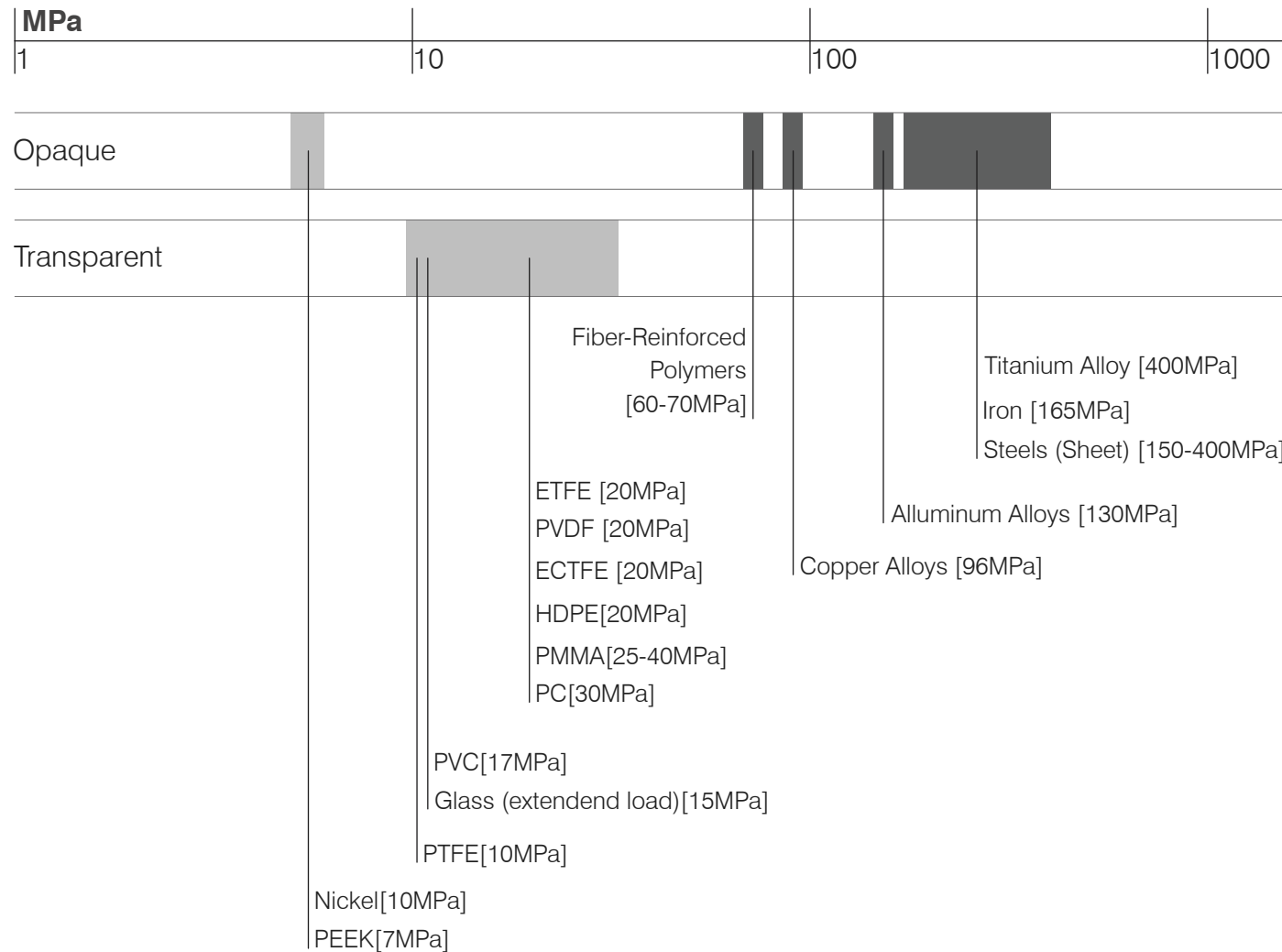
ANNEXES

Annex 1.1 :: Modulus of elasticity of elastic materials
Ref.: [Fernandez, John, 2006]

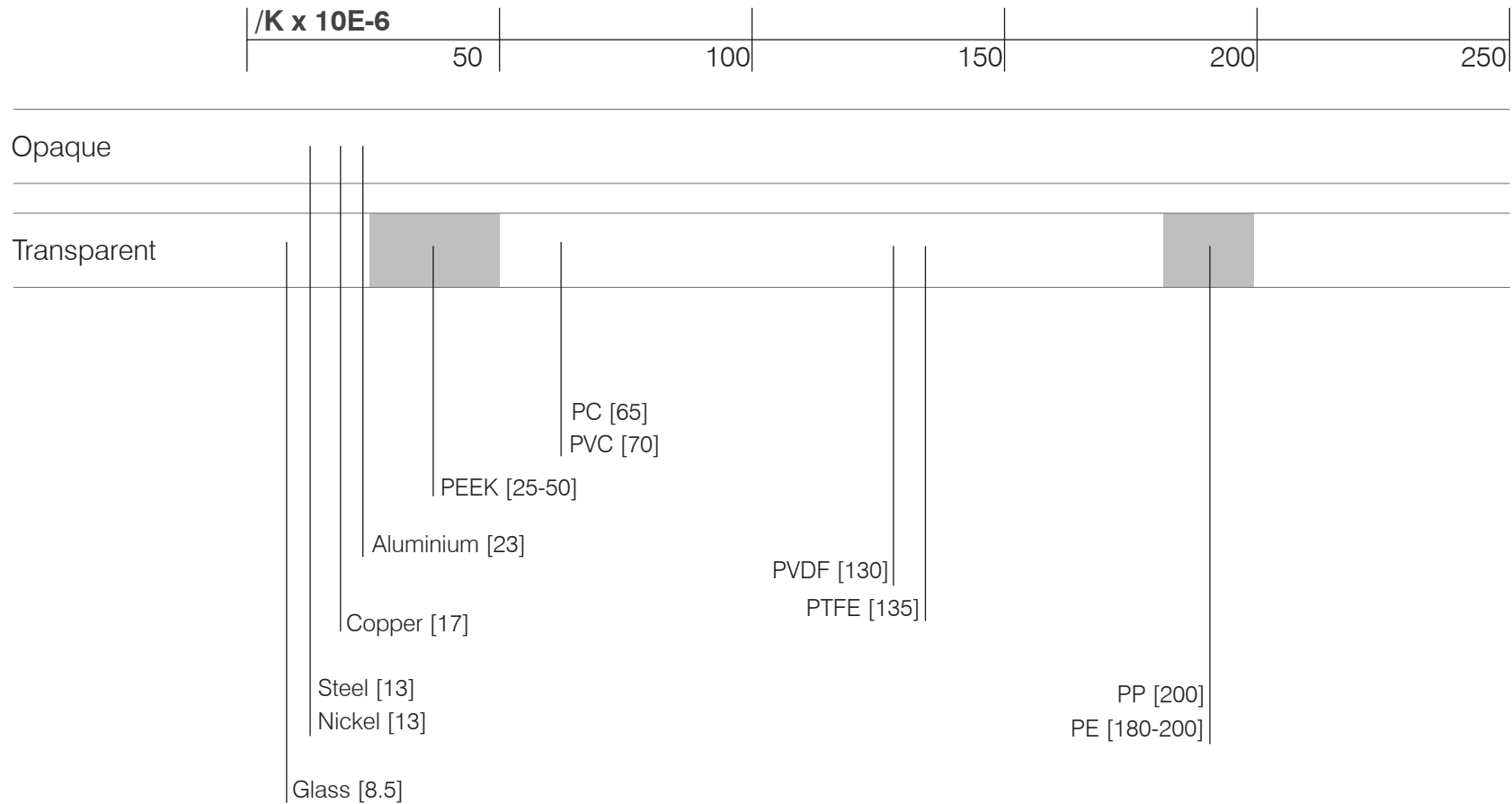


Annex 1.2 :: Fatigue limit of elastic materials

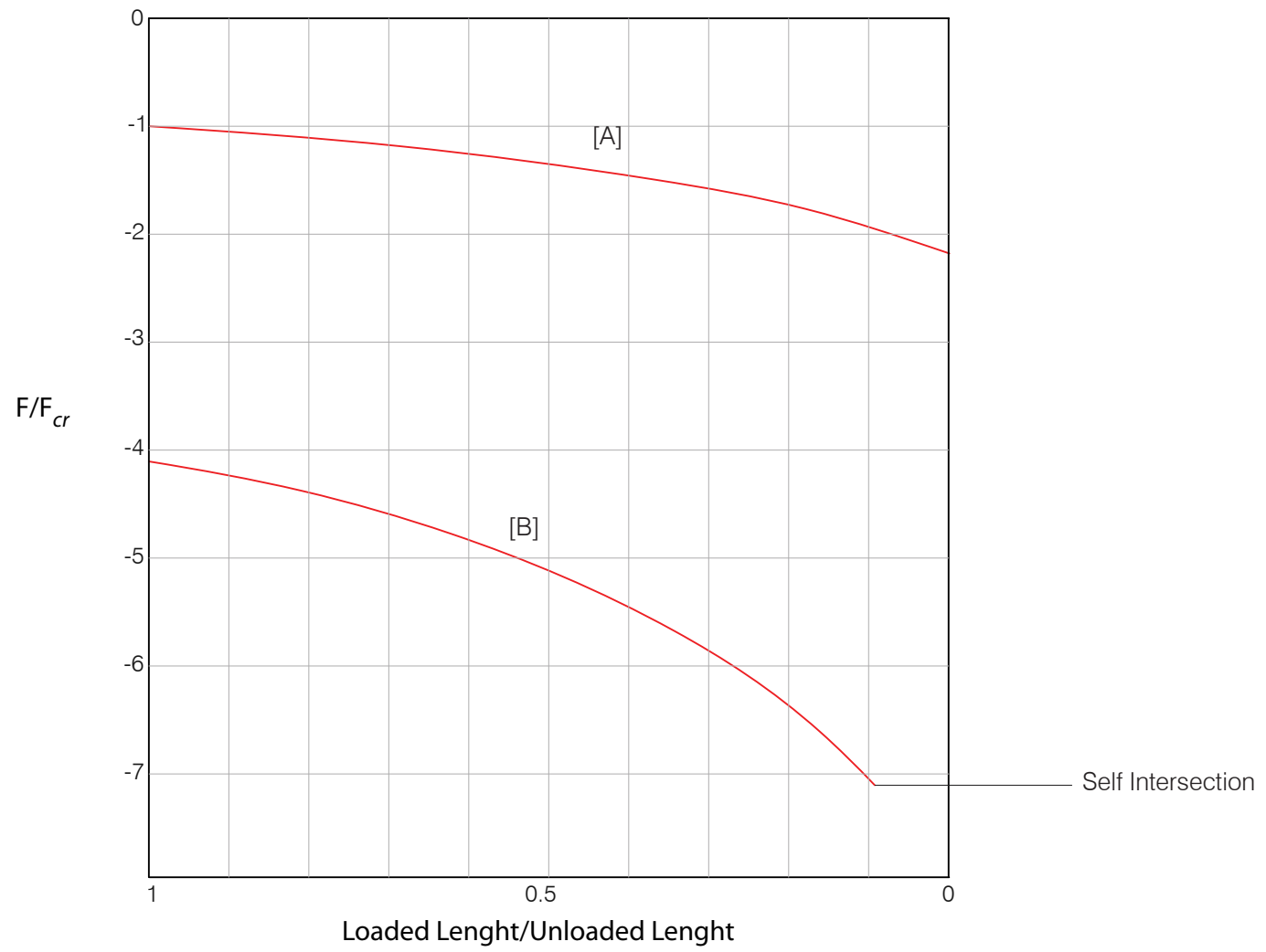
Ref.: [Dowling, Norman E., 2007 ; Fernandez, John, 2006 ; Hibbeler, R. C., 2008]



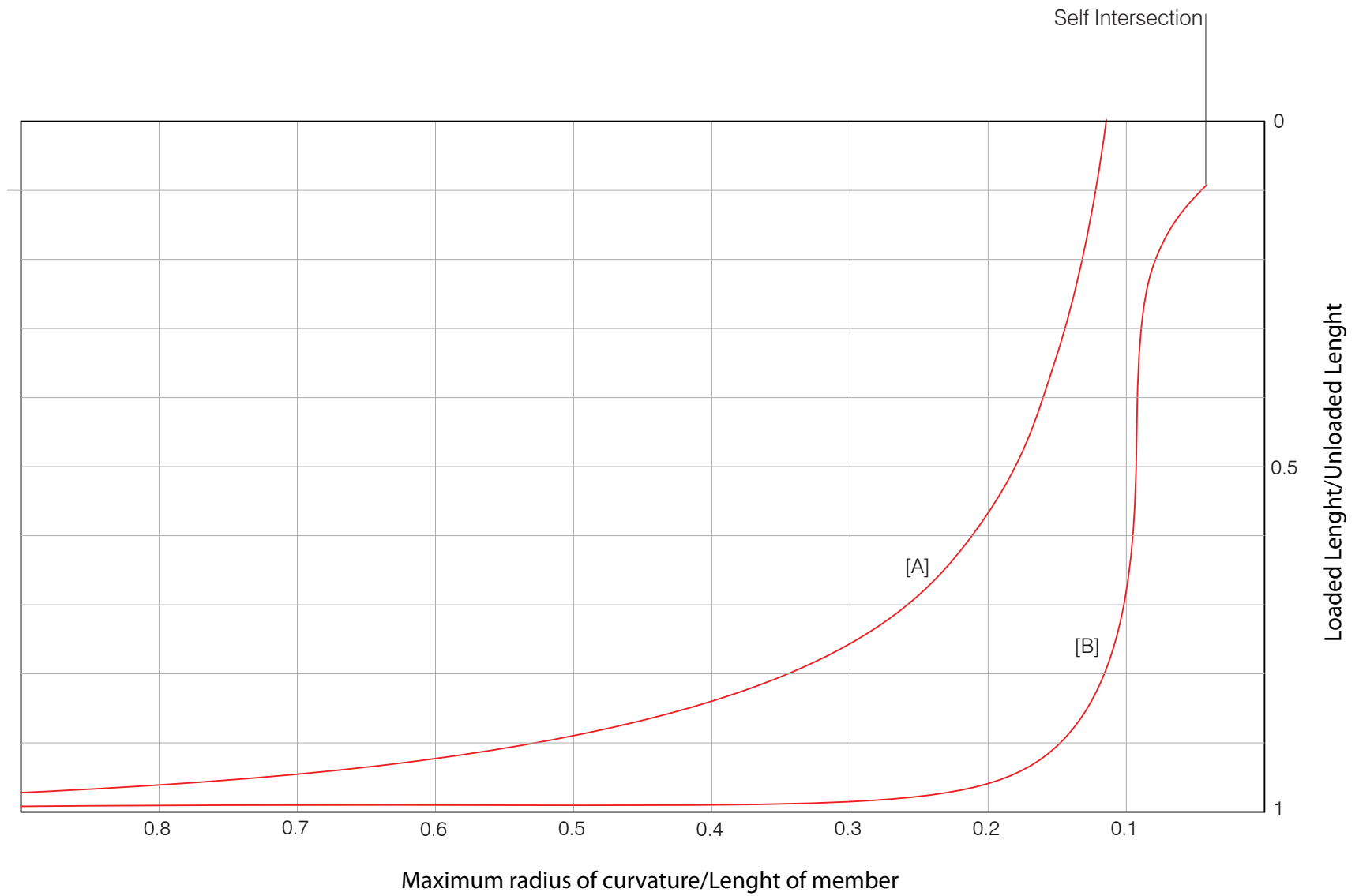
Annex 1.3 :: Coefficient of thermal expansion of elastic materials
Ref.: [Hibbeler, R. C., 2008]



Annex 2.1 ▣ Loading in relation to displacement of supports



Annex 2.2 ■ Maximum curvature in relation to displacement of supports



Annex 3 :: Stress to curvature relationship in plastically curved members

The relationship of stress at distance y from neutral axis in relation to the radius of curvature in a member in bending can be derived from *Fig A.1* as follows:

$$\begin{aligned}
 L &= r\theta \\
 l &= (r - y)\theta \\
 \varepsilon &= \frac{L - l}{L} \\
 \varepsilon &= \frac{r\theta - (r - y)\theta}{r\theta} \\
 \varepsilon &= \frac{-y}{r} \\
 \sigma &= \varepsilon E \\
 \sigma &= \frac{-y}{r} E
 \end{aligned}$$

When a unloaded member already has local curvature, the stress at a distance y from neutral axis is defined in relation to initial and final radiuses of curvature from *Fig A.1* and *Fig A.2* as follows:

$$\begin{aligned}
 L &= r\theta = r'\theta' \\
 l &= (r - y)\theta \\
 l' &= (r' - y)\theta' \\
 \varepsilon &= \frac{l - l'}{l} \\
 \varepsilon &= \frac{(r - y)\theta - (r' - y)\theta'}{(r - y)\theta} \\
 \varepsilon &= \frac{(r - y)\theta - (r' - y)\frac{r}{r'}\theta}{(r - y)\theta} \\
 \varepsilon &= \frac{(r - y) - (r' - y)\frac{r}{r'}}{(r - y)} \\
 \varepsilon &= 1 - \frac{(r' - y)r}{(r - y)r'}
 \end{aligned}$$

As the initial radius tends towards infinity, the relationship reverts to the original:

$$1 - \lim_{r' \rightarrow \infty} \frac{(r' - y)r}{(r - y)r'} = 1 - \frac{(r' - y)}{r'} = \frac{r'}{r'} - \frac{(r' - y)}{r'} = \frac{-y}{r'}$$

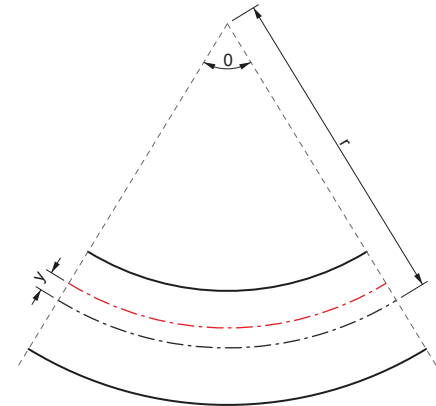


Fig.A.1

Ref:[Mattioni, Weaver, Potter, Friswell, 2007]

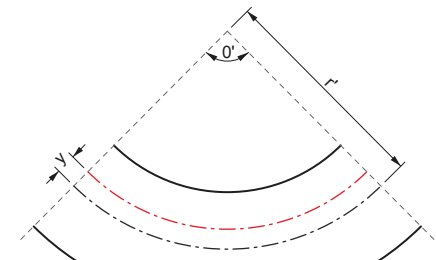
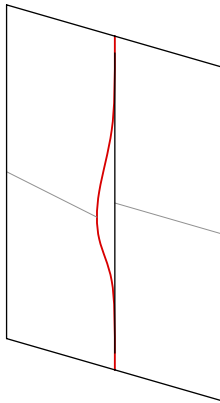


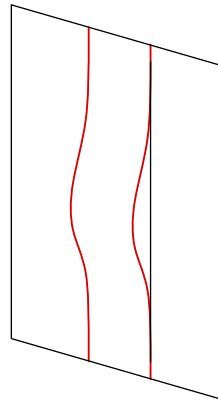
Fig.A.2

Annex 4.1 :: Possible responsive surface discontinuity

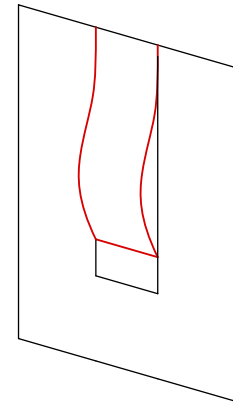
Possible Opening Configurations



Manipulations:
Local Stiffness
Arc Length Elongation

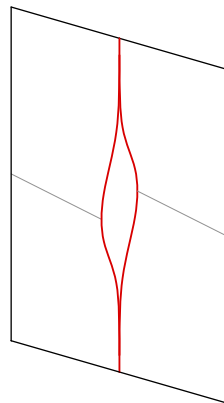


Manipulations:
Local Stiffness
Arc Length Elongation

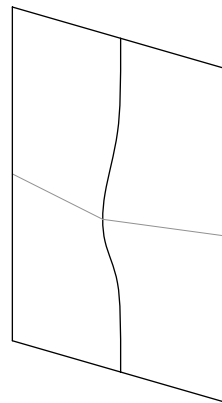


Manipulations:
Local Stiffness

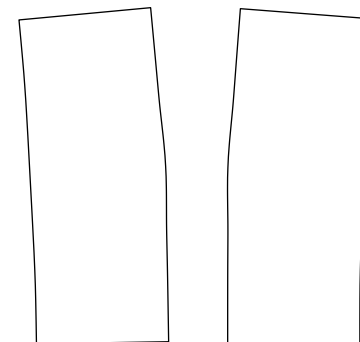
Opening configuration using
material stable state switching



Open

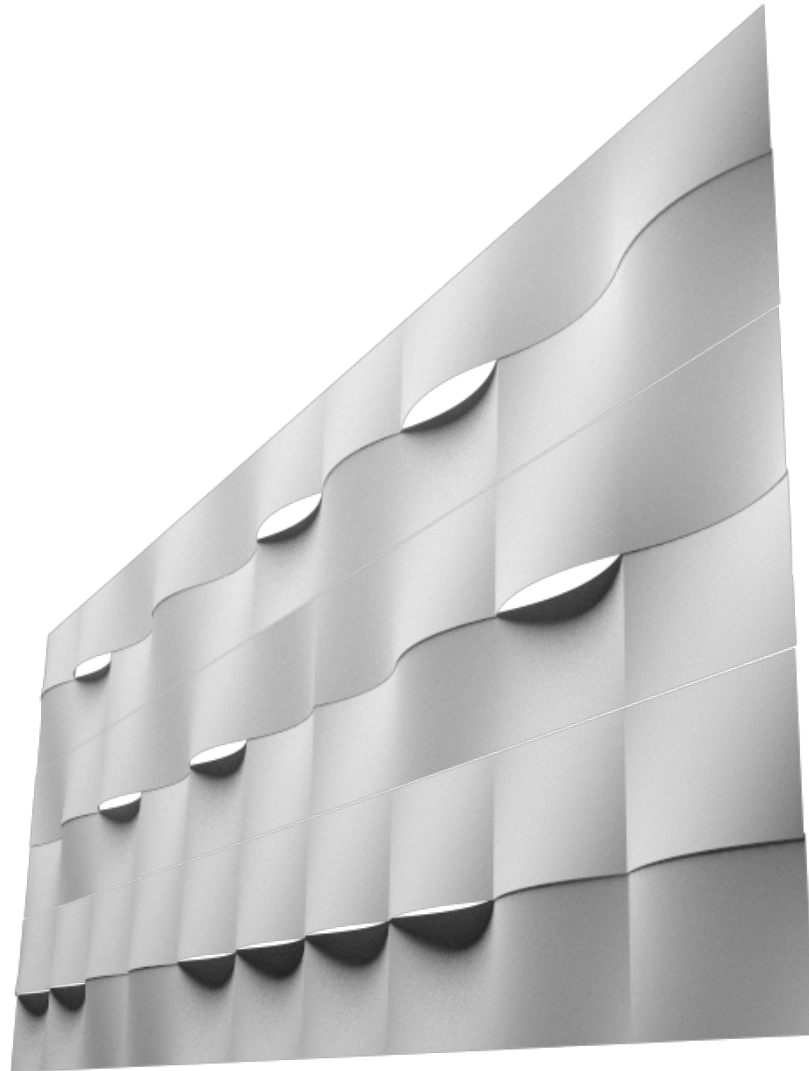


Closed



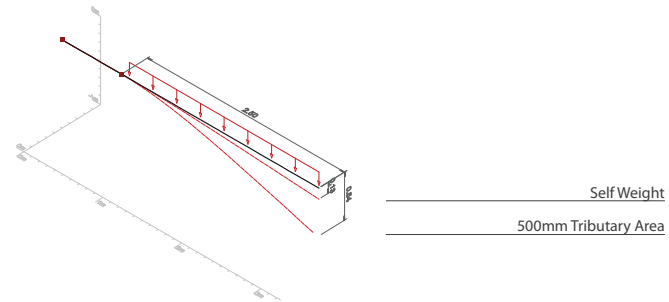
Unfolded Shapes

Annex 4.2 :: Possible responsive surface discontinuity

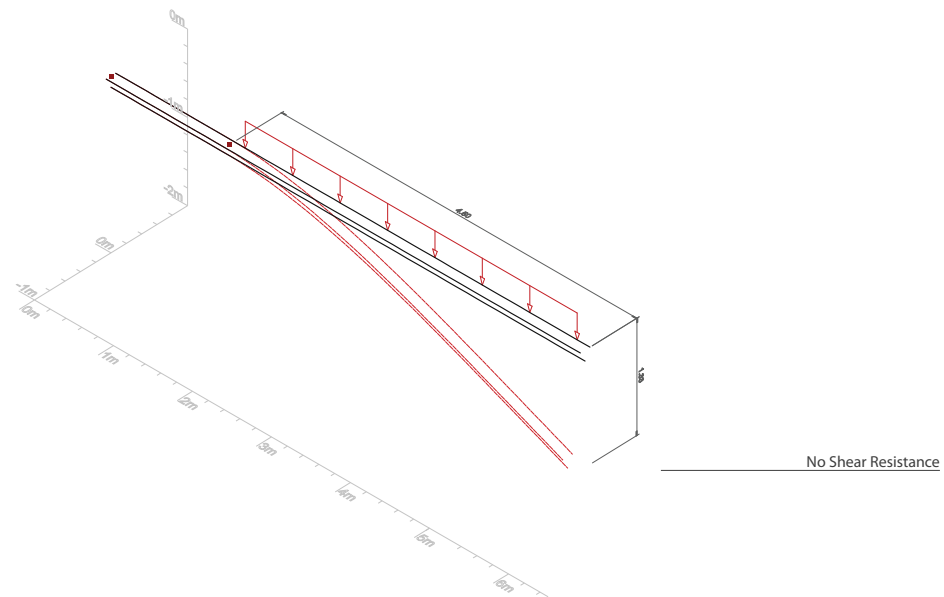


Annex 5.1 :: Simulation of large scale deformation

1/2" Pencil Wire

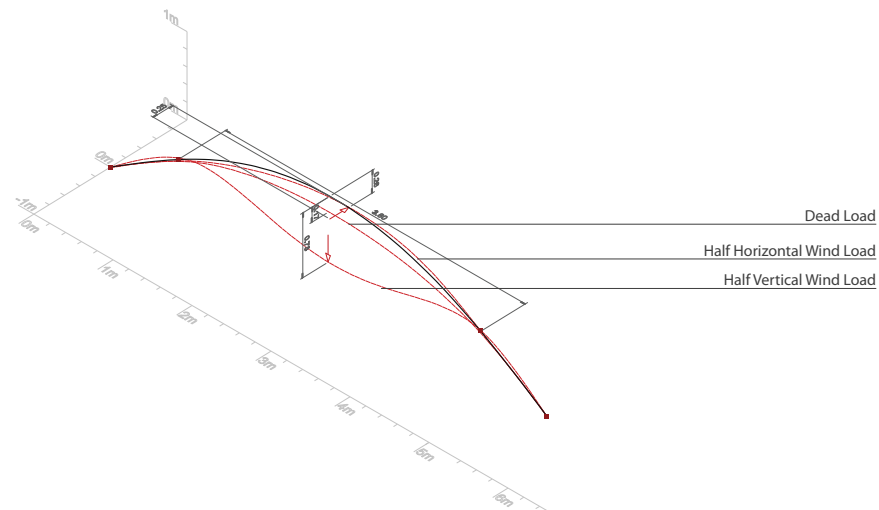


Cantilever Type 1

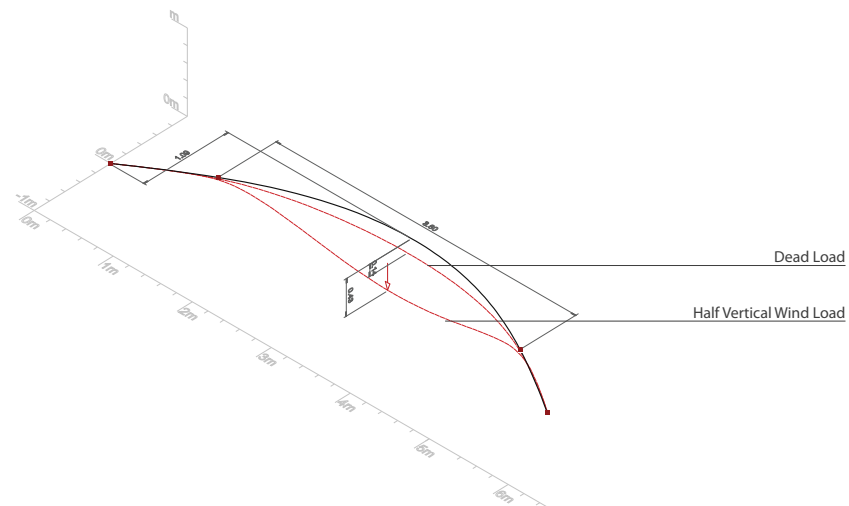


Annex 5.2 ■ Simulation of large scale deformation

Vertical Arch with
Double Supports



Horizontal Arch with
Double Supports

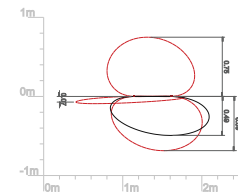
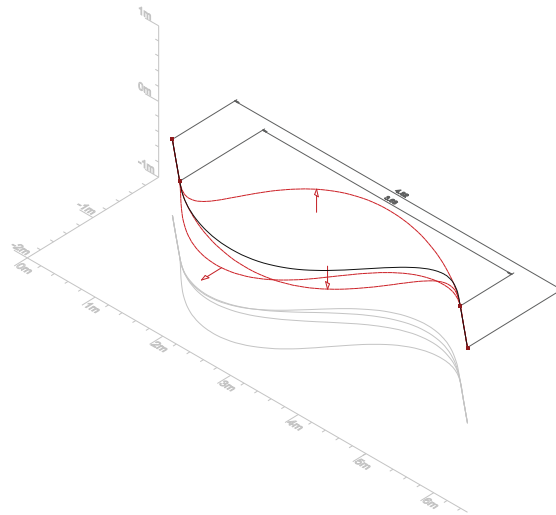


Annex 5.3 ■ Simulation of large scale deformation

[TWO 1/2" PENCIL RODS BOUND VERTICALLY]

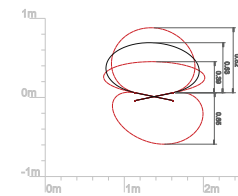
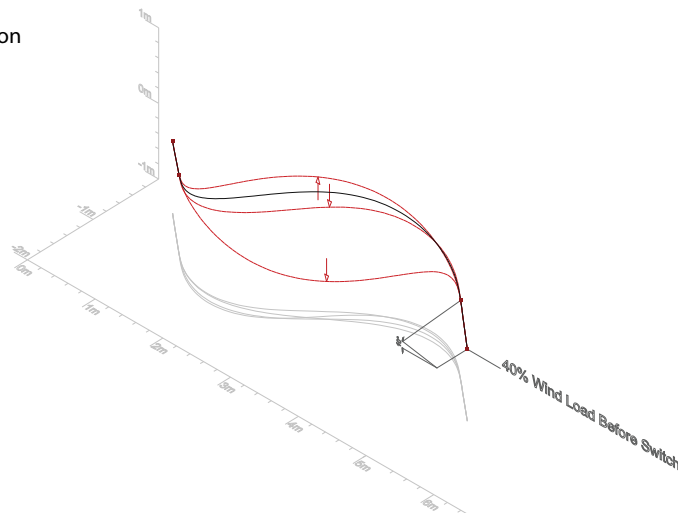
S Shape - Horizontal

Large deflections under all wind loads



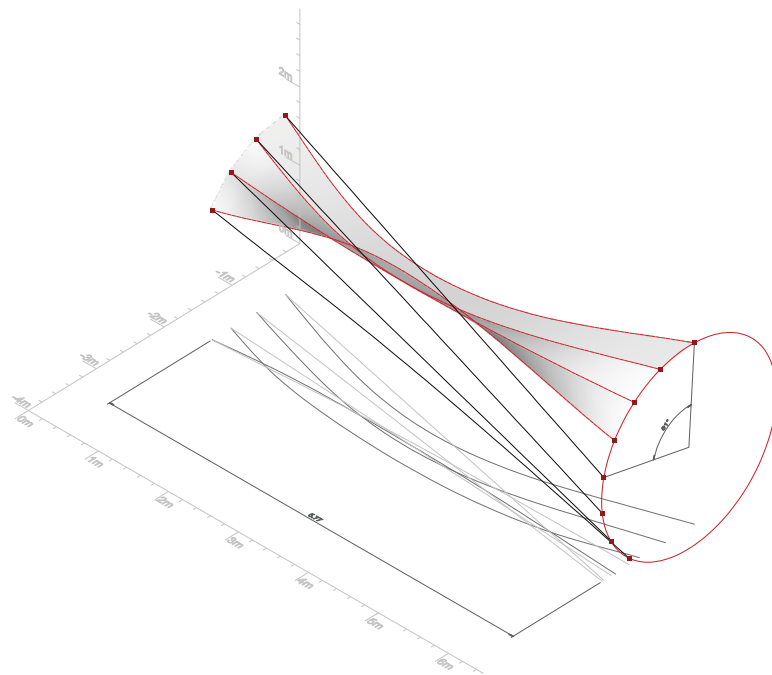
S Shape - 10 degree Rotation

Switch at 40% wind load

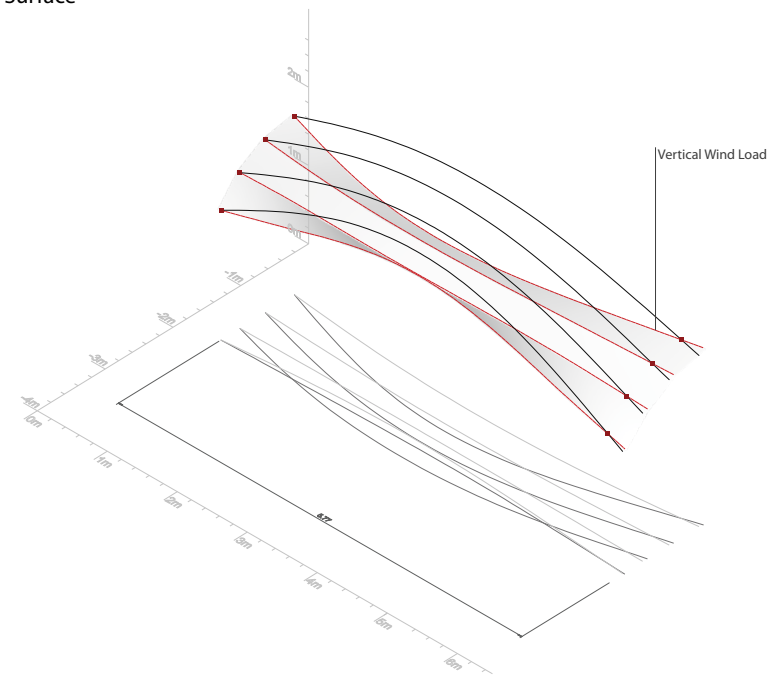


Annex 5.4 :: Simulation of large scale deformation

Unconstrained Twist

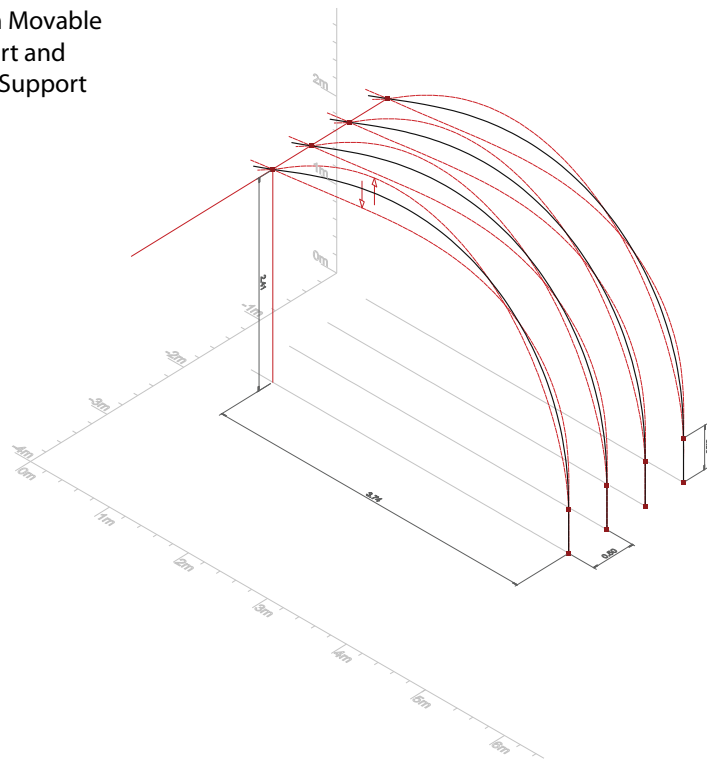


Laterally Supported Surface

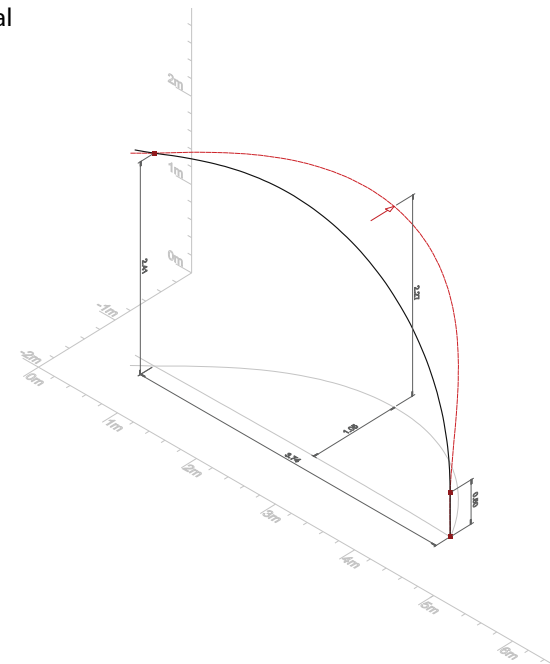


Annex 5.5 ■ Simulation of large scale deformation

Half Arch with Movable
Simple Support and
Fixed Double Support



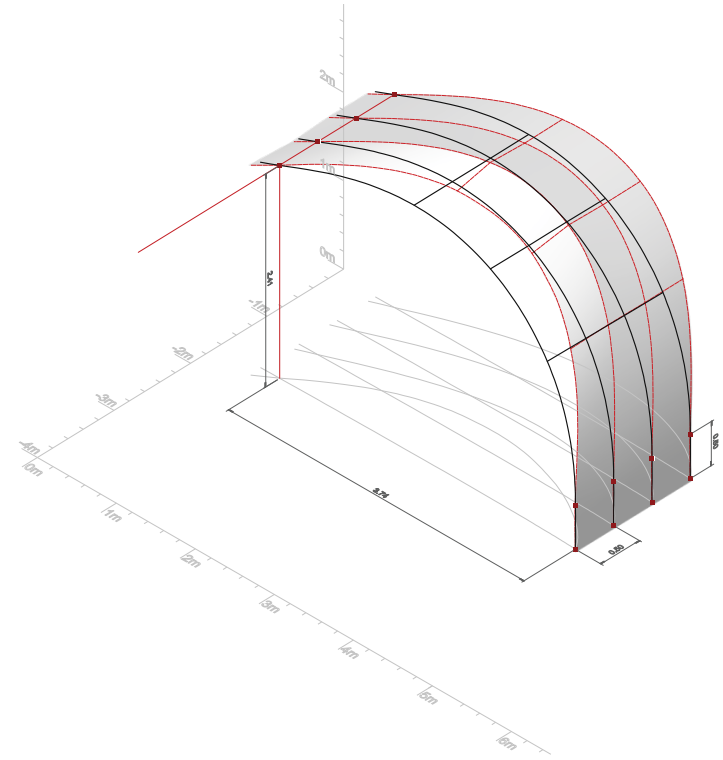
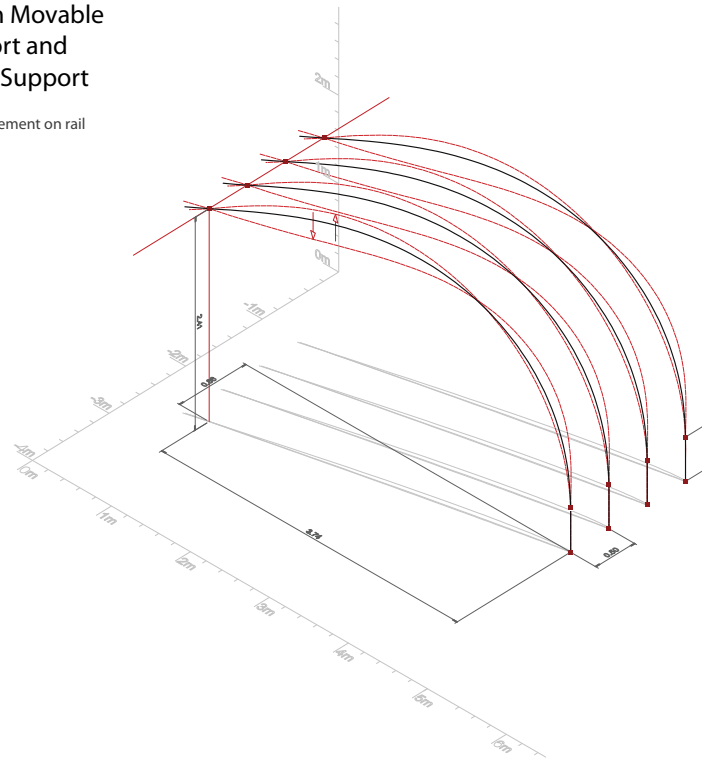
Unsupported Lateral
Deflection



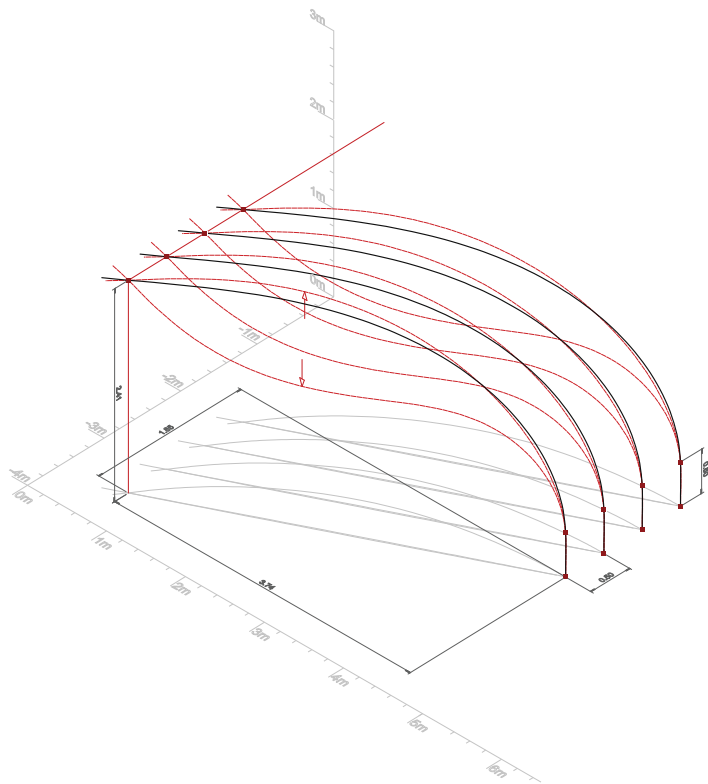
Annex 5.6 ■ Simulation of large scale deformation

Half Arch with Movable Simple Support and Fixed Double Support

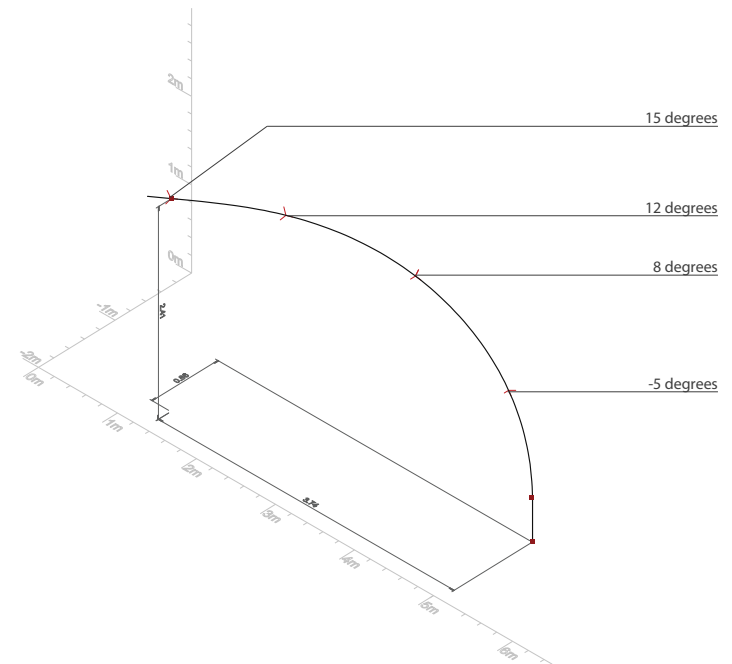
800mm lateral displacement on rail



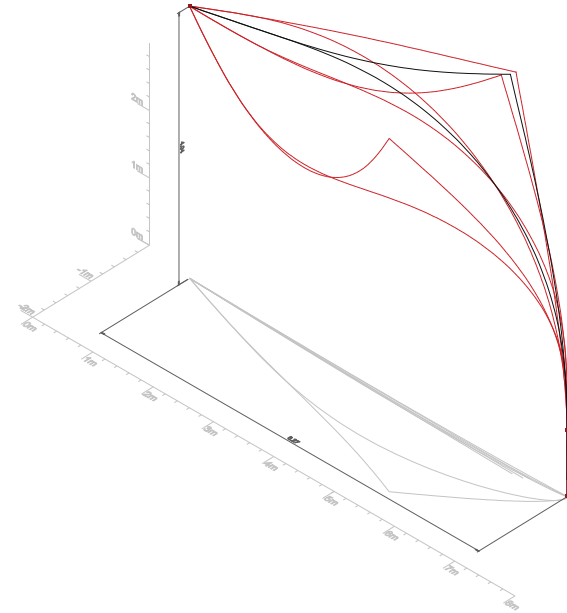
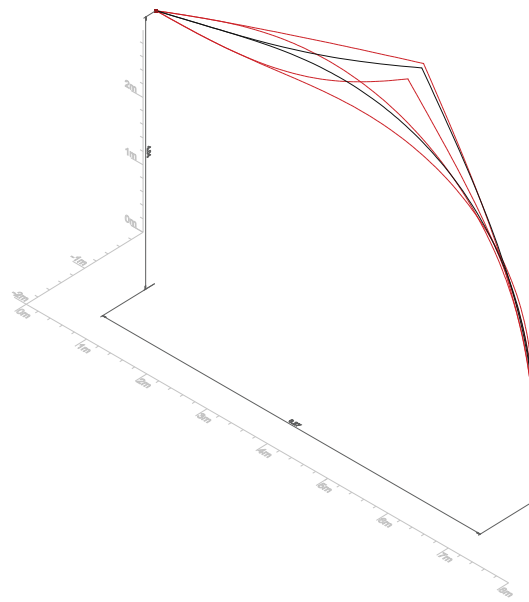
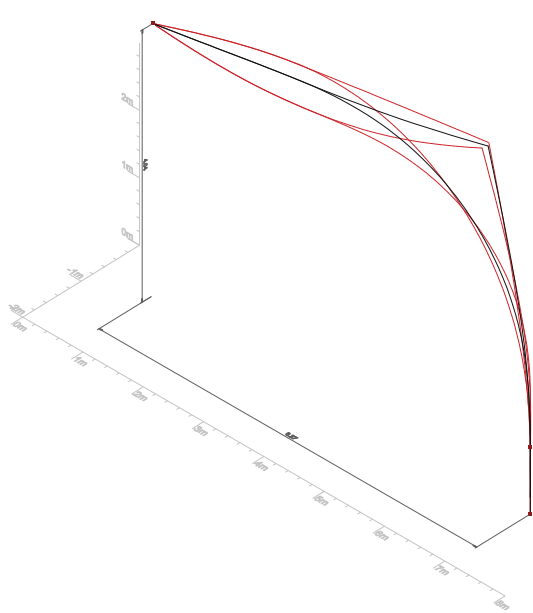
Annex 5.7 ■ Simulation of large scale deformation



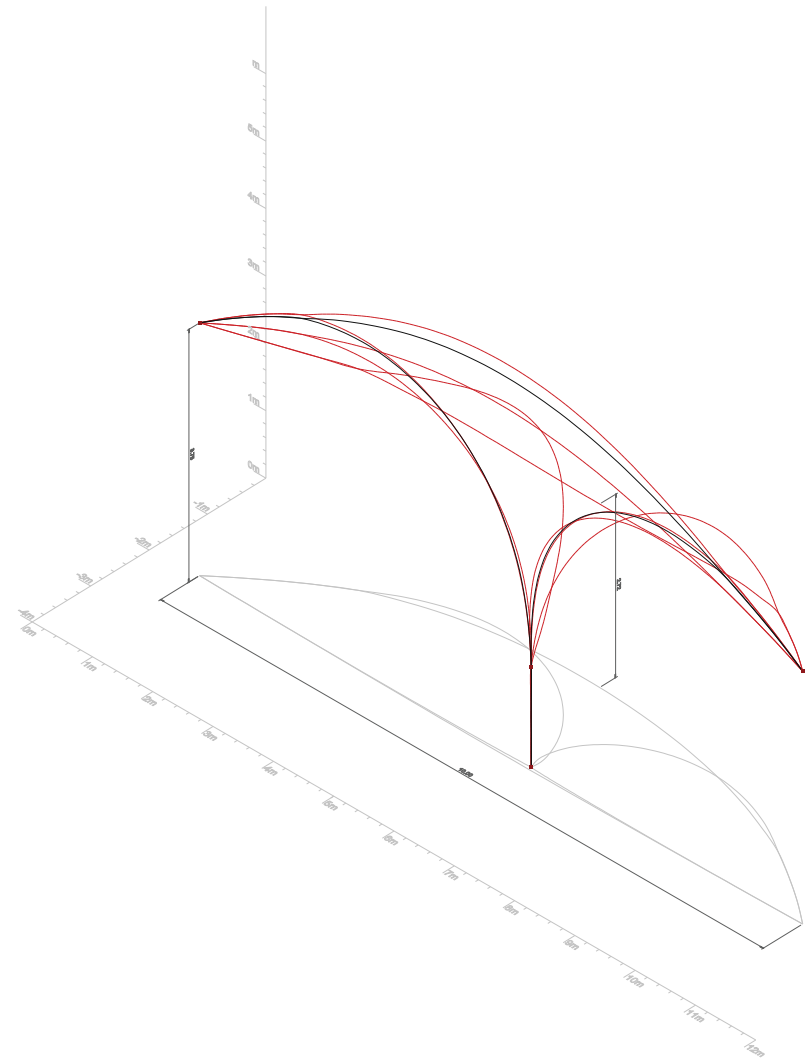
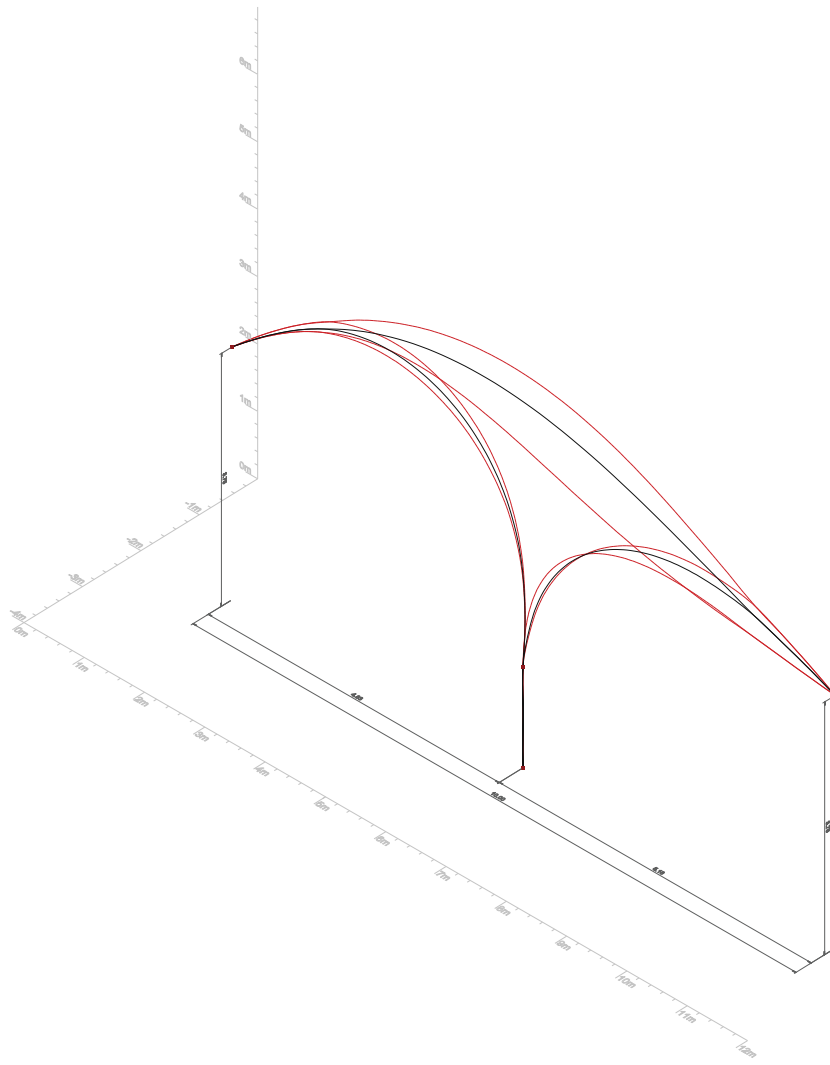
Axial Twist in Rod



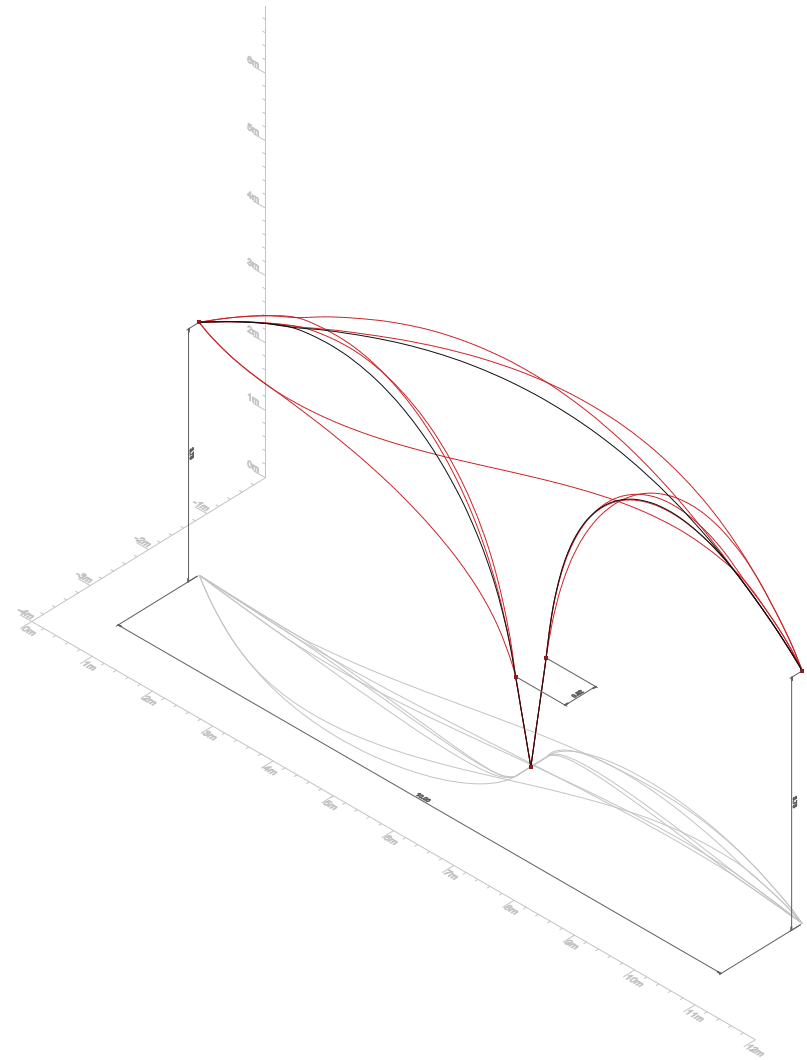
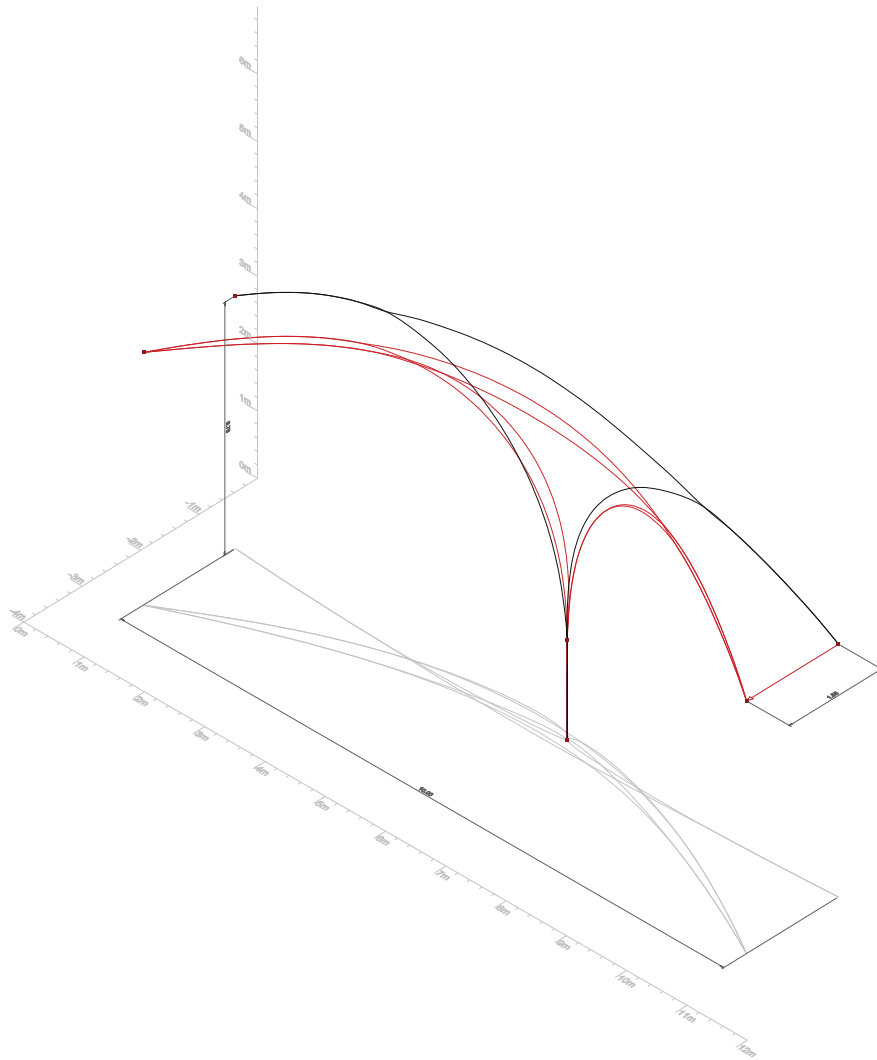
Annex 5.8 ■ Simulation of large scale deformation



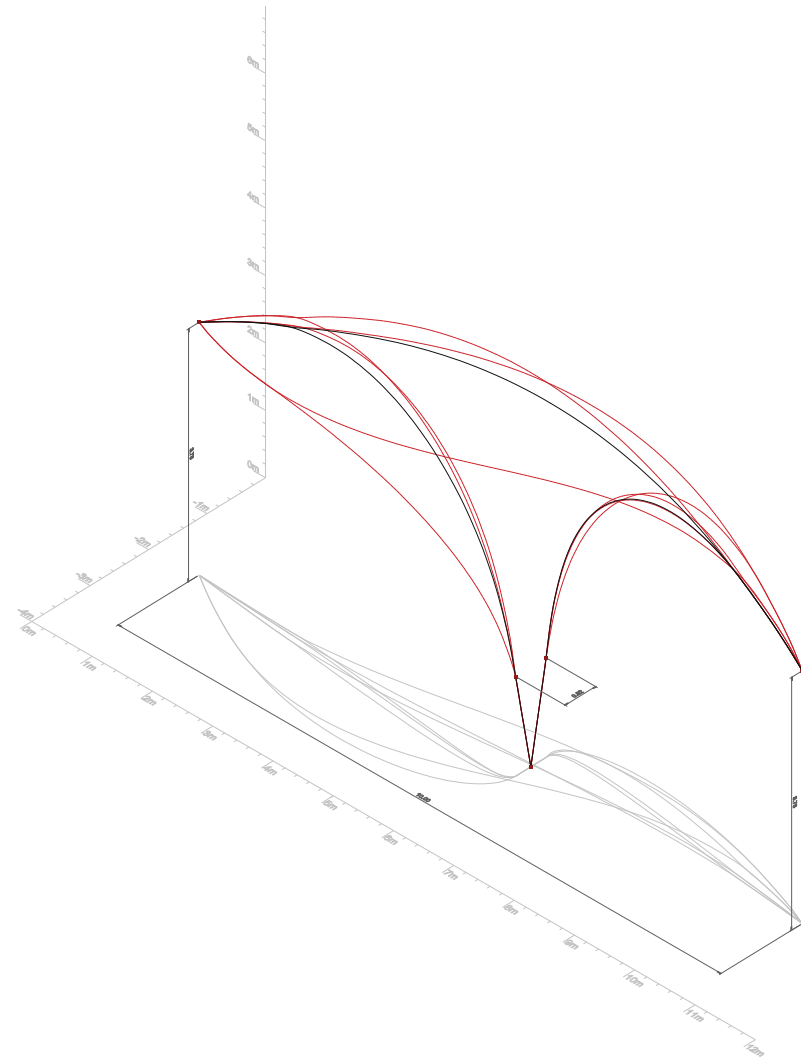
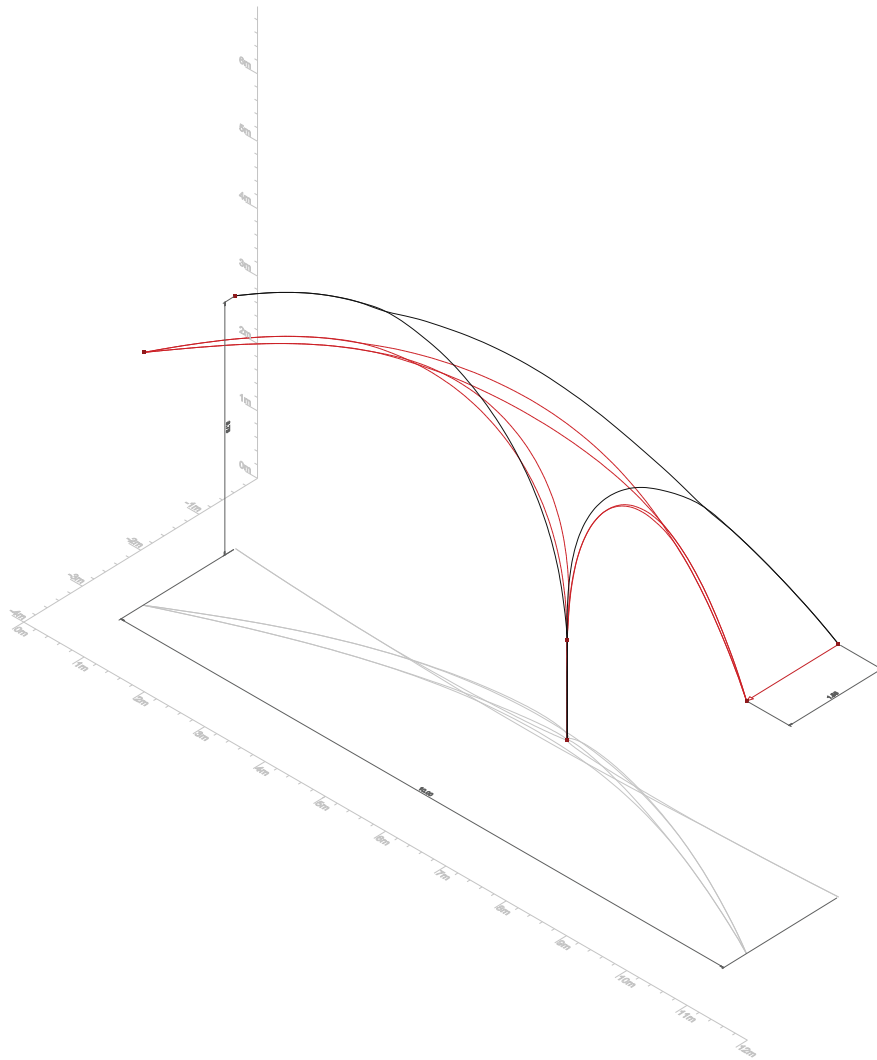
Annex 5.9 ■ Simulation of large scale deformation



Annex 5.10 :: Simulation of large scale deformation

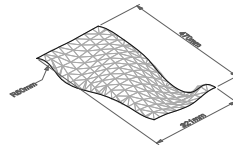
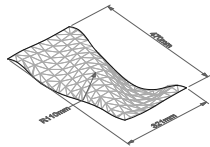
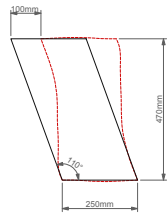


Annex 5.11 ■ Simulation of large scale deformation

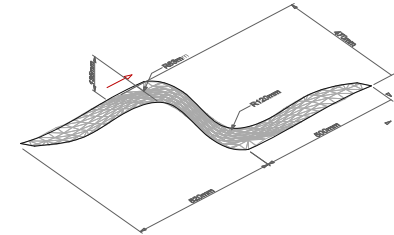
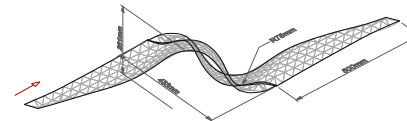
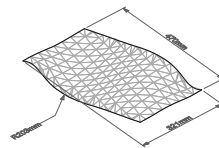
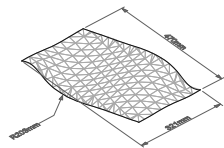
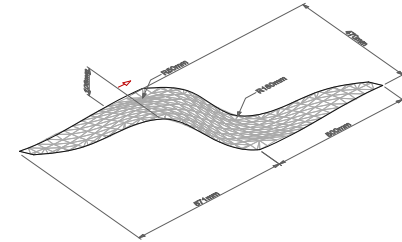
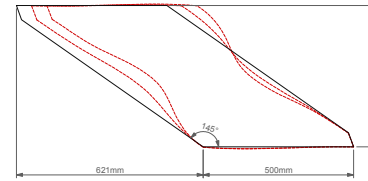


Annex 5.12 ■ Simulation of large scale deformation

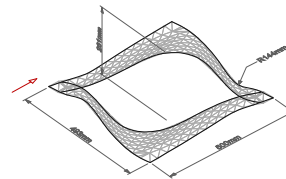
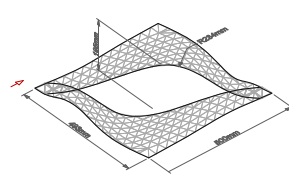
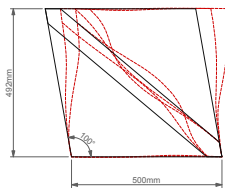
Instability of Stable States



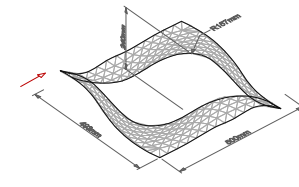
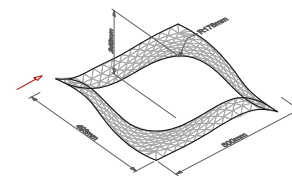
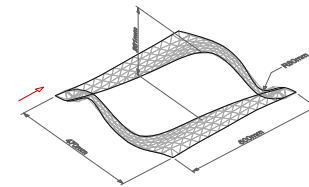
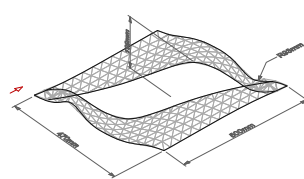
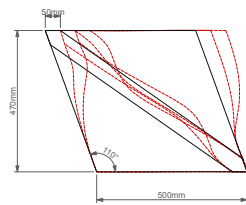
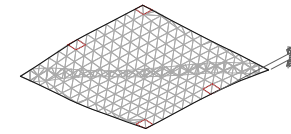
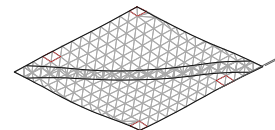
Moment Connections and Shear Bending in Quadrilateral Sheet Materials



Angle Variation and Relationship to Opening and Maximum Curvature

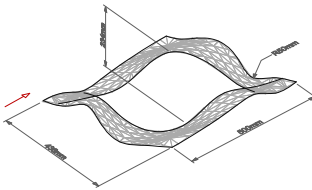
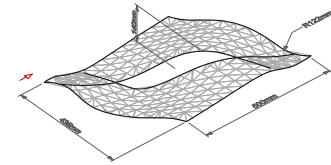
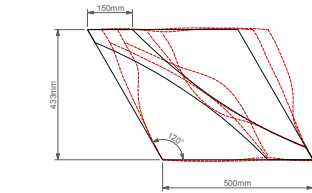


Support Variation Optimizing the Opening/Curvature Relationship

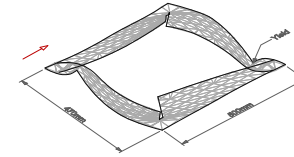
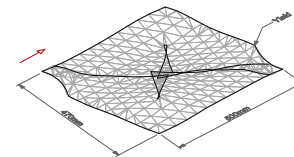
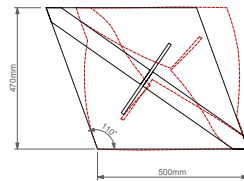


Annex 5.13 ■ Simulation of large scale deformation

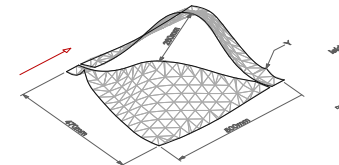
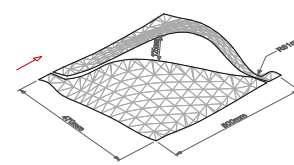
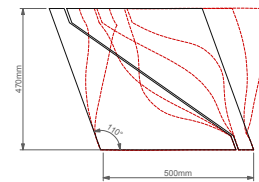
Effect of Wider Support Condition



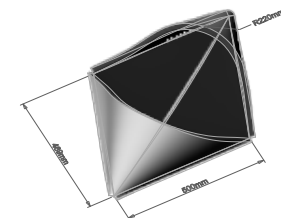
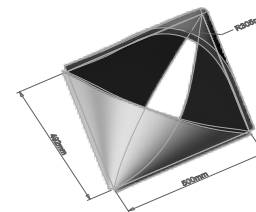
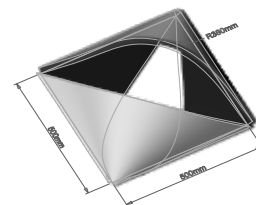
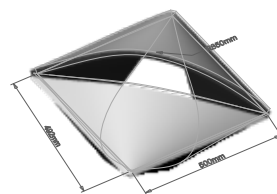
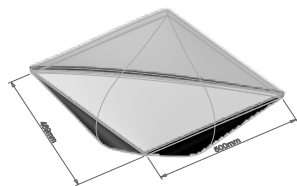
Introduction of Cuts and Its Effect on Shape and Stability



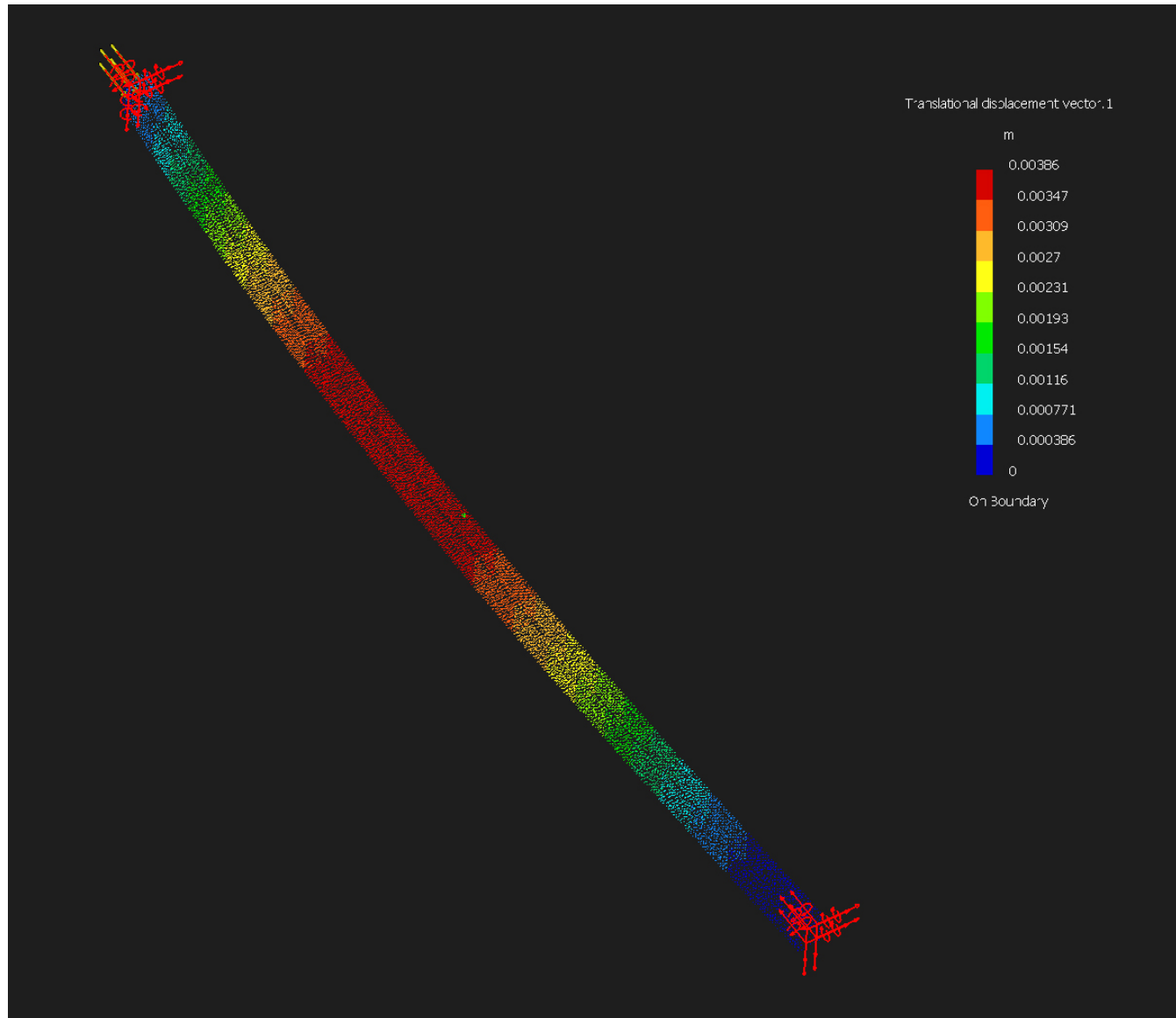
Introduction of Cuts and Its Effect on Shape and Stability

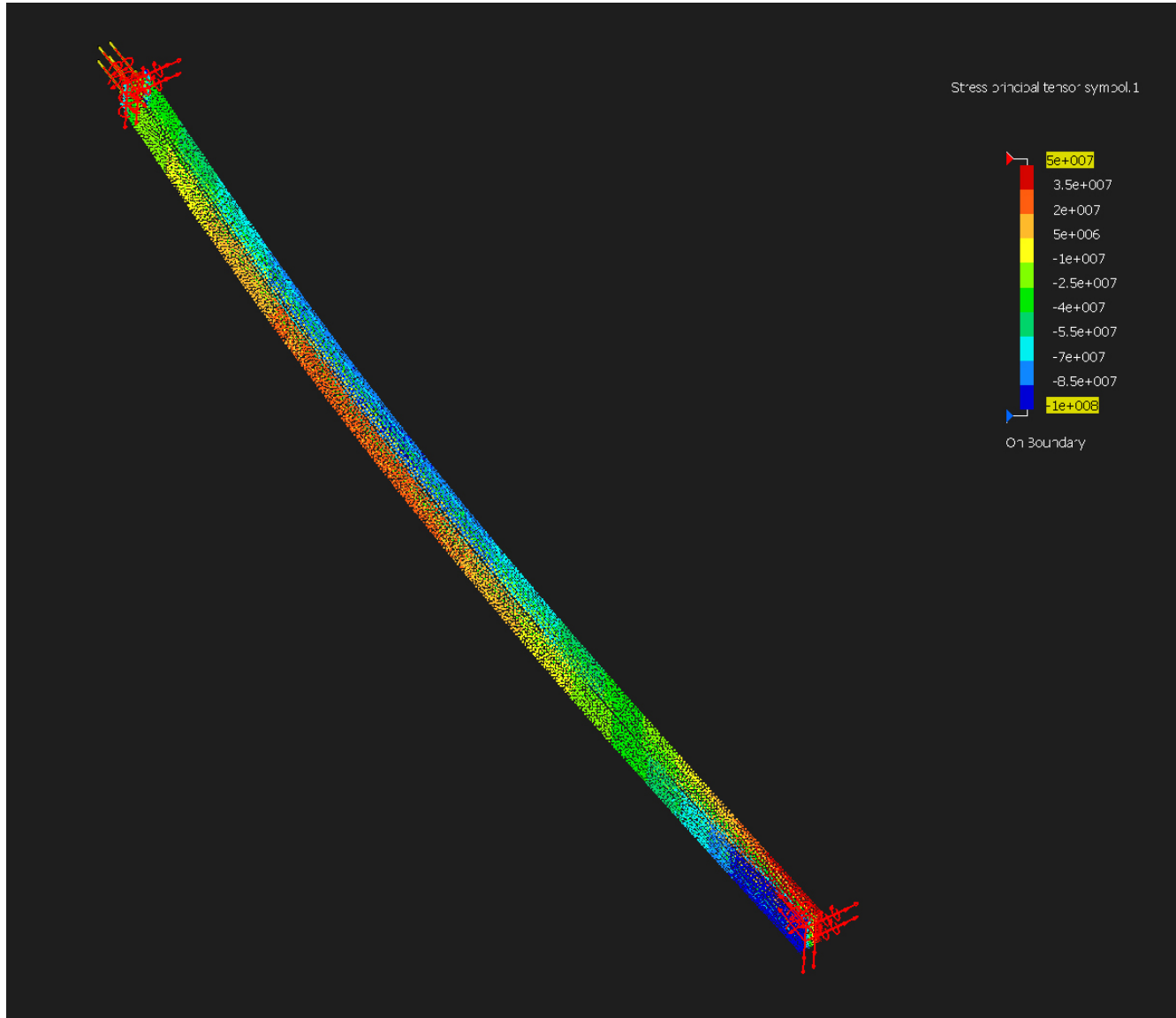


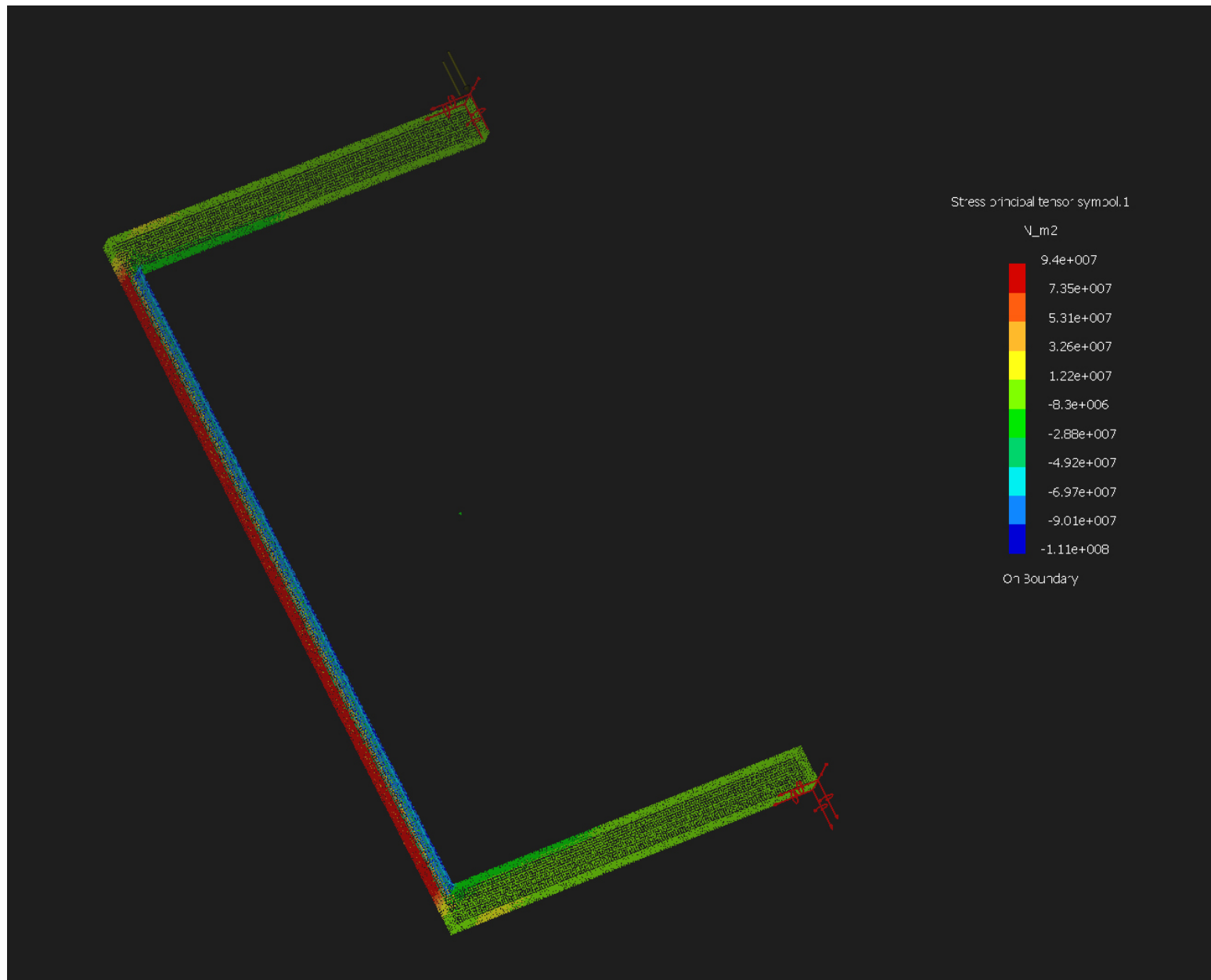
Acoustic Module Test

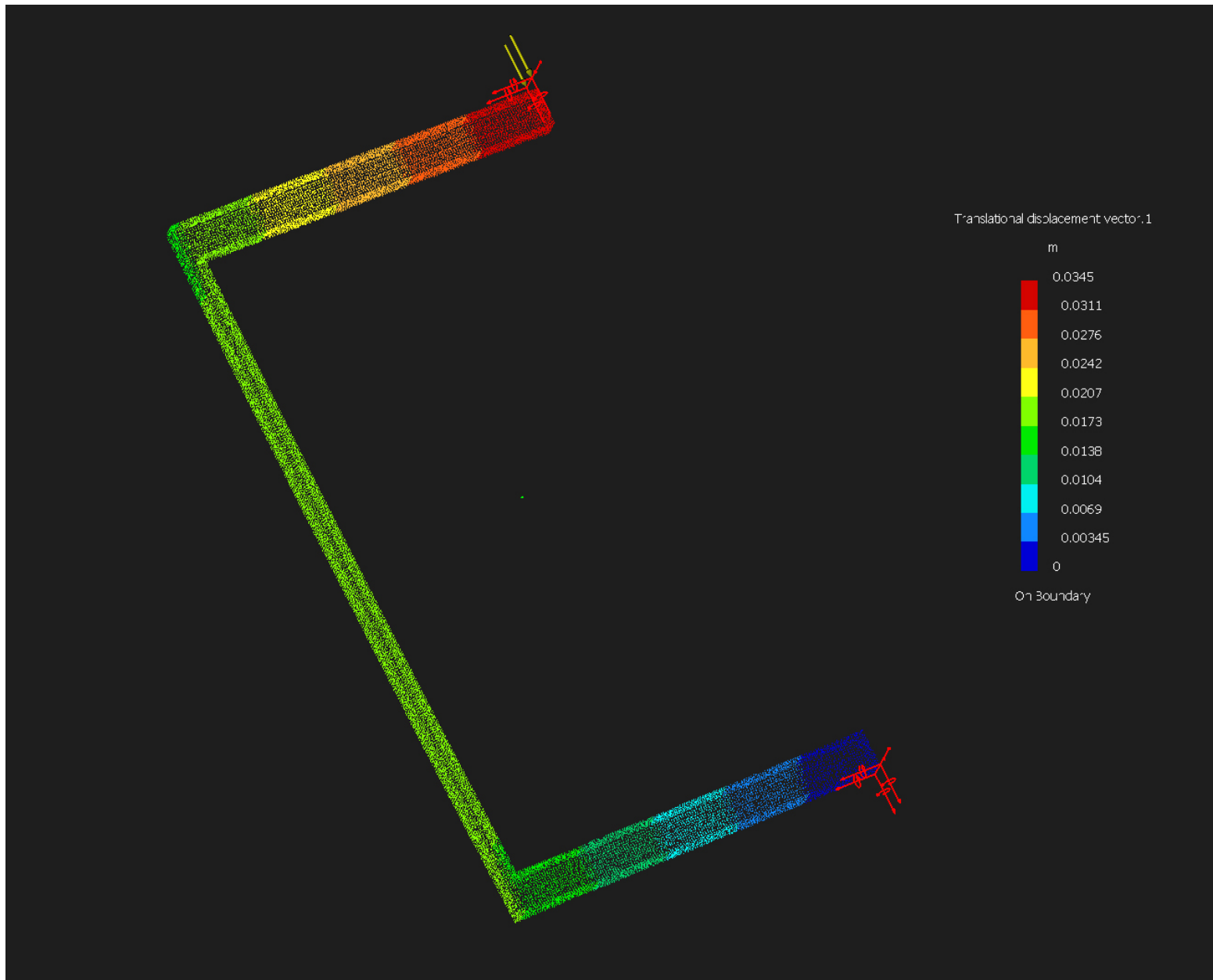


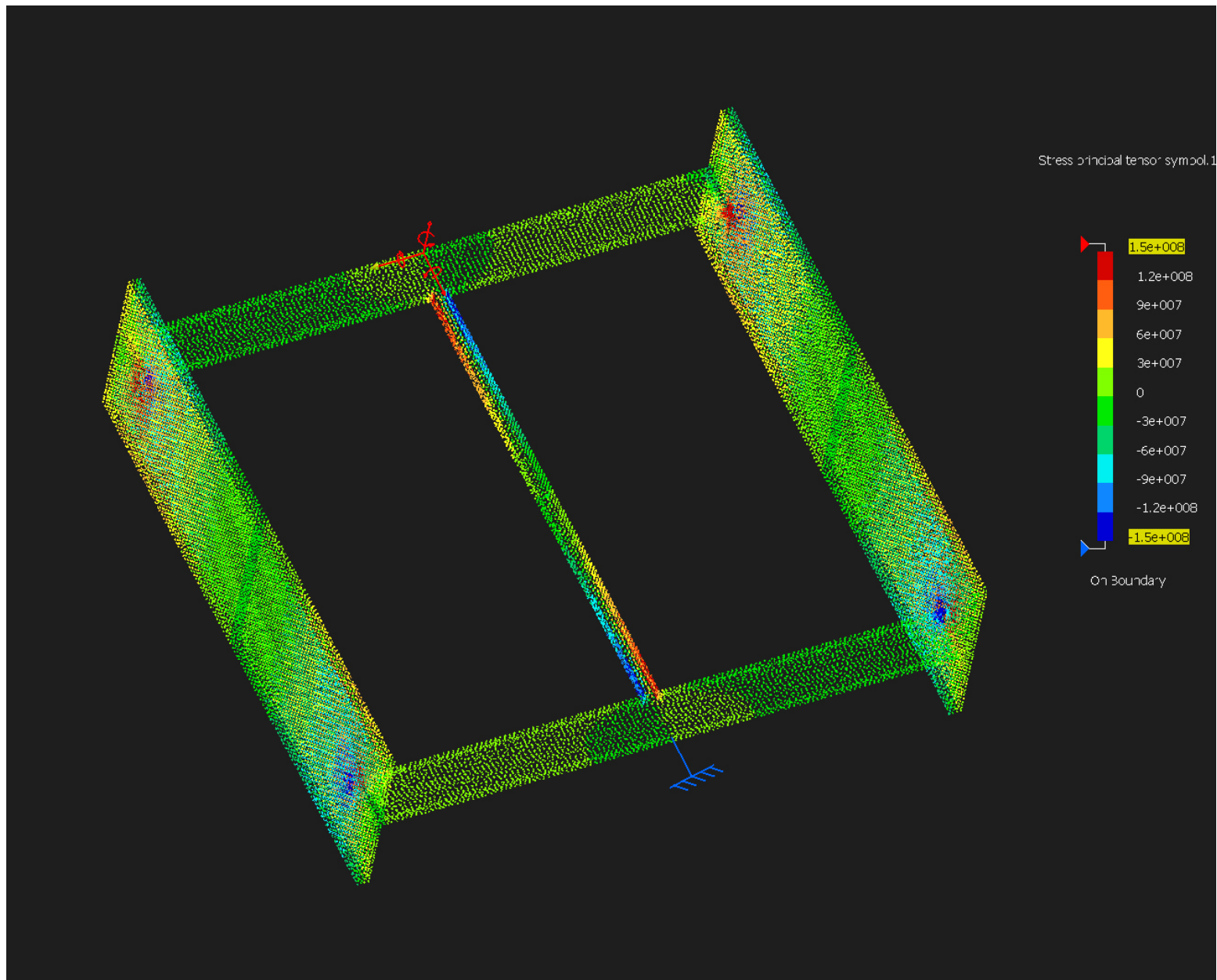
Annex 6 :: Finite element analysis

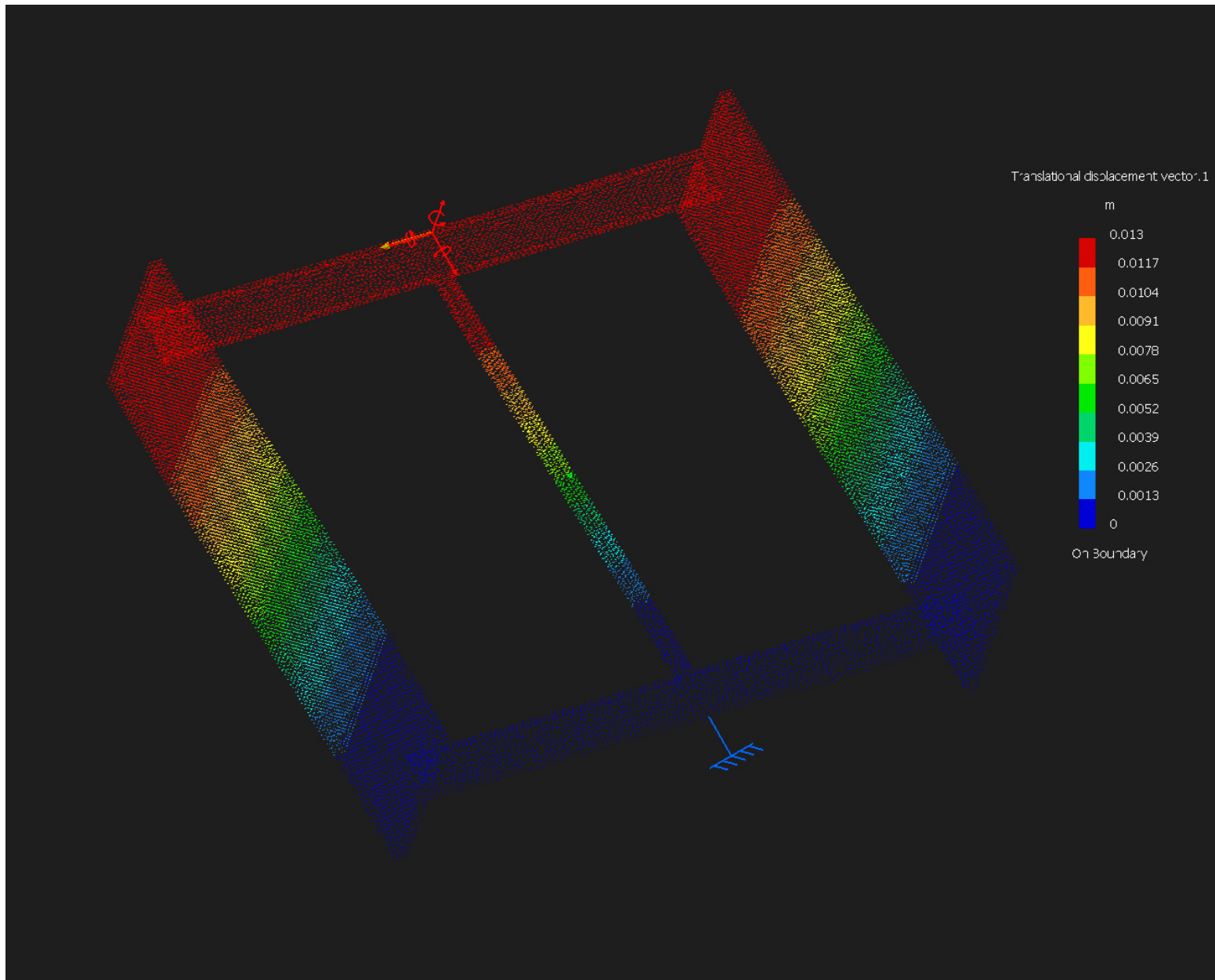


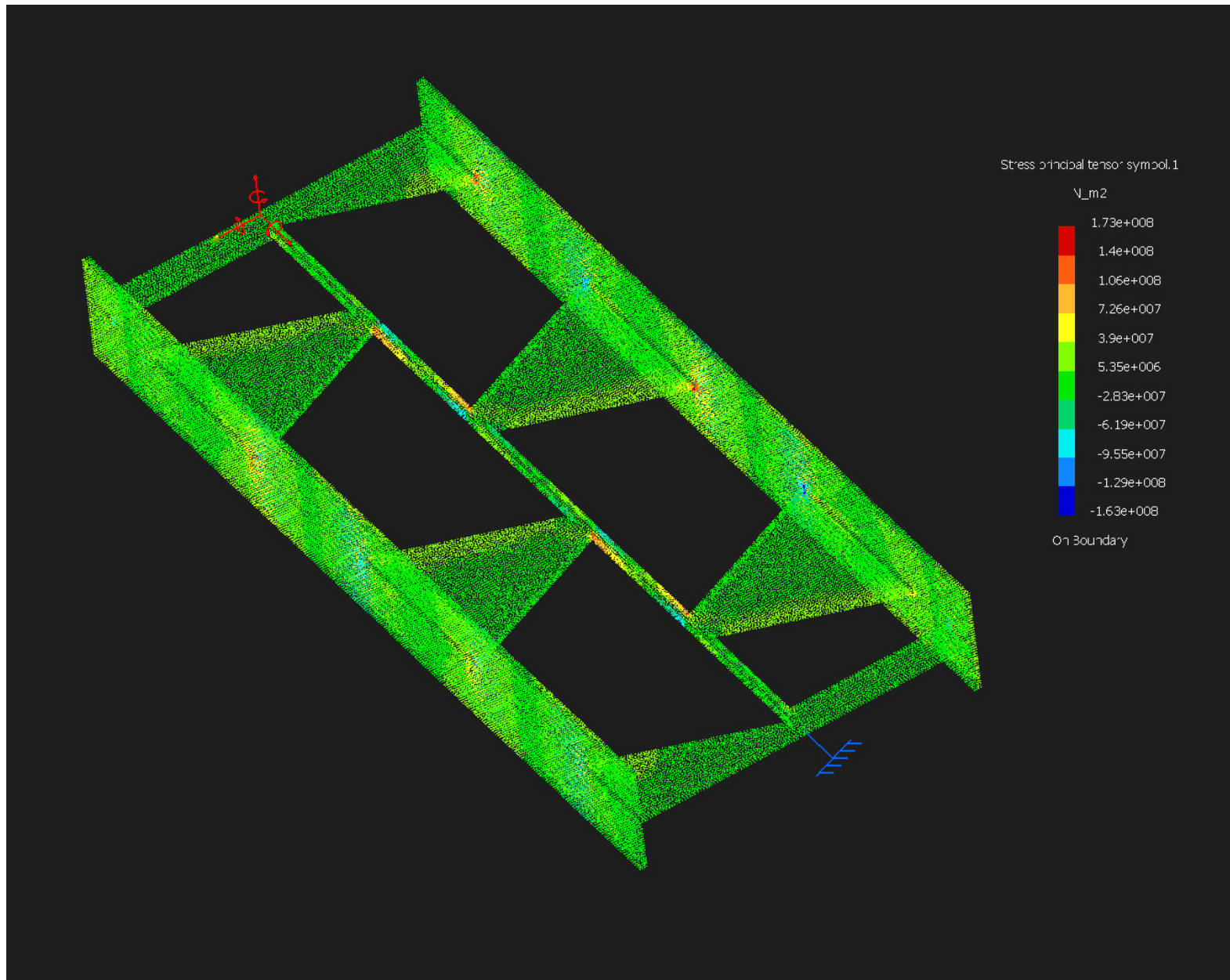


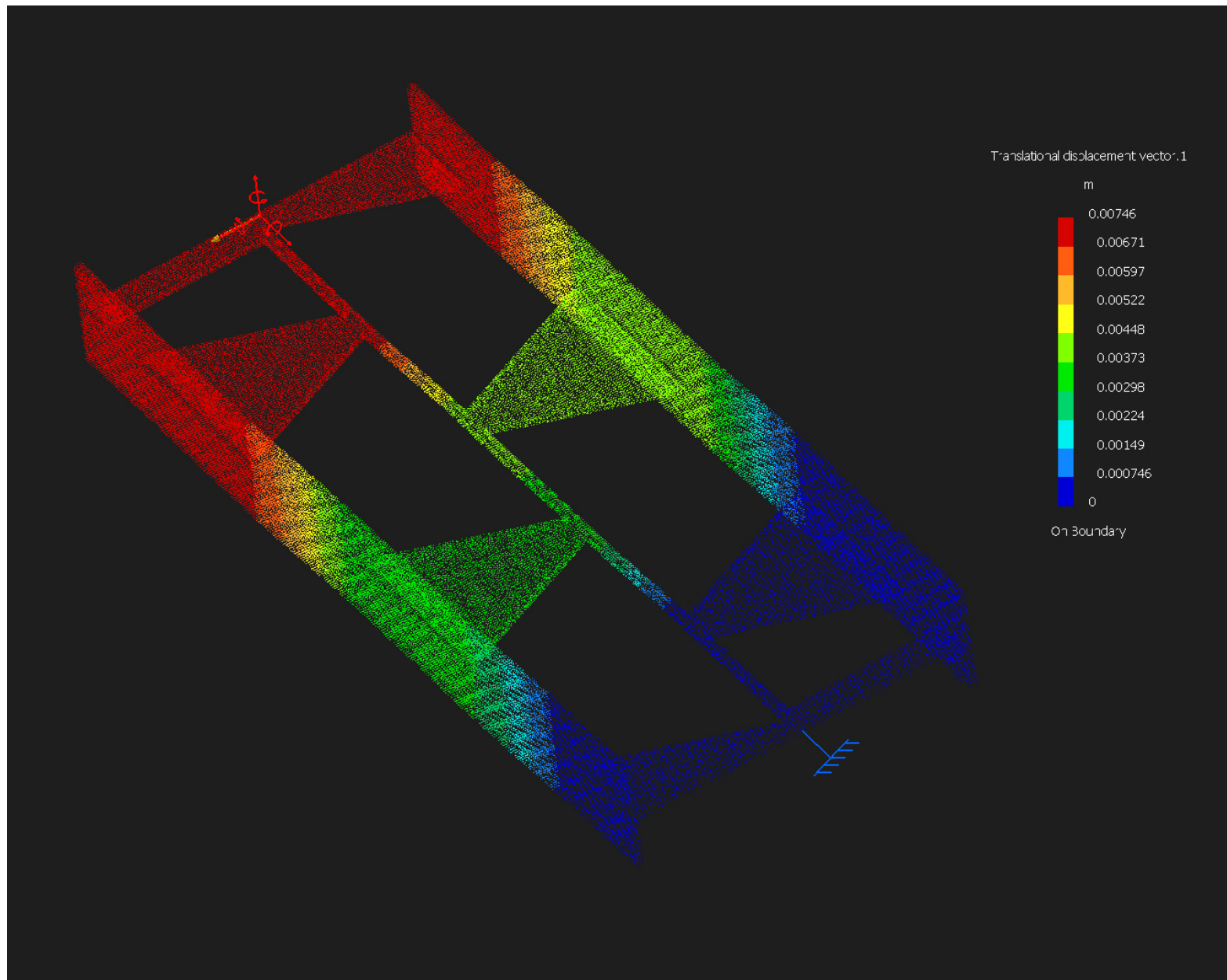


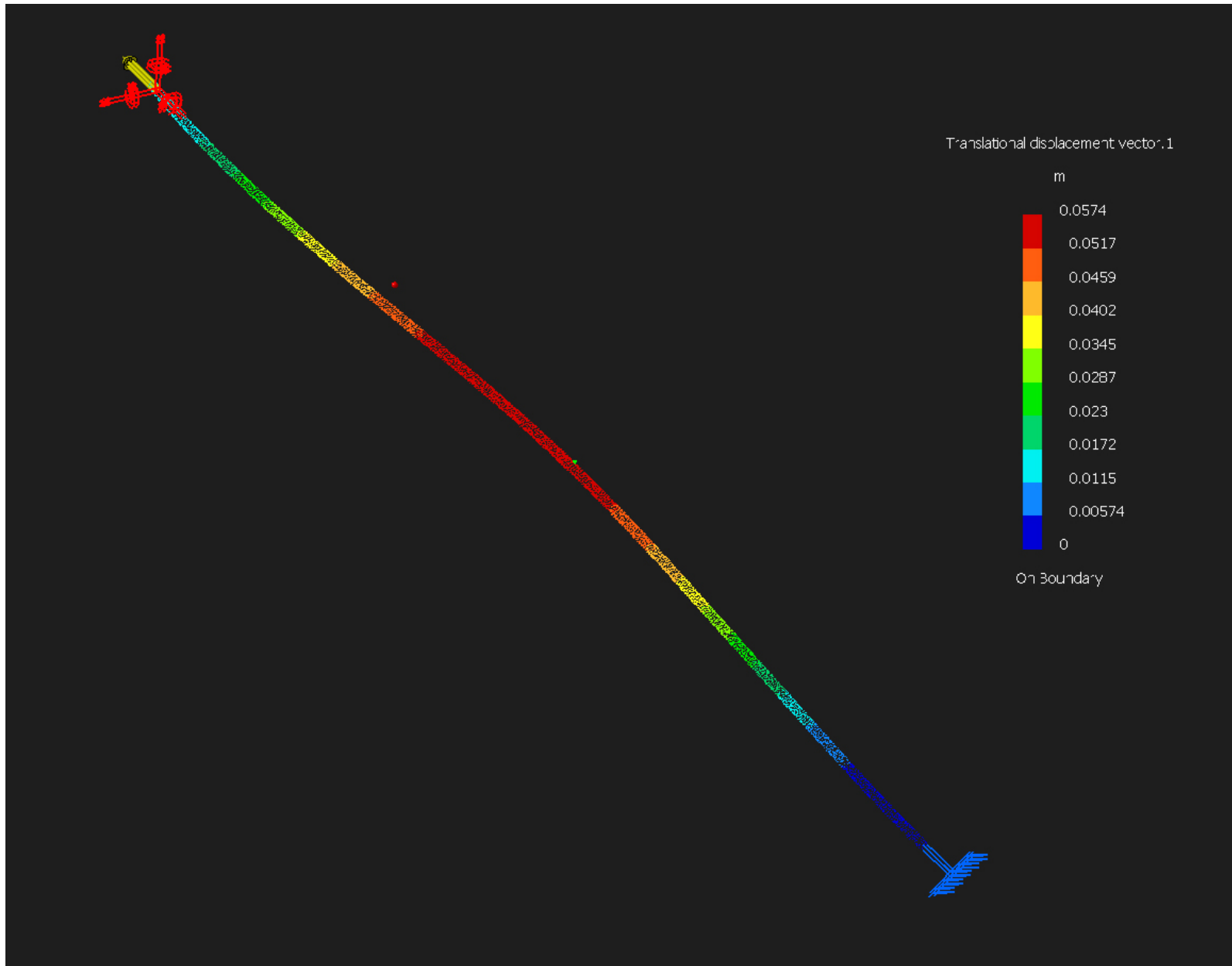


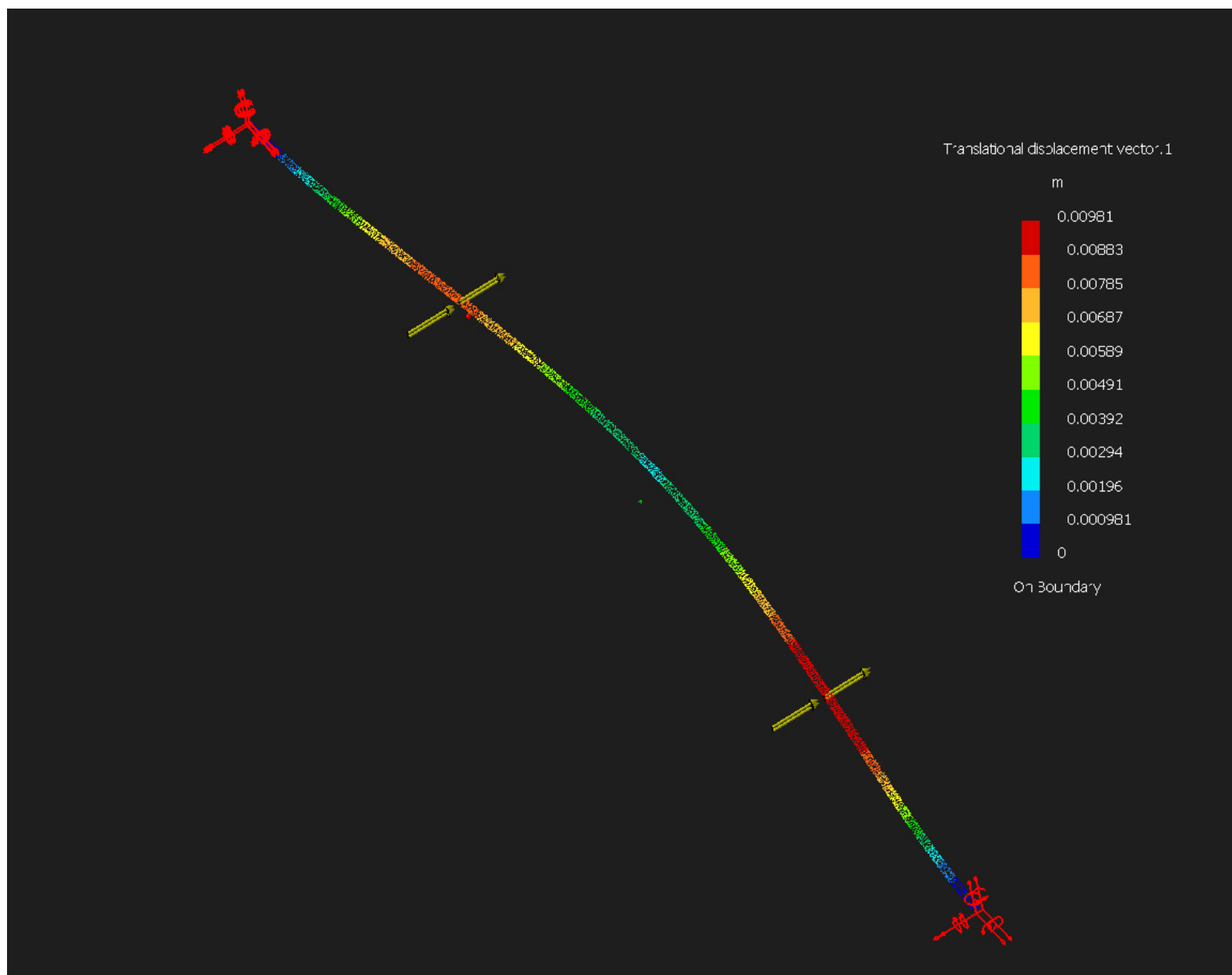












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