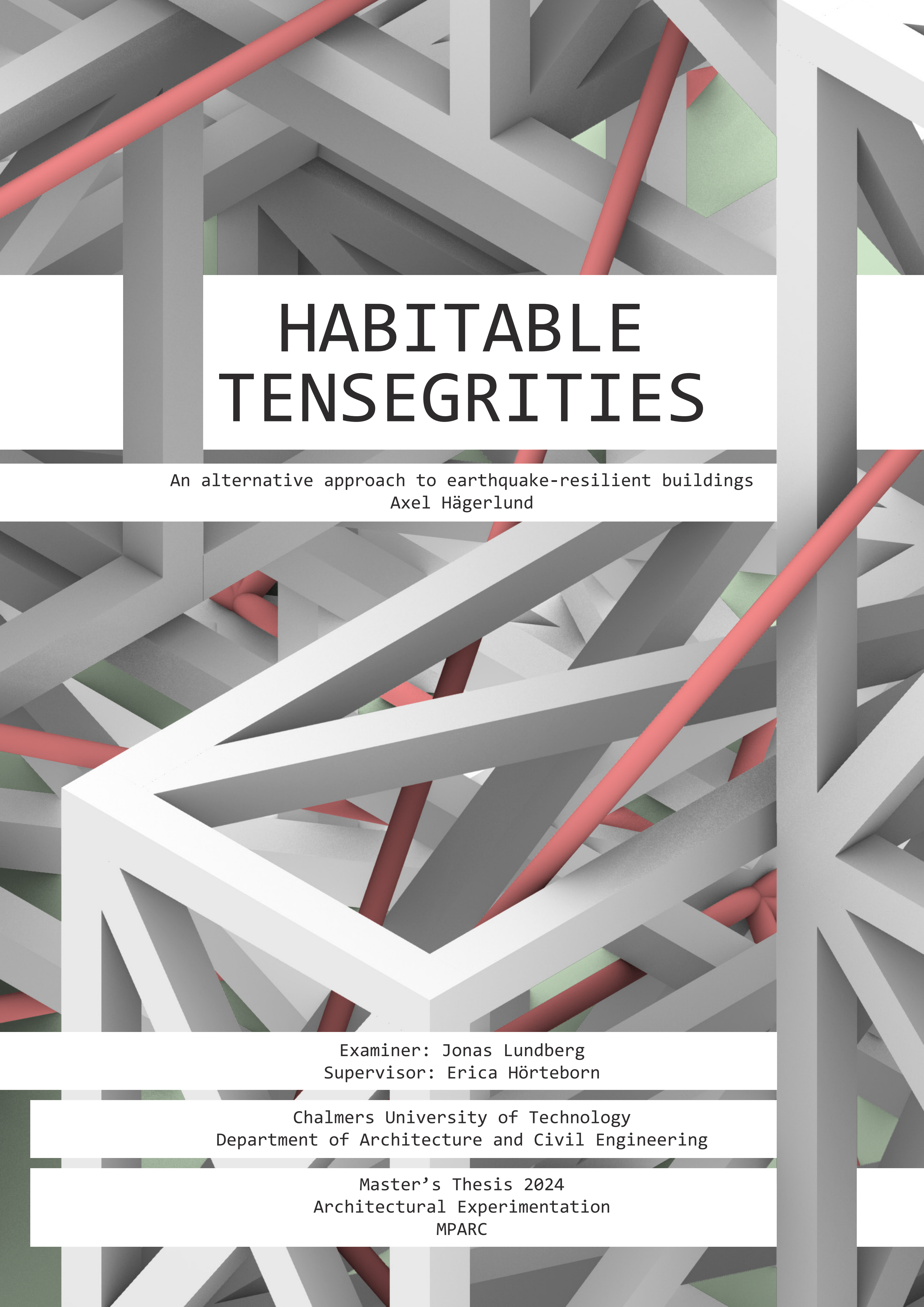

HABITABLE TENSEGRITIES

An alternative approach to earthquake-resilient buildings

Axel Hägerlund

Examiner: Jonas Lundberg
Supervisor: Erica Hörteborn

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Master’s Thesis 2024
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Thank you, Erica Hörteborn, my supervisor for this thesis, for your great insight as well as the invaluable dialogue we had that helped shape this project.

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A misunderstanding between myself and Jonas Lundberg in a previous course was what initially led me to discover and become interested in tensegrity.

I have always had an interest for mechanical construction and how to gainfully integrate it into the expression of buildings. Any good design stems from an inspiring problem, and the process of tying together the solution by designing enjoyable spaces is the core of what makes architecture.

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Abstract

The aim of this thesis is to find architectural implementations for tensegrity within earthquake-resilient buildings and to explore which opportunities, challenges, and design implications arise from harnessing this seldom utilized structural principle.

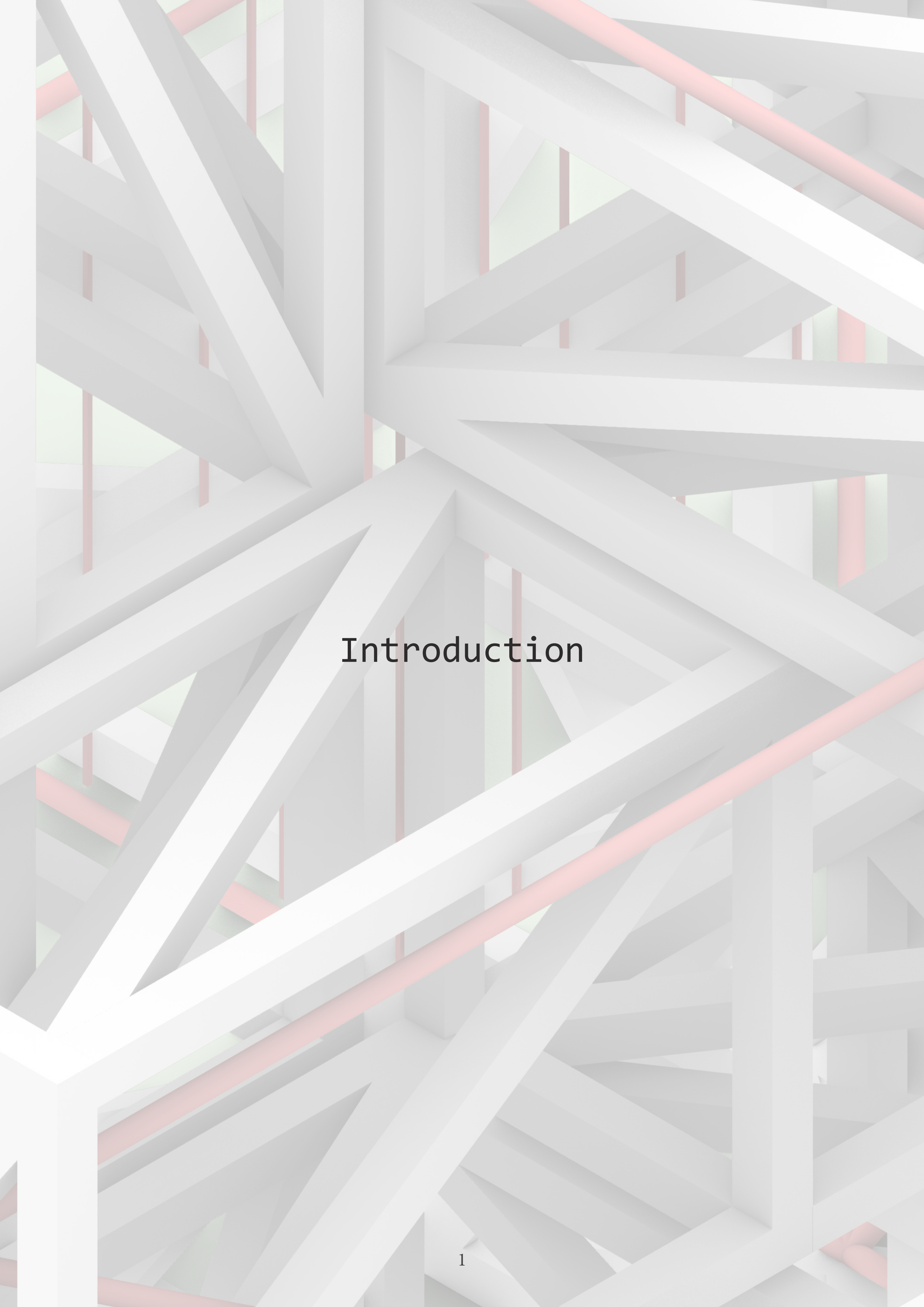
Earthquakes are responsible for a majority of deaths caused by natural disasters according to WHO (n.d.). They state that 125 million people were affected by earthquakes globally during a 19-year timespan, and list building design and materials as one of six factors that determine how severe the impact is. This implies an enormous potential benefit for buildings that are better able to withstand this phenomenon.

In a nutshell, a tensegrity system is a set of otherwise unstable compressive components connected to each other and made stable by a set of tensile components. Tensegrity as a structural principle offers flexibility and elasticity whilst being lightweight.

While this work is based on an established theoretical framework the main focus has been experimentation and exploration regarding how to apply the pre-existing knowledge. Much of this investigative process has been carried out through iterative digital physics simulations, backed by further verification in the form of physical scale models.

The findings from the explorations are integrated into a general concept for an earthquake-resilient building to highlight the practical applications for tensegrity as well as to provide a basis for discussion regarding architectural ramifications of design choices and structural logic. In order to best make the case for the viability of tensegrity for any type of building it will be applied to a residential building, arguably the most ubiquitous type. This design is not location-specific and instead explores the concept in a general sense.

Keywords: tensegrity, parametric design, digital simulation, habitable tensegrity, seismic architecture



Introduction

Definition

The very definition of tensegrity is contentious. The classical and purest definition of tensegrity is that “A tensegrity system is established when a set of discontinuous compression components interacts with a set of continuous tensile components to define a stable volume in space.” (Pugh, 1976, p.3). The specific mention of the continuum of tensioned components is not echoed by Skelton and de Oliveira (2009). Indeed, a system may retain largely the same mechanical properties despite forgoing this specific requirement.

Skelton and de Oliveira further argue that “[a] tensegrity configuration that has no contacts between its rigid bodies is a class 1 tensegrity system, and a tensegrity system with as many as k rigid bodies in contact is a class k tensegrity system.” (Skelton & de Oliveira, 2009, p.3). This provides a broader understanding of tensegrity, permitting multiple compression components to be connected to the same node through frictionless ball joints, illustrated in figure 1. Such a system retains the same mechanical properties as a more traditional tensegrity system as described by Pugh (1976) but deviates somewhat in terms of aesthetical expression. It should be noted that this is a contentious topic within tensegrity.

This thesis considers tensegrity structures which fall under the classical definition as well as those that fall under the more permissive conditions outlined by Skelton and de Oliveira.

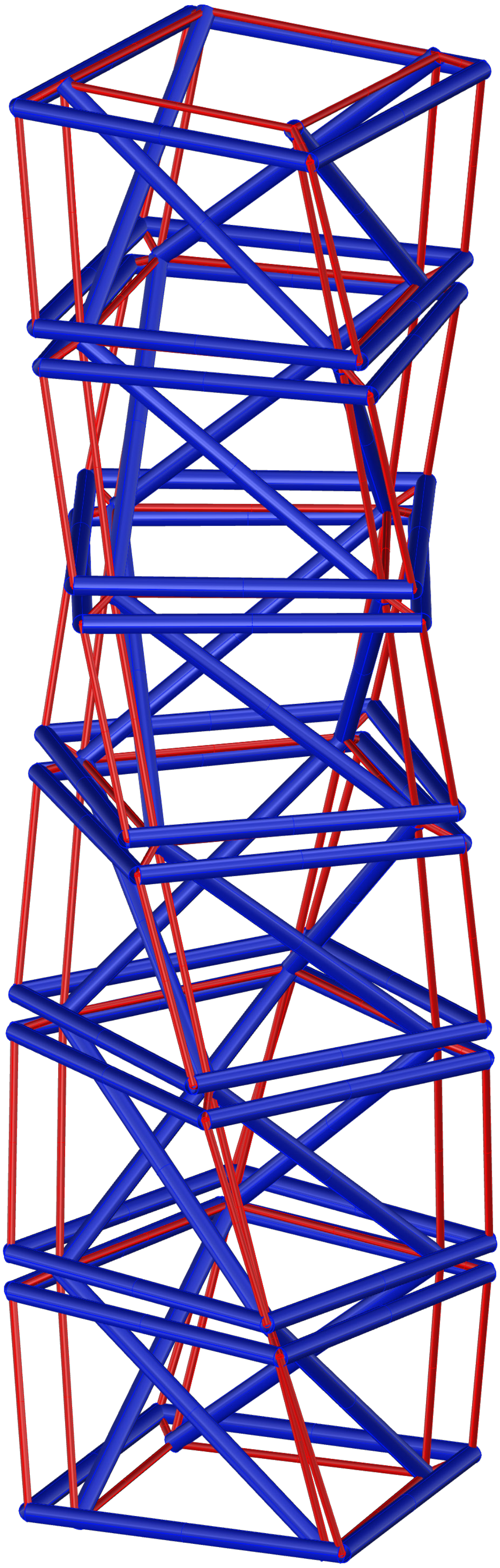


Figure 1. Class 2 tensegrity tower.

Background

Tensegrity is a relatively new concept within the field of structural systems, first being patented by David Emmerich, Buckminster Fuller, and Kenneth Snelson at around the same time as each other in the 1960’s. Tensegrity as a structural system offers advantages compared to traditional construction methods. Each constructive component is exclusively under tension or compression and there is no torque or shear stress within the system. This allows for selecting materials which are very effective in either tension or compression and provides lightweight yet mechanically durable structures.

Previously, tensegrity has not been meaningfully applied to habitable architecture, rather being used for monuments, roofs, and bridges, along with other applications outside the field of architecture. While it cannot be argued that the roofs are not applications of tensegrity for buildings there is a distinction to be made between a structure that sits on top of the load-bearing system and one that supplants it entirely or works alongside it. A regular building with a tensegrity roof is a building with a tensegrity feature, not a tensegrity building.

While it is difficult to prove that something does not exist, the most promising case of tensegrity applied to an entire building found when searching for the terms ‘tensegrity house’, ‘tensegrity home’, and ‘tensegrity building’ is an unbuilt design for a hotel in Tasmania with little to no news coverage from the past few years. Furthermore, whether this hotel was meant to incorporate tensegrity is not abundantly clear as the articles that fail to mention it far outnumber the single one that does. It could be a matter of a misunderstanding, or that they initially planned it, or perhaps they are still planning it.

However, while not yet having found success in man-made structural systems, tensegrity as a concept exists in nature. Both Skelton and de Oliveira (2009) and W.M. Galil (2010) give the elbow as a concrete example for tensegrity in our own anatomy. In this example, the muscles and tendons make up the tension components whereas the bones serve as the compression components.

Over recent years tensegrity has garnered interest and been subject to extensive research regarding its viability for planetary landers and exploration vehicles. This is to a large degree due to its nature of being strong, durable, and lightweight, whilst allowing locomotion by means of actuation.

Research questions

1. What concrete benefits are there to using tensegrity when designing earthquake-resilient buildings?

2. What would a multifamily residential building with tensegrity as the main structural principle look like?

3. How would the usage of a multifamily residential building with tensegrity as the main structural principle differ from a more traditional building?

Glossary

Tension component:
A constructive element exclusively subject to pulling forces. Often in the form of a cable but it can have any shape. Illustrated in red in this thesis.

Compression component:
A constructive element primarily or exclusively subject to pushing forces. Often in the form of a beam but it can have any shape. Illustrated in blue in this thesis.

Equilibrium:
A system where the sum of all forces is 0. All systems where the internal components are not moving are examples of this.

Habitable volume:
A body with a discrete interior and exterior which protects from local climate. Its interior can be used as one or multiple normal rooms.

Delimitations

Sustainability:
This thesis chiefly relates to sustainability by attempting to minimize the impact of earthquakes and their consequences such as displacement of people.

Geometry:
The habitable volume should be easy to use and efficient in relation to the dimensions of the tensegrity system. This thesis takes a pragmatic approach, focusing on creating internal volumes with horizontal floors and vertical walls, ideally rectangular cuboids. A tensegrity structure whose configuration encroaches excessively on the habitable space or creates odd angles, whilst architectonically interesting, is not as viable. By taking what some may consider to be a mundane approach this thesis better showcases how an unorthodox system can become part of the built environment.

Architecture vs engineering:
This is an architecture thesis which focuses on architecture with structural guidance through digital simulations rather than dealing with the complicated maths behind finding the ideal shapes for tensegrity structures. This thesis hinges on the structural understanding of these shapes and is focused more so on finding applications and derivations of established shapes than finding altogether new shapes.

Tensegrity and earthquakes

Murty et. al. (2012) describe the effect of earthquakes on buildings as a haphazard movement of the ground and thus also the points of the buildings which connect to it. This subjects the rest of the building to inertial forces proportional to the weight of the building. In other words, a simple way to design an earthquake-resilient building is to make it lightweight.

Apart from being lightweight, tensegrity offers an advantage in the ability to elastically deform on a system level rather than being rigid. As a consequence, forces are distributed throughout tensegrity systems along multiple load paths according to SunSpiral et al. (2013), thus reducing the load on the otherwise most stressed components. Their testing showcases how a probe with a payload with an equal mass to as itself can sustain a 15m/s impact, which whilst not directly applicable to an earthquake scenario does highlight the structural viability of tensegrity.

Fraternali & Santos (2019) specifically showcase how tensegrity structures can serve to better dissipate the energy of an earthquake. Through the use of superelastic shape memory alloys, a type of material able to return to its original shape after deformation, for the tension components a tensegrity structure can allow for significant movement and eventually return to its original shape. Hence, the damage sustained in an earthquake can be minimized or altogether avoided. They describe their d-bar solution, see figure 2, as "… a lightweight design to mitigate against buckling, high energy dissipation capacity, and strong re-centering ability." (Fraternali & Santos, 2019, p.7).

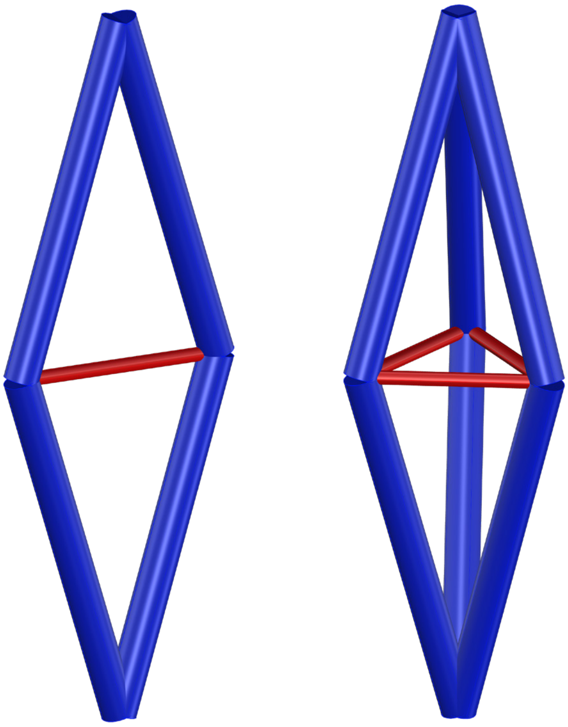


Figure 2. D-bar tensegrity.

Another strength of some tensegrity systems, and specifically Jessen's icosahedron, is being able to withstand structural failure of a few component. This would "gracefully degrade performance" (SunSpiral et al., 2013, p.3) rather than the system violently collapsing.

A building with tensegrity as its main structural concept could integrate a horizontally damping foundation, a more traditional means of damage mitigation for earthquakes. The idea of such a structure is to allow the base of the building some freedom of movement relative to the ground and thus better insulate the entire structure from the horizontal forces it is subjected to by an earthquake.

Method

Literature studies served as the basis for this work and have been made in parallel with exploratory work. An emphasis was put on developing an intuitive understanding of tensegrity systems as well as finding potential configurations to use as starting points in the architectural design process.

The bulk of the exploration has been carried out in Rhino 8, enabled by the two plugins Grasshopper and Kangaroo2. In conjunction they allow for physics simulation in a parametric 3D-modeling environment. This setting allows for testing systems observed during literature studies with or without modification, as well as to experiment with new ones. This has been done with the integration or creation of habitable modules in mind.

Physical modeling has been used as an additional tool to further verify findings from digital models from some of the more promising shapes, as well as an aid to developing a more intuitive understanding of the systems. While the exact scale of the these models does not impact the general function of the system mechanically they have been constructed from wood and fishing wire at an approximate scale of 1:100 for convenience.

The most auspicious design candidates were selected and developed further in an architectural context.

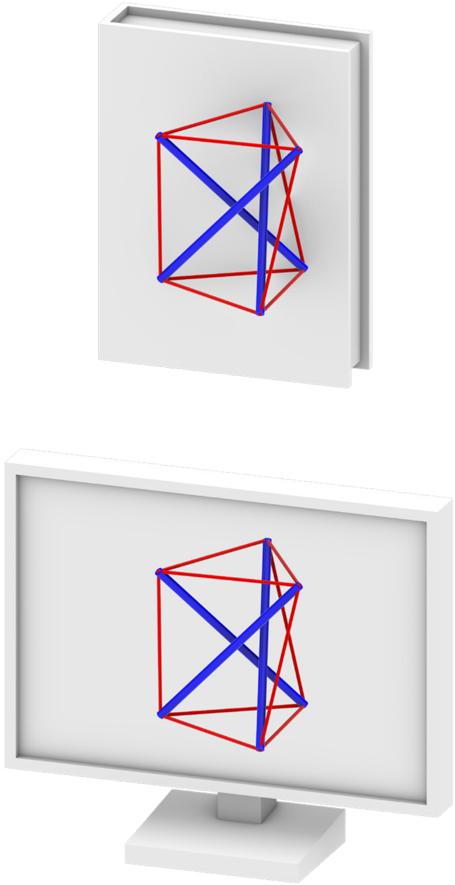


Figure 3, 4. Method illustrations.

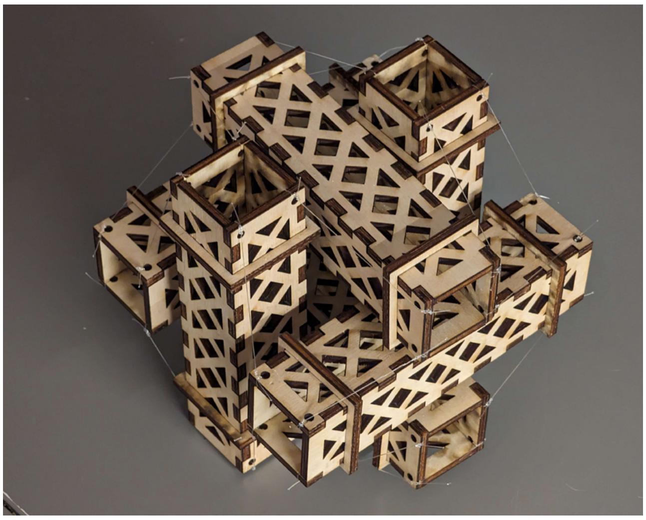


Figure 5. Physical tensegrity model.

Digital workflow

0. The starting shape is constructed with compression components and tension components in separate groups. This can be done either directly in Grasshopper or with geometry drawn in Rhino. This is illustrated in figure 6.

1. Gravity load is applied to the center of each compression component, as well as any bodies supported by the tensegrity system. The size of this load can be parametrically controlled in real-time while simulating. It is expressed as a floating point number between 0 and 1 and applied in the -Z direction.

2. Pre-stress is applied to each tension component. The amount of pre-stress can be parametrically controlled in real-time whilst simulating. It is expressed as a factor between 0 and 1, and is multiplied with the starting length of each tension component.

3. A floor is created to prevent the system from falling off the screen.

4. Items from steps 1-3 are entwined and used as input for the Kangaroo2 solver. As no change in length has been given for the compression components these are rigid, leaving only the tension components to deform.

5. Output from the Kangaroo2 solver is piped and color-coded.

Neither the gravity load nor the pre-stress is given as a specific number of SI-units. Hence, this simulation does not output any specific loads within the system and cannot be used for dimensioning. They should instead be understood as motors for deformation, to highlight how the system behaves as one or both of them are altered.

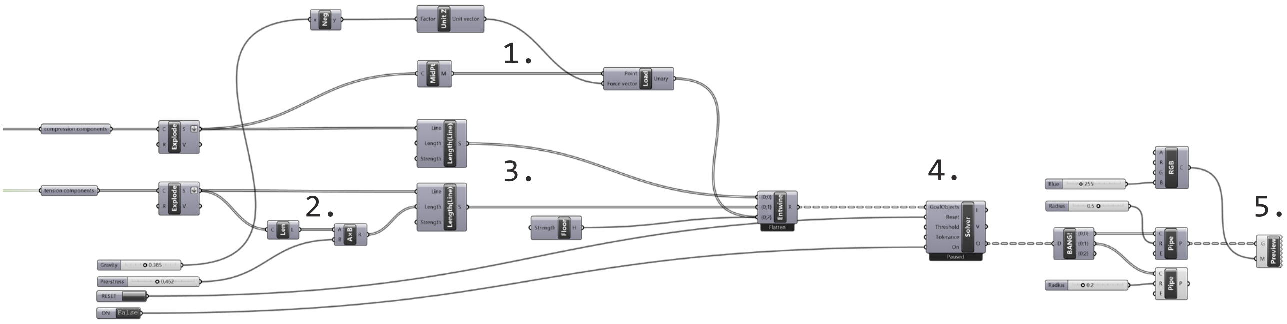
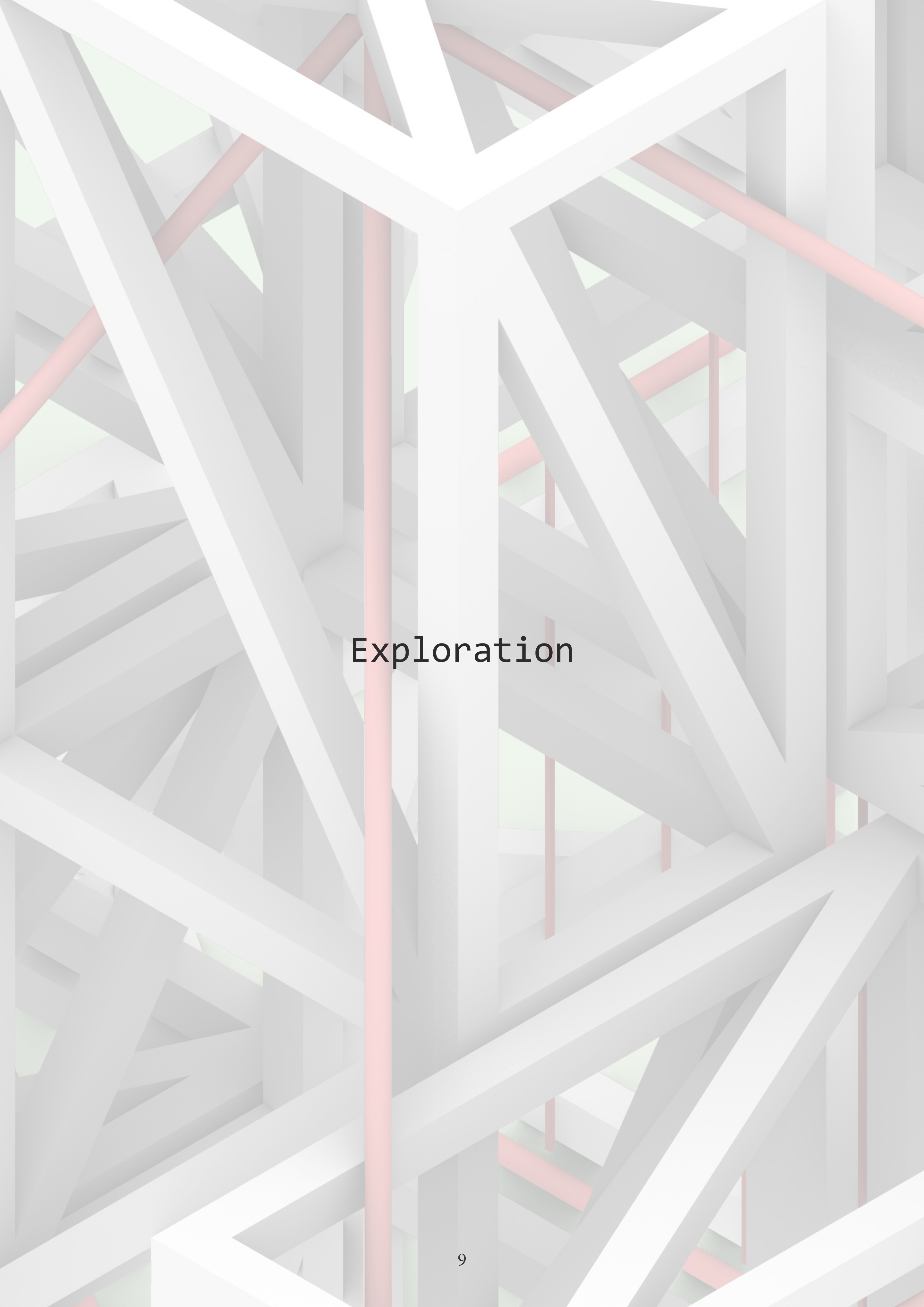


Figure 6. Grasshopper workflow.

As a means of simulating an earthquake as described by Murty et. al. (2012) a modification to the core method shown above was used. As Kangaroo2 does not work with mass, the approach was to simulate the effect of inertia on the building by introducing horizontal force to the system with a linear increase relative to the height above the ground. Through a Python script in Grasshopper the XY-components of the force vector were randomized for every iteration, which ran at approximately 10Hz. This was primarily used to compare different tensegrity shapes, to see how many iterations they could handle without plastic deformation under given parameters.



Exploration

Interaction with habitable volumes

There are a few different approaches for enabling a tensegrity system to interact with a more traditional structure. They cannot simply be connected to another structure or the ground with rigid joints as this would not permit a self-equilibrated state. For a true tensegrity system to be gainfully integrated into a larger non-tensegrity structure one of the approaches discussed and illustrated below can be utilized. Load is illustrated in green on this page.

Tensegrity system bearing a simply supported structure on top. To facilitate deformation in the tensegrity system the connections to the habitable volumes need to permit movement.

Tensegrity system bearing a structure through tension. This approach hangs the habitable volumes from the top of the structure through tension components.

Tensegrity system supporting a structure directly through compression components. This approach places the load of the habitable volumes on the compression elements, ideally with a relatively evenly distributed load on the compression component.

Tensegrity system directly integrating a structure as compression components. Rather than considerig the compression components as 1-dimensional lines typically seen in tensegrity structures this approach utilizes rigid habitable volumes as compression components.

Nesting one suspended tensegrity system within another to create discrete interior and exterior surfaces. As the point of the compression components is to push nodes away it seems needlessly convoluted to create new interior nodes through tensegrity.

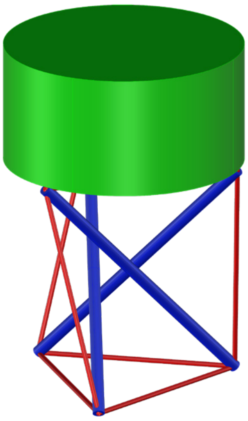


Figure 7. Simply supported.

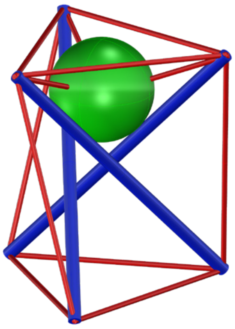


Figure 8. Hanging.

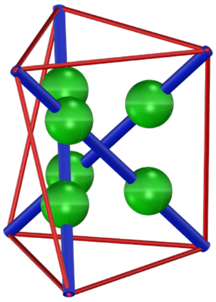


Figure 9. On compression.

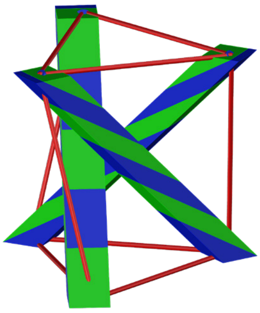


Figure 10. Integrated.

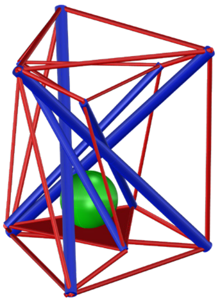


Figure 11. Nesting.

Ideal shape

In any tensegrity structure there is an ideal shape which will be approached as the pre-stress increases, see figure 12. For some systems, this shape is stable and will result in a structure that will not change regardless of how much stress is applied.

The ideal shape of certain configurations will result in an unstable structure, resulting in a collapse as the stress increases. However, these configurations remain viable, although it must be ensured that the stress never exceeds safe parameters. It should be noted also that they necessarily will deform depending on the stress.

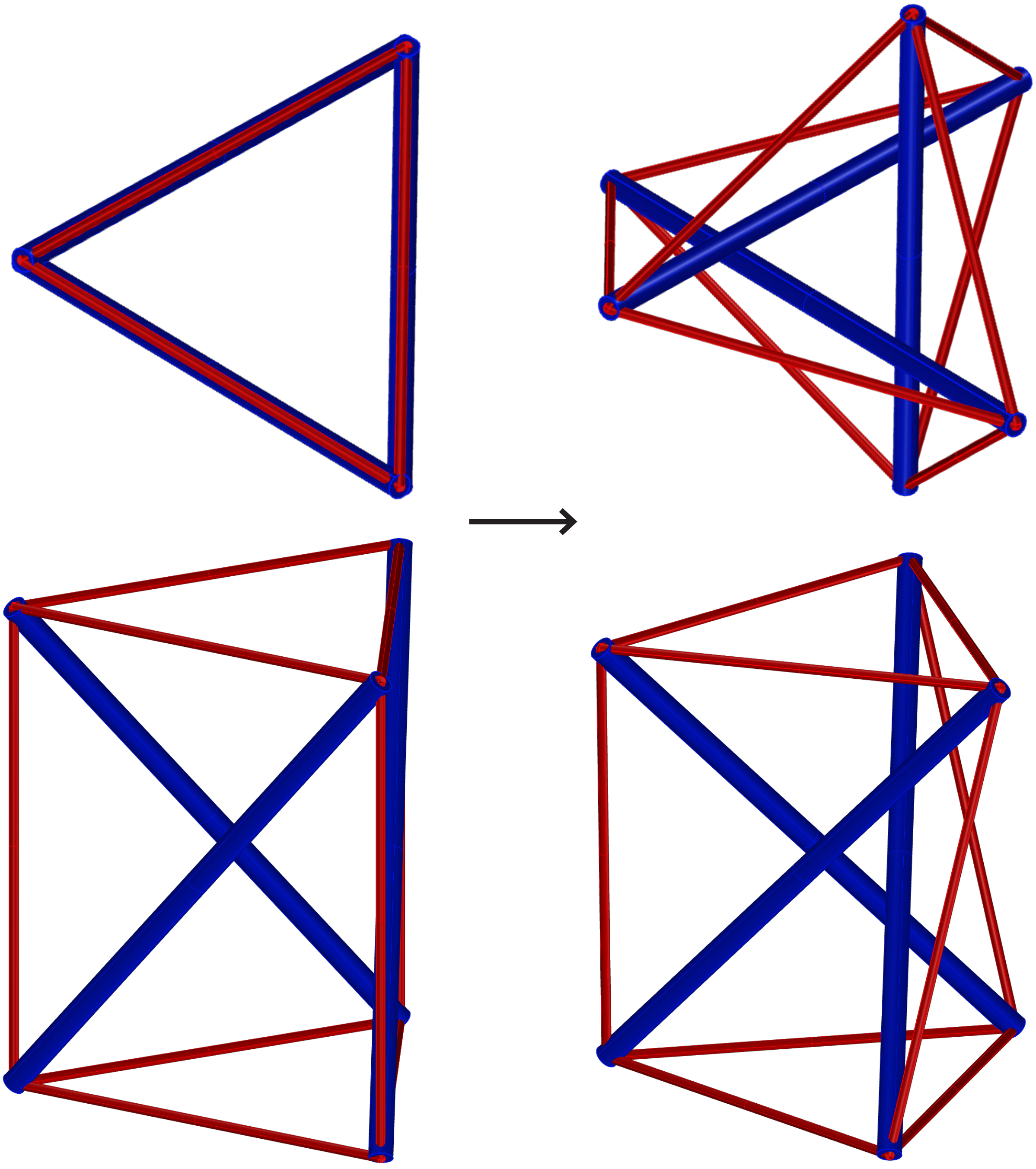


Figure 12. Ideal shape of tensegrity.

Diamond pattern

The name of the Diamond pattern comes from the basic shape that it is derived from. It can be expanded arbitrarily to create a prismatic tensegrity with an increasingly large number of sides. A diamond pattern tensegrity, figure 13, can also be layered, expanding in the vertical direction. These structures fall under what Skelton and de Oliveira (2009) refer to as class 1 tensegrities, where no two compression components are directly attached to each other.

In order to connect multiple tensegrity modules under the stricter definition of the diamond pattern they must be connected exclusively through tensile components.

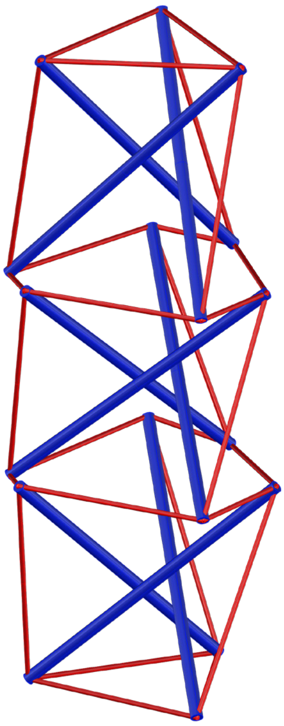


Figure 13. Diamond pattern tensegrity tower.

Circuit pattern

These systems are formed through connecting compression components through ball joints, see figure 14, and thus fall under the class 2 tensegrity system classification as described by Skelton and de Oliveira (2009). Accordingly, they may or may not be considered true tensegrity systems by some. For instance, they do not adhere to the definition of Pugh (1976) or Motro (2003) which specify that compression components should be discontinuous.

Unlike the diamond pattern, the circuit pattern permits an array of tensegrity modules where the nodes connect directly, in addition to the tensile connections described for the diamond pattern.

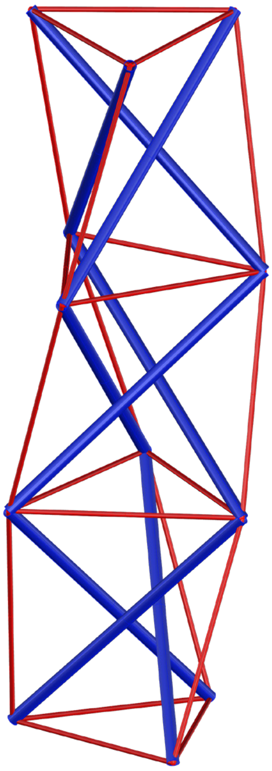


Figure 14. Circuit pattern tensegrity tower.

Prismatic tensegrities

(Diamond pattern)

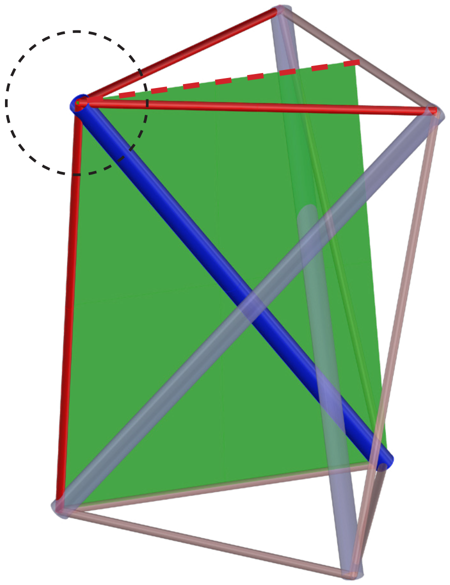


Figure 15. Connection plane of prismatic tensegrities.

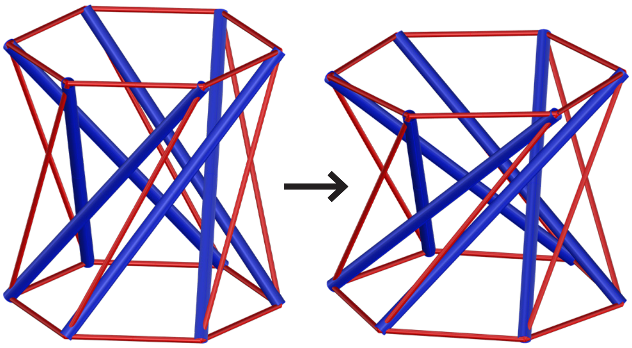


Figure 16. Prismatic tensegrity structure under stress.

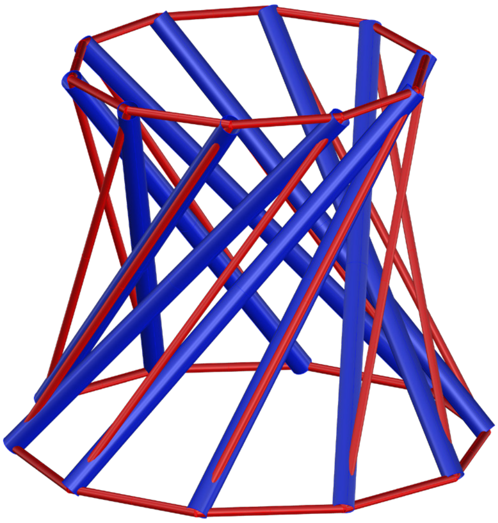


Figure 17. Prismatic tensegrity with unequal radii.

An elementary form of tensegrity is the prismatic. The direction of all connections for any given node must fall on a plane (illustrated in green in figure 15) for the system to be in equilibrium. Since both the horizontal tension members always are coplanar they can be replaced by a virtual tension member directly between the actual ones. This means that an inherent property of prismatic tensegrities is that the top is rotated by (90n-180)/n relative to the bottom where n is the number of vertices of the top/base of the prism. As the number of vertices increases, the required rotation approaches 90°.

The hexagon has an interesting property in that the required rotation is equal to the angle per side, 60°, meaning that the top and bottom perfectly overlap each other as shown in figure 16.

When stressed, the base and top radii of these structures increases while the height decreases. This can be counteracted by increasing the twist of the prism, but this results in more diagonal compression components and an arguably less useful space. Since the compression components form diagonals in the interior of the volume, they emphatically define it, both aesthetically as well as how it can be used.

The larger the number of vertices, the less intruding the compression components become to the interior of the room. However, an increase of vertices also decreases the stability of the system. As seen in the figure 17, the radius of the top and bottom need not be equal.

Jessen’s icosahedron

(Diamond pattern)

Also known as the six-strut tensegrity system or expanded octahedron, this is another typical tensegrity structure. The compression components bisect each face of a cube (illustrated in gray in figure 18), parallel ones sharing orientation. Each node is connected to its four closest neighbors through tension components.

Much like the required rotation for a stable tensegrity prism, there are optimal parameters for a tensegrity structure based on Jessen’s icosahedron. The angles of the compression components remain orthogonal, but they must be twice as long as the length of the side of the cube they are based on. This effectively means that, apart from arraying it, there is only one ideal configuration.

This is an example of a 2-layer diamond pattern tensegrity and can be derived from the 3-gon prismatic tensegrity system, with one on top of the other. As opposed to the way these systems often are depicted this allows them to stand on their own without support even if one imagines the nodes as being true geometrical points, see figure 19.

As a potential variation of this shape each face of the imagined cube can receive multiple compression components, see figure 20. This is beneficial in the sense that it provides a greater internal usable volume and a simple way to interact with the interior of a building. However, the tall rectangles formed by coplanar compression components deform to parallelograms under stress, thus compromising the stability of the entire system.

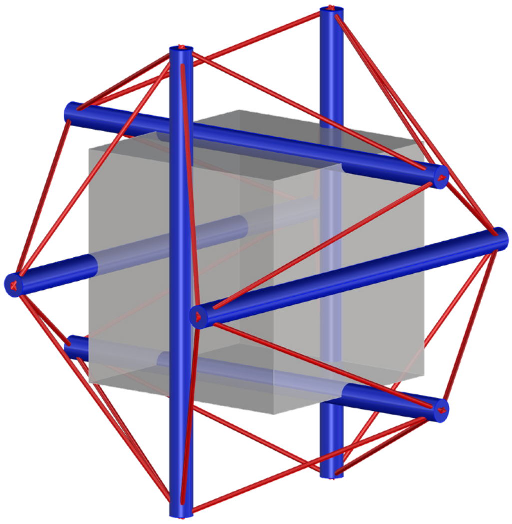


Figure 18. Jessen’s icosahedron upright.

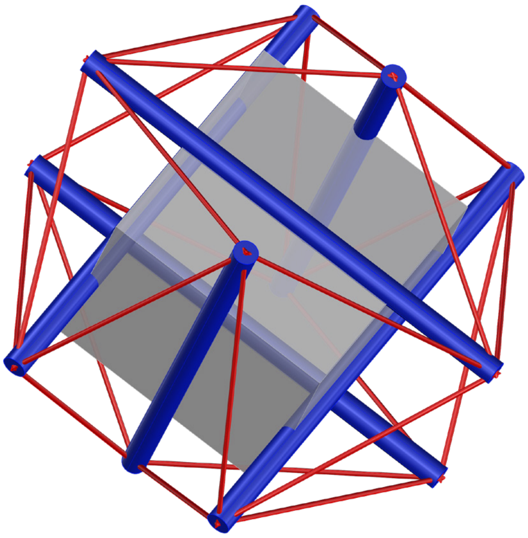


Figure 19. Jessen’s icosahedron tilted.

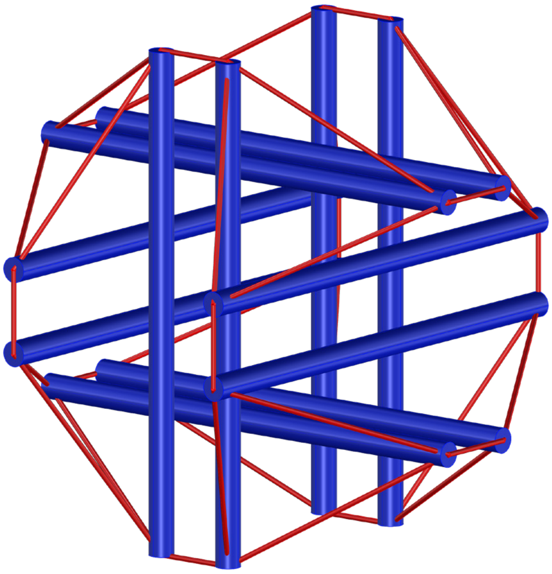


Figure 20. Icosahedron variation with multiple compression components per face.

n-ring straight prism

(Circuit pattern)

The discontinuous compression components, pillars, in this shape are arranged as per the vertical edges of a prism and are surrounded by at least one polygon which has the same number of sides as the number of pillars, see figure 23. The pillars contract towards the center when stressed. If there are ring segments which are offset relative to the midpoint of the pillars they move towards it, however without any deformation in their own shape. The ring part of the system being offset towards either extreme end of the pillars results in the pillars leaning towards the center closer to the other extreme end.

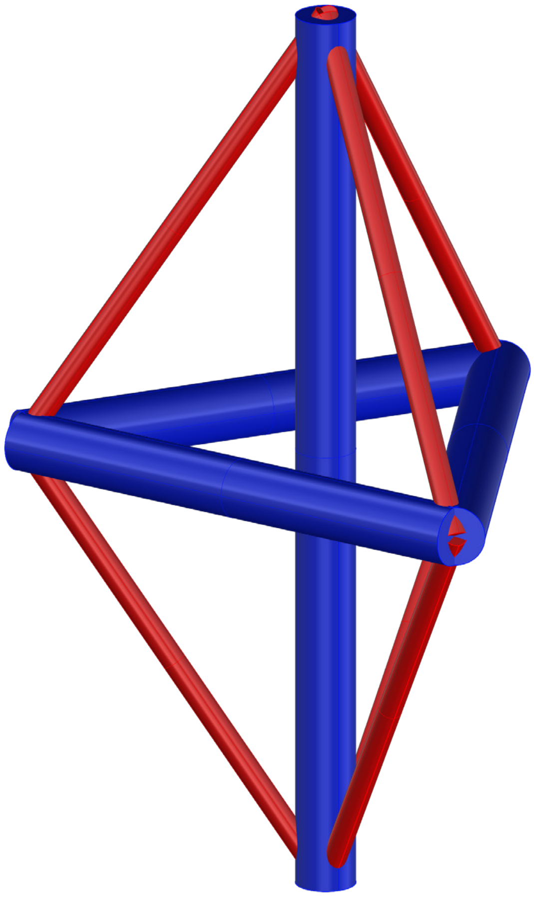


Figure 21. Ring-and-pillar tensegrity.

This configuration is similar to the simplistic ring-and-pillar system, figure 21, where the pillar can be thought of as a prism based on a monogon. Unlike the n-ring straight prism system, the ring-and-pillar system features a different number of sides for each ring than the number of pillars.

The ends of the pillars can be connected pillar-to-pillar to another identical system as illustrated in figure 22, seemingly without any inherent detriment to its mechanical properties. This allows for stacking along the axis of the system, for example horizontally or vertically. Any non-horizontal stacking direction will subject the systems towards the bottom with increased stress and thus increased deformation. The only exception being the vertical stacking of components with vertical pillars.

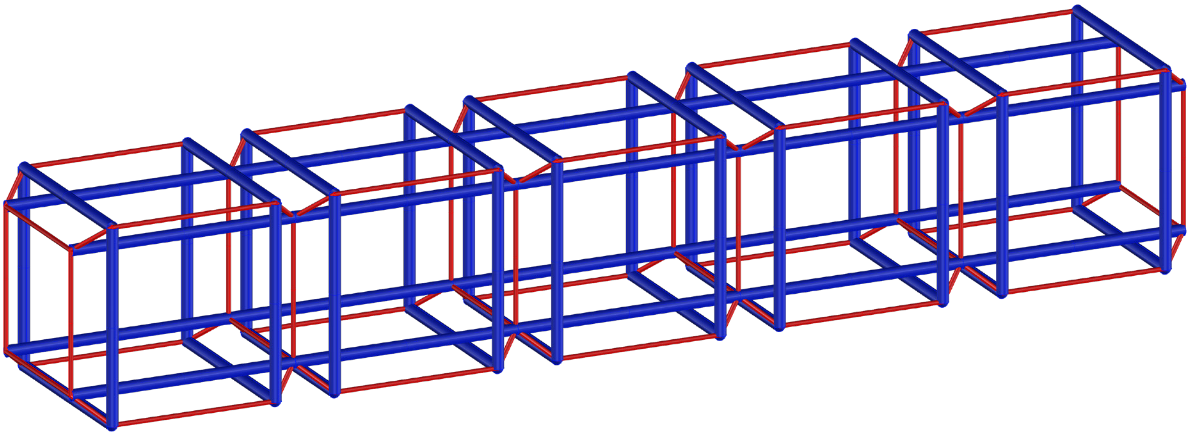


Figure 22. 2-ring straight prism array.

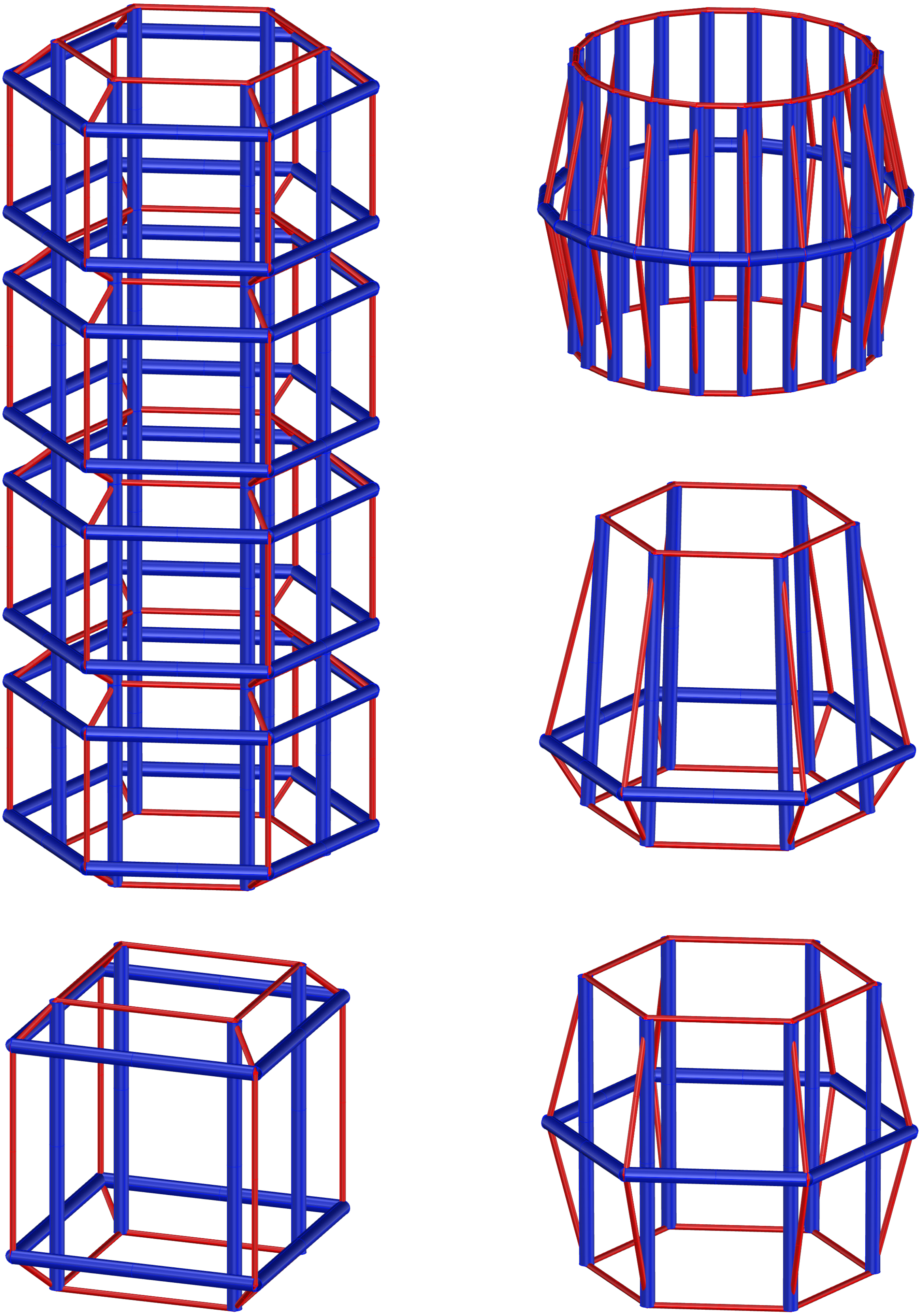


Figure 23. N-ring straight prism variants.

n-ring twisted prism

(Circuit pattern)

By offsetting either the tension components or compression components by one step per ring count a system reminiscent of the classic prismatic tensegrity systems can be created, see figure 24-26. Offsetting the tension components seems to provide better results than offsetting the compression components.

These systems are less stable than typical prismatic tensegrities but have one property of interest: under certain stress conditions the interior forms a straight prism without any interfering diagonal components. Much like the basic prismatic tensegrity this shape becomes more stable as the height/diameter ratio grows, implying that a single tall tensegrity structure of this type is preferable to stacking.

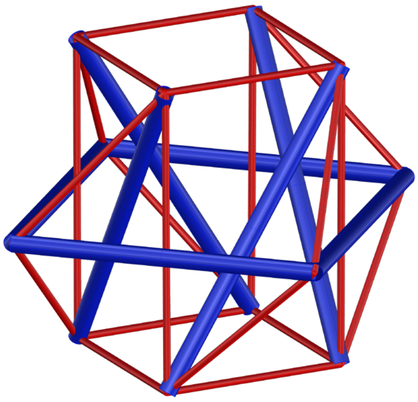


Figure 24. 1-ring twisted prism perspective.

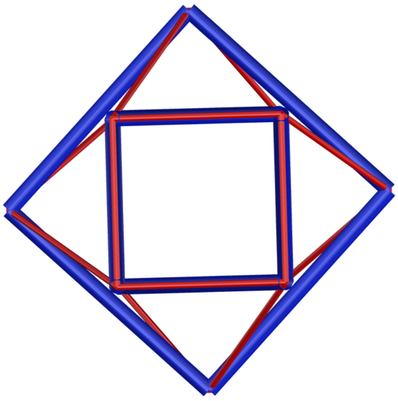


Figure 25. 1-ring twisted prism top view.

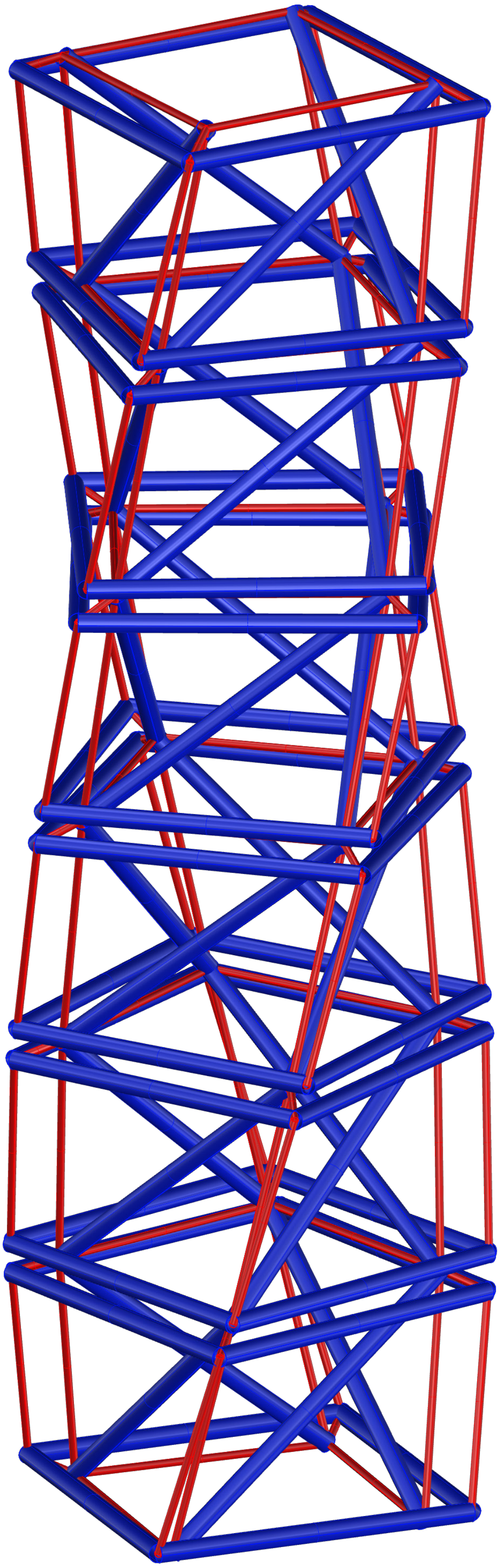


Figure 26. 2-ring twisted prism tower.

Rhombicuboctahedron

(Circuit pattern)

The rectangular faces deform to create parallelograms when stressed. While the triangular faces shrink, the faces which were originally square grow uniformly and the sides of the faces that were originally rectangular grow closer to each other in length. Introducing load in the form of gravity to the system rotates the vertical parallelograms further and reduces the rotation of the horizontal parallelograms.

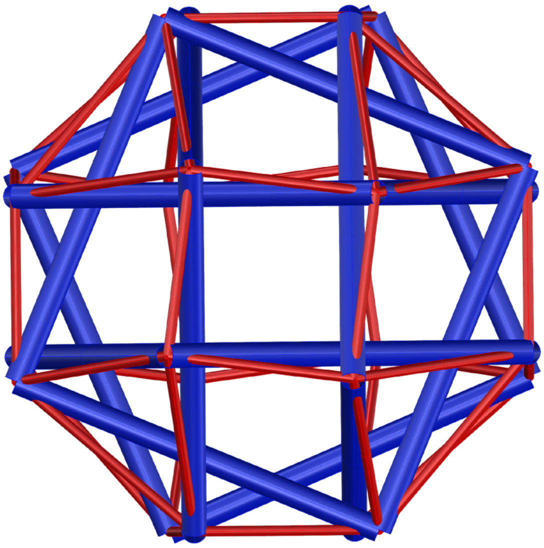


Figure 27. Rhombicuboctahedron top view.

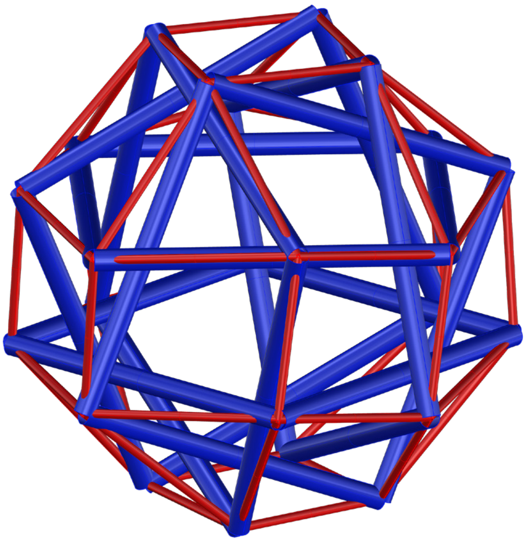


Figure 28. Rhombicuboctahedron perspective.

Snub cube

(Circuit pattern)

This shape is made up by 6 square frames, arranged much like the compression members of Jessen’s icosahedron, see figure 29-30. Each pair of frames are rotated around their own axes an equal amount. Coplanar frames are rotated the opposite direction to each other. The square faces grow when stressed and their rotation relative to the rest of the cube is reduced. The dominant deformation under load from gravity is an almost uniform vertical such.

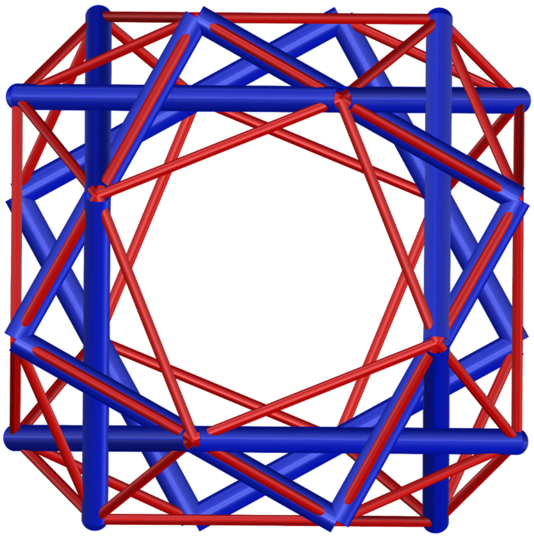


Figure 29. Snub cube top view.

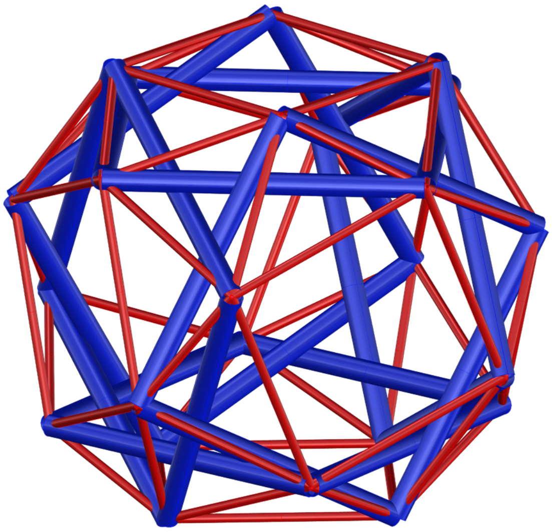
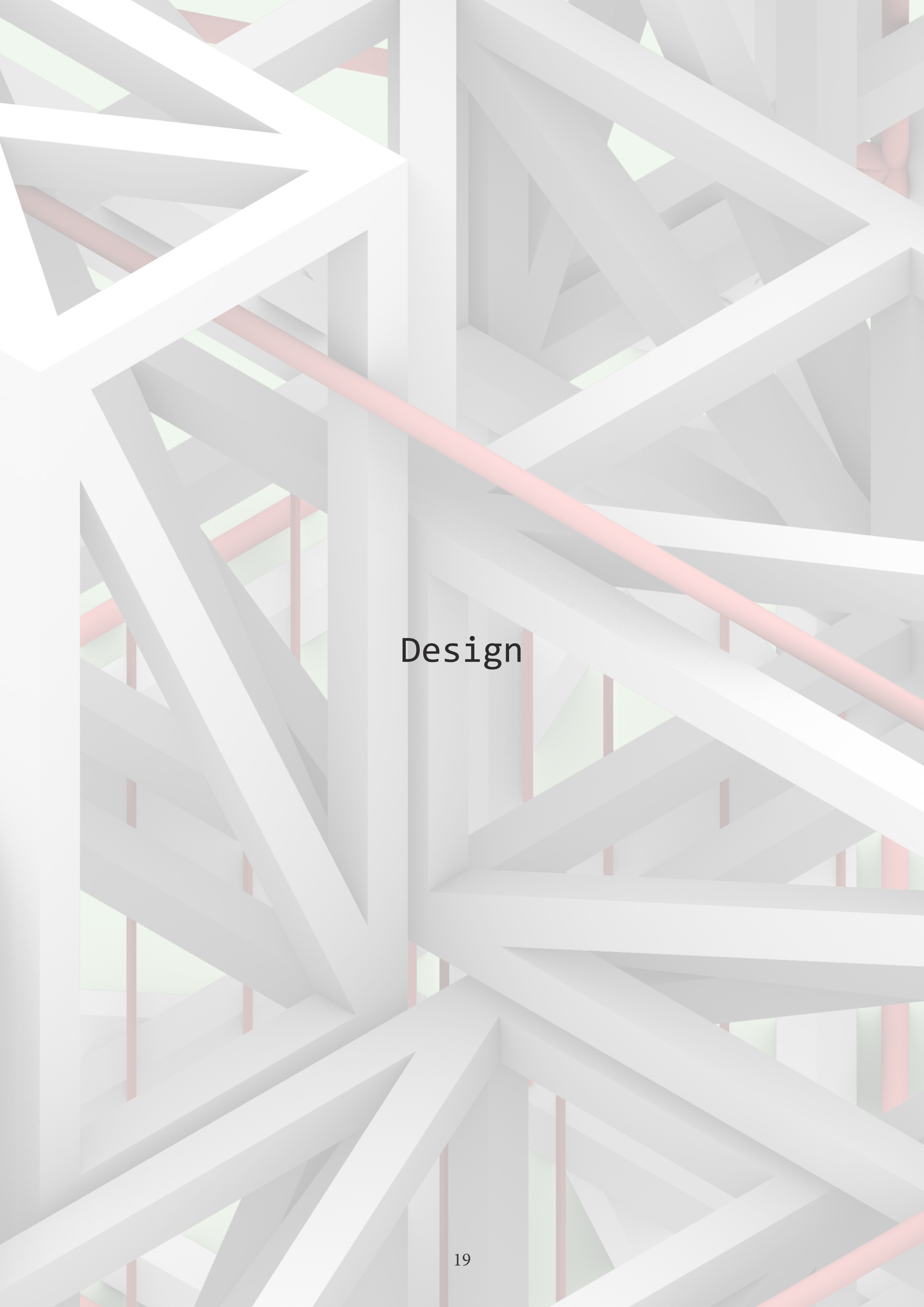


Figure 30. Snub cube perspective.



Design

Integrated Jessen’s icosahedron

Moving forwards, this study will focus on Jessen’s icosahedron. Compared to other tensegrity configurations it offers better opportunities for being incorporated in a building, largely due to the ideal orientation of its compression components being orthogonal as well as its predictable and stable behavior when subjected to stress. In the context of this thesis, it possesses a perceived advantage in being an established configuration with well known properties, enabling the design phase to put a greater focus on architectonic composition.

Integrating the exterior shapes of the buildings into the tensegrity system as compression components, see figure 31, simplifies the interface between them. Provided that each individual block of the building functions as a rigid shape this configuration shares the mechanical properties of the classical tensegrity system upon which it is based.

The end faces of the blocks can be any shape, and their exact proportions relative to the length of each module can be adjusted with no apparent detrimental effects. This is true under the assumption that they do not get so big that different blocks touch each other. Doing so would inhibit the system’s ability to deform, thus arguably moving such a structure outside the scope of tensegrity altogether. A further constraint for this design is that the axial cross section cannot be square, as this causes the tension components to intersect the edges of the habitable volume. The ramification of this would be that the framework of the habitable is unable to fully use the pre-existing edges of the shape, adding complexity to the design.

This shape has a large surface area relative to the interior volume, meaning that it may be more fit for locations where insulation is not of great importance.

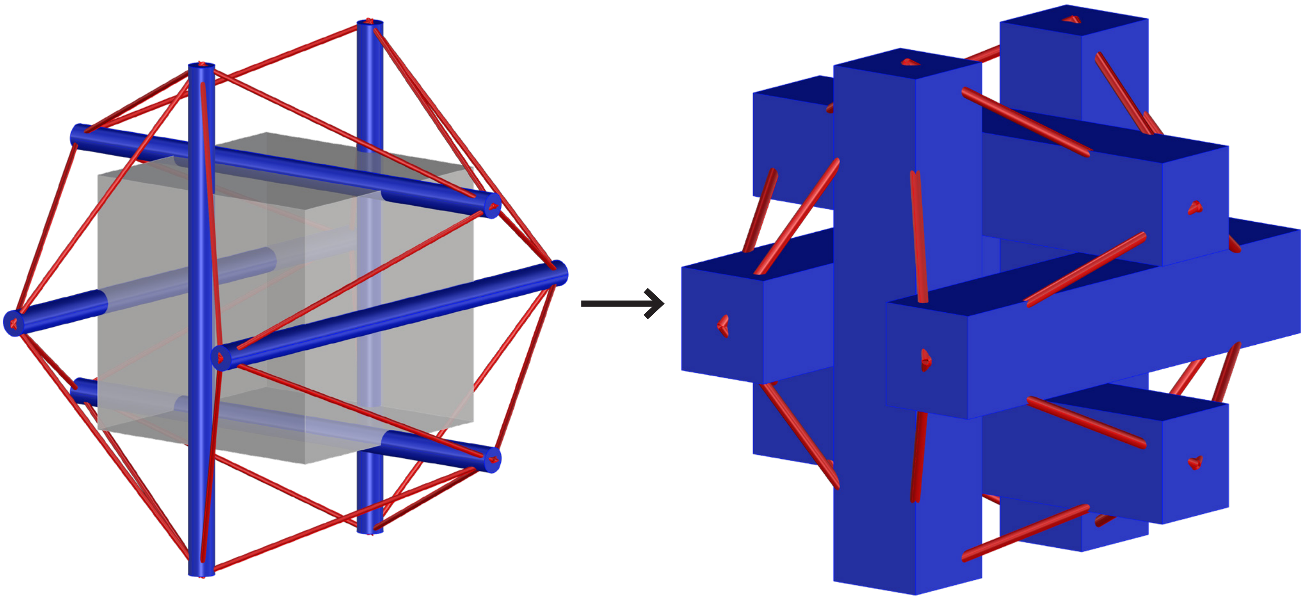


Figure 31. Integrated Jessen’s icosahedron.

Tensile connectivity

The connections between the building blocks can be configured in a few different ways. Tying back to the discussion about the interaction between the habitable volumes and the tensegrity system, these shapes could be used in one of two ways, by directly integrating the structure as compression components (case 3), or supporting a structure directly through compression components (case 4). Which one is preferred largely boils down to how the compression component, in this case a beam, interacts with the spatiality of the structure.

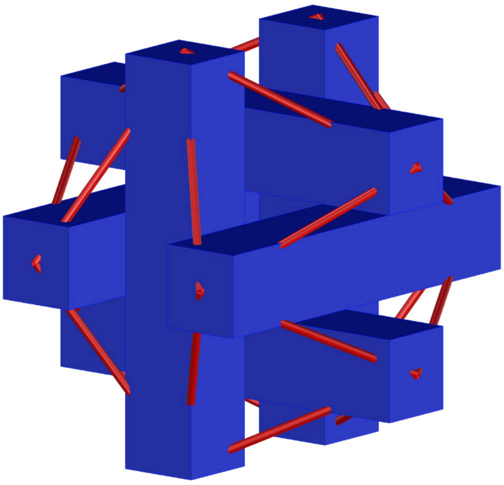


Figure 32. Integration option A.

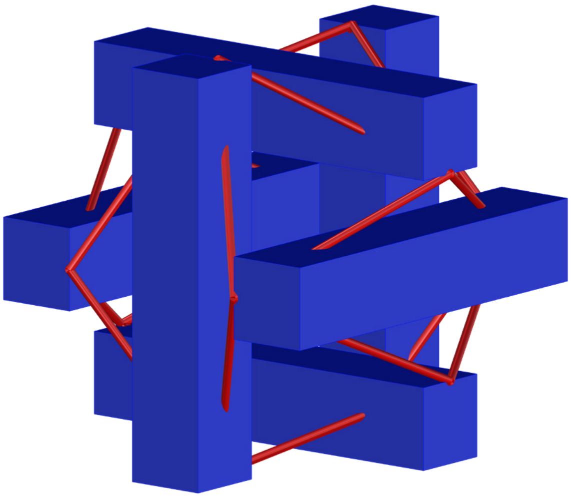


Figure 33. Integration option B.

First and perhaps most obviously they can be connected center-center, effectively extruding the compression components of the tensegrity structure, see figure 32. This configuration enables free rotation around the axes of the compression components. A perceived practical weakness is that the ends of each block will be strongly defined by the tension components running through it at non-orthogonal angles. However, this may create interesting opportunities for expression of the building.

Whether or not a beam running directly through this system is beneficial largely depends on if there is a floor in the middle of the block.

As a variation of the above shape, the blocks can instead be connected midpoint-midpoint of the edge closest to the center of gravity, see figure 33. This mitigates the issue of the interior volume being intruded upon by the tension components as well as placing the compression elements at the edges of the blocks. This configuration seems to exacerbate the potential rotation around the compression components as the center of gravity of each block is moved away from its compression component.

Neither of the shapes illustrated on this page are true tensegrity systems, rather being derivations of the concept which share a lot, but not all, of the properties seen in tensegrity systems. They do not qualify under the requirement for tensegrity systems to incorporate continuous tension components. This creates stress inside the building blocks.

A weakness of the systems illustrated in figure 34-35 is that they create a degree of imbalance as the different nodes in each block are supported by tension components at different angles. Some of these being almost horizontal, others are almost vertical. Consequently, the blocks on the outsides of the vertical blocks tend to rotate slightly and sag under gravity as the outside nodes aren not as well supported as the inside ones.

The shape shown in figure 34 divides each node of the pure system seen on the previous page into two nodes and places them on opposite midpoints of edges, each taking two tension components as opposed to four. This somewhat mitigates the rotational issue. Another benefit is that the internal volume is kept free of intruding components of the tensegrity system, making for a more easily utilized space. In a less practical and more aesthetical sense it does however deviate somewhat from the typical expression of a tensegrity system.

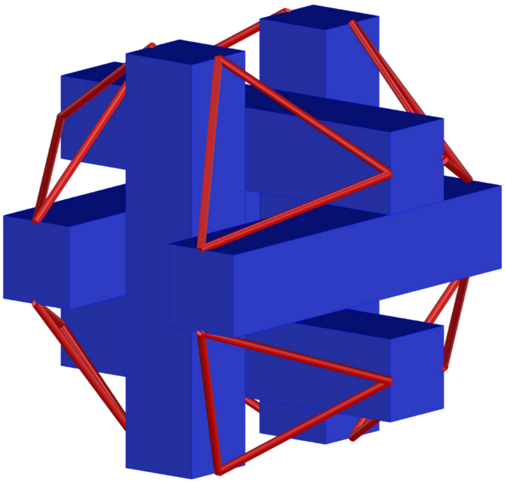


Figure 34. Integration option C.

This shape shown in figure 35 is similar to the one above, but places the nodes on the vertices of the building block. This offers a more intuitive configuration as it takes advantage of pre-existing nodes instead of creating new ones. Issues with side elements being free to rotate around their own axes are exacerbated as the angles of the tension components are closer to vertical and horizontal.

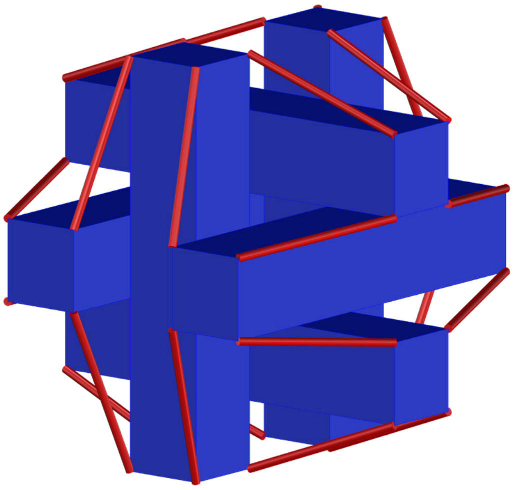


Figure 35. Integration option D.

Option A was selected as the best all-round option, and the only one without problematic properties regarding the balance of the compression components. On a conceptual basis, it is most similar to the basic system which aids the architectonic legibility. Furthermore, options C and D fall outside the scope of true tensegrity.

Habitable volumes

From a functional point of view, the most crucial requirement for the habitable volumes is structural rigidity. Interpreting the cuboids as truss structures pragmatically satisfies this need whilst visually conveying the load bearing status of the shell as shown in figure 36.

Trusses and tensegrity systems share a mechanical property in their components either being under tension or compression. This calls for a choice regarding the visual language of the tensile truss components, whether they should be portrayed as such or as thicker compressive components. In this thesis, the visual logic of the tensegrity system is prioritized over that of the trusses - the entire trusses are aesthetically interpreted as the compressive components they form in the context of the tensegrity system. This logic makes for a more visually coherent design.

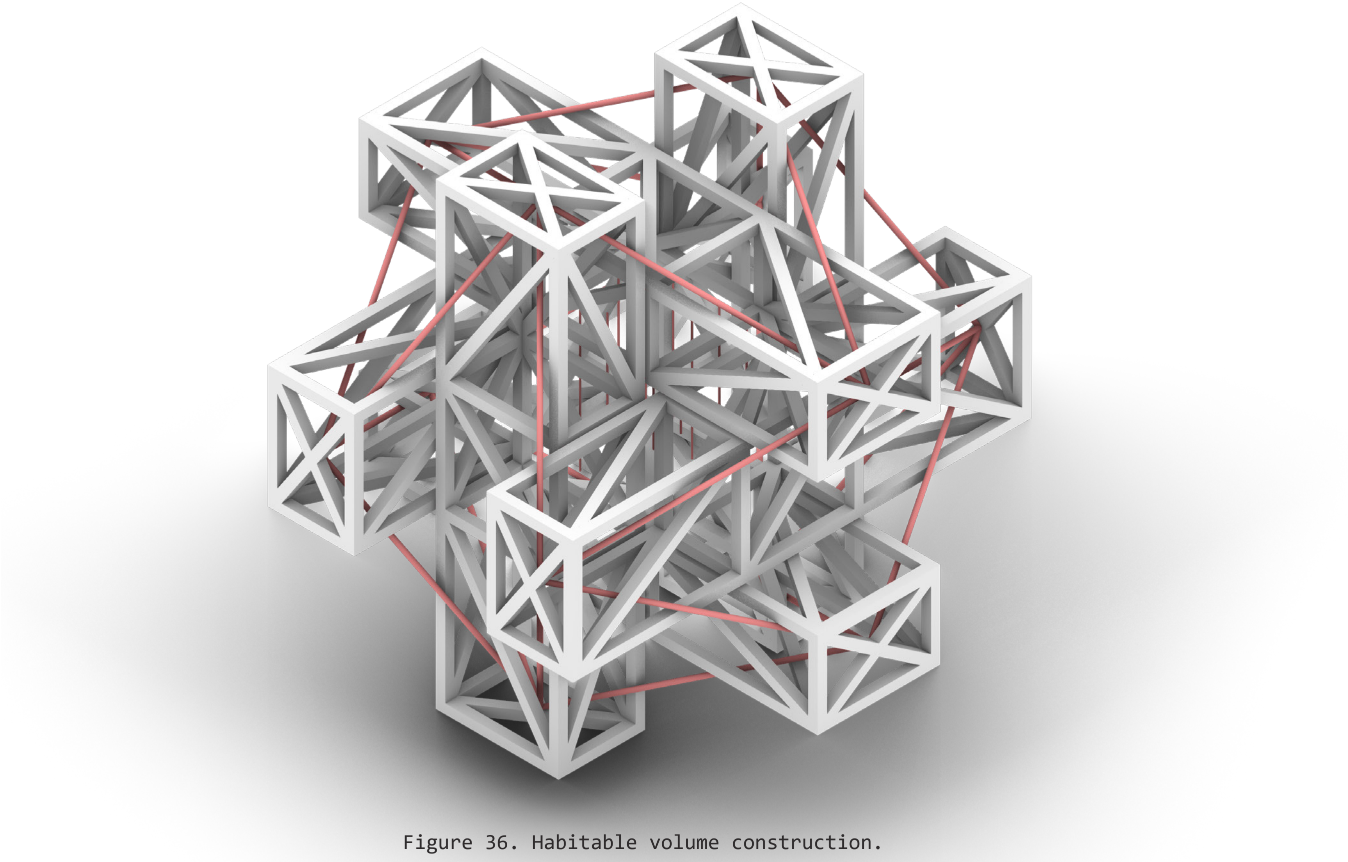


Figure 36. Habitable volume construction.

The proportions of the habitable volumes are dictated by the tension components. Their axial cross section, the smallest faces of the rectangular cuboids, should not be square as this would mean that the tension components intersect the edges of the habitable volumes, thus meaning that the truss would not be able to use the pre-existing edges of the shape as its basis. To avoid such issues, a rectangular cross section is selected.

Regarding the choice of the rectangular cuboid as starting point for the habitable volumes, it is the orthodox form for buildings. It is practical and easy to utilize, unusual properties in the context of tensegrity.

Support polygon

For any practical object not to fall over it needs a support polygon, it should be supported by three or more “legs”. At least one “leg” must be non-coaxial relative to the others, such that a polygon is formed under the object. The object’s center of gravity must lie over its support polygon.

When its components are considered as lines without thickness, it becomes clear that an upright orthogonal orientation of Jessen’s icosahedron is not feasible. Whilst this design explicitly renders the compressive components as substantial bodies with thickness, the general trend persists where it is prone to tip over. This is unacceptable for a structure meant to sustain substantial stress from an earthquake.

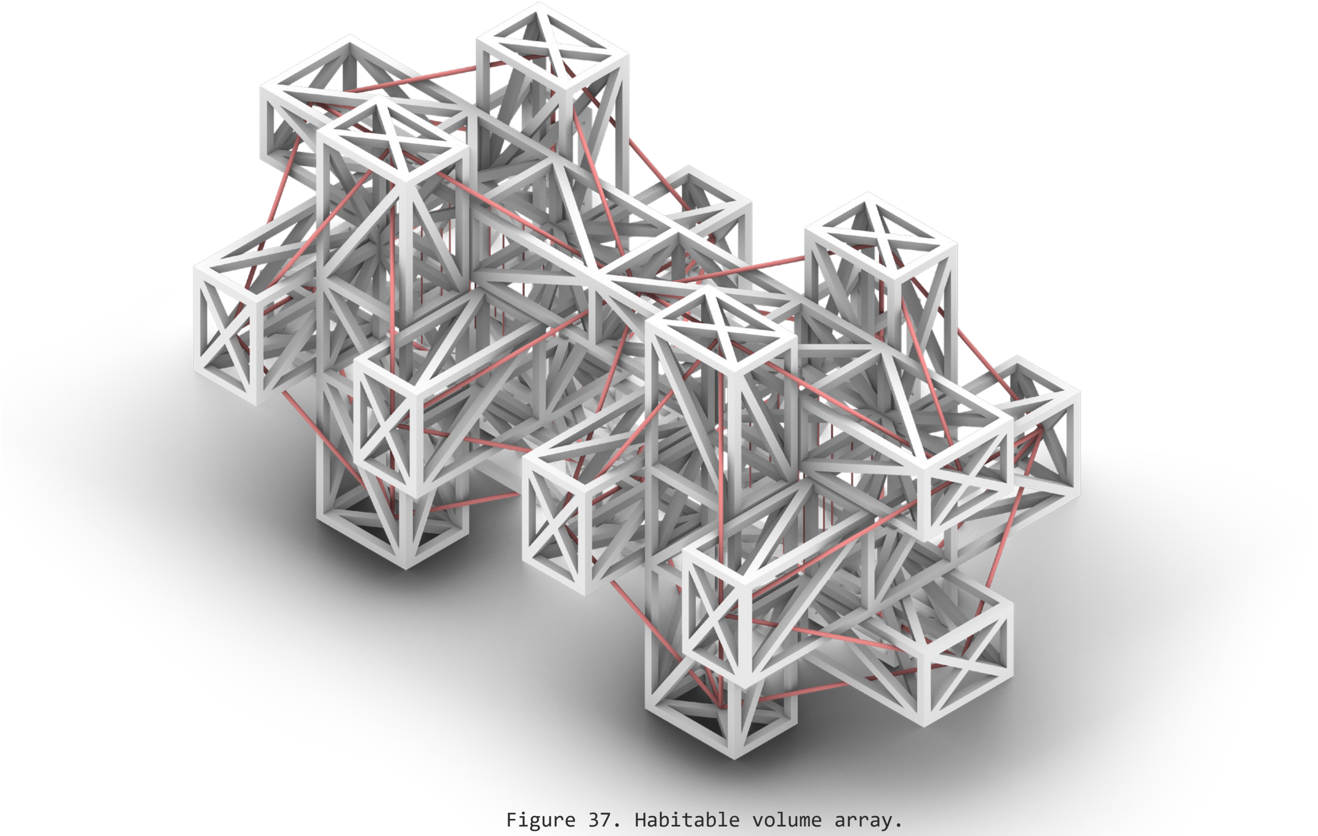


Figure 37. Habitable volume array.

By conjoining at least two icosahedrons perpendicular to the direction of their individual support axes a support polygon is created. This forms a modular tensegrity system with flexible connections between the individual systems. Arraying this tensegrity system can be arbitrarily expanded in any orthogonal direction. This thesis will focus on the smallest possible array, as illustrated above, as a larger array would take focus away from the individual tensegrity systems and detract from the architectonic legibility.

The connection between the two halves could be either rigid or flexible. Testing with Kangaroo2 suggests minimal sag towards each other, on this basis a rigid connection between the halves was selected, see figure 37.

Ground connection

As one of the main features of a tensegrity system is its flexibility, it cannot be rigidly connected to the ground. It should be connected such that a degree of lateral movement and ideally also slight rotation is enabled. This is shown in figure 38.

The former is an established concept within the context of earthquake-resilient structures and is usually referred to as seismic base isolation. The idea behind seismic base isolation is relatively simple; by decoupling the motion of the base of the building from the ground the overall movement and thus the forces resulting from inertia decreases. As such, any true, free-standing, tensegrity system inherently implements a relatively conventional form of earthquake damage mitigation.

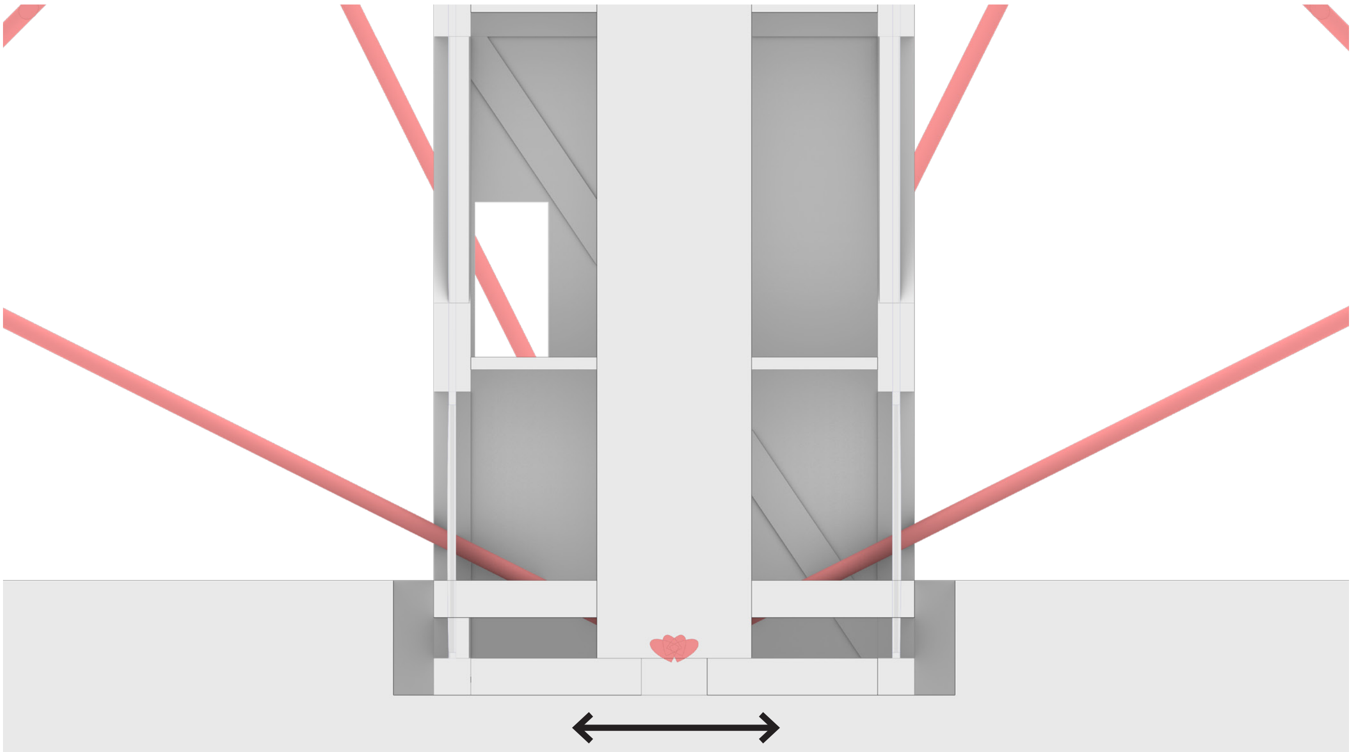


Figure 38. Section of ground connection.

The topic of the ability of the components of the tensegrity system which meets the ground to rotate relative to it is not as axiomatic. From the perspective of optimal mechanical performance of the tensegrity system they should allow for rotation. On the other hand, giving the stairwells better conditions for remaining upright in aid of their programmatic function is, in this application, more important. Thus, the bottoms of the vertical habitable volumes should be flat to avoid rotation relative to the ground. The alternative solution would have been a design with a chamfered or convex bottom.

All connections to grids for water and power are routed horizontally out to the habitable volumes with the elevators and then vertically down into the ground. This connection to the ground is constructed from flexible materials as it needs to be able to facilitate lateral movement and rotation.

Program

The vertical volumes serve as stairwells, two of which house stairs, the other two house elevators. The horizontal volumes contain the apartments, two per volume in the taller ones and one per volume in the wider ones for a total of twelve. The roofs of the apartments are utilized as terraces.

As elevators require a pit below the bottom floor level the entire building is slightly dug down into the ground for accessibility. This design utilizes a machine room-less elevator, along whose shaft the connections to water and electricity are routed. These water and electricity connections are flexible to facilitate interaction with a non-static relation to the ground and other building volumes.

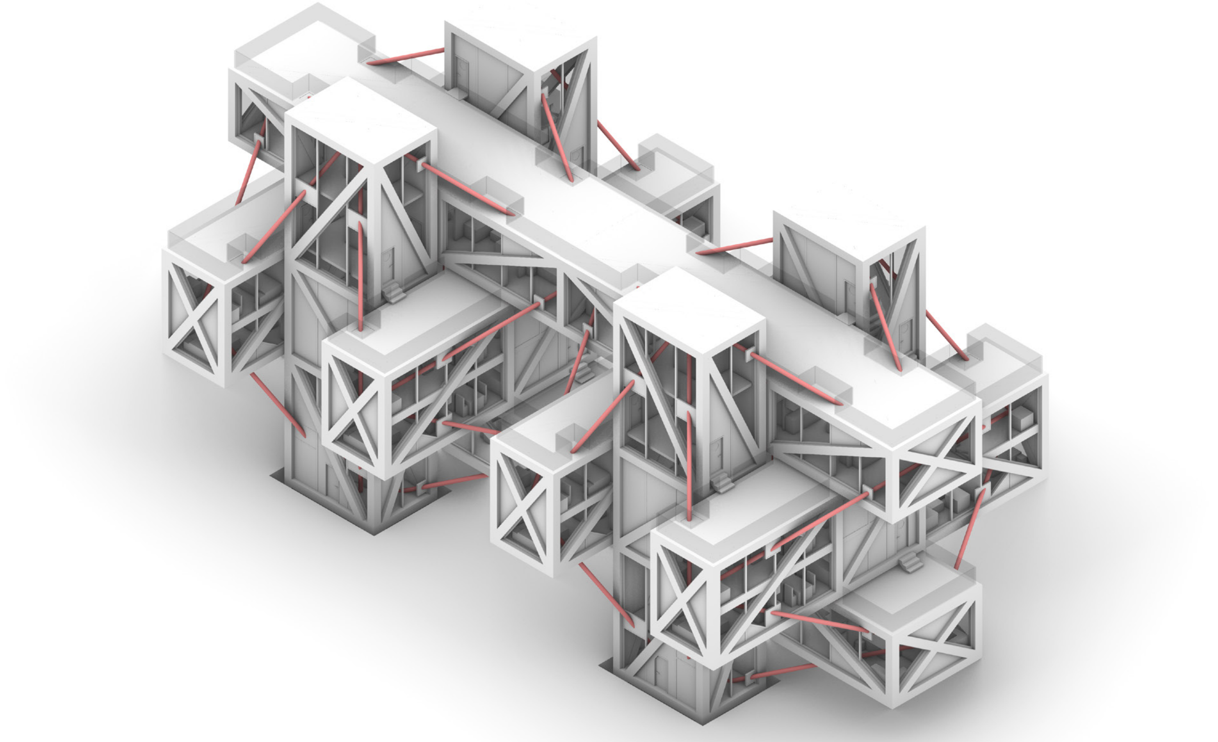


Figure 39. Tensegrity building concept.

Many of the negative volumes in the structure are utilized as terraces, most of which are apartment-specific due to privacy concerns. The top of the highest horizontal habitable volumes is used a shared terrace. It seems unsuitable to include any extensive vegetation on these spaces as per the stability concerns outlined earlier.

One of the internal middle horizontal volumes is designed as a shared space, to enable a more closed facade and thus avoid privacy concerns for the habitants of its neighboring habitable volume.

The ground clearance of the lowest horizontal habitable volume is sufficiently high to allow convenient movement underneath it, something that is crucial given that the stairwells serve different purposes.

Plans

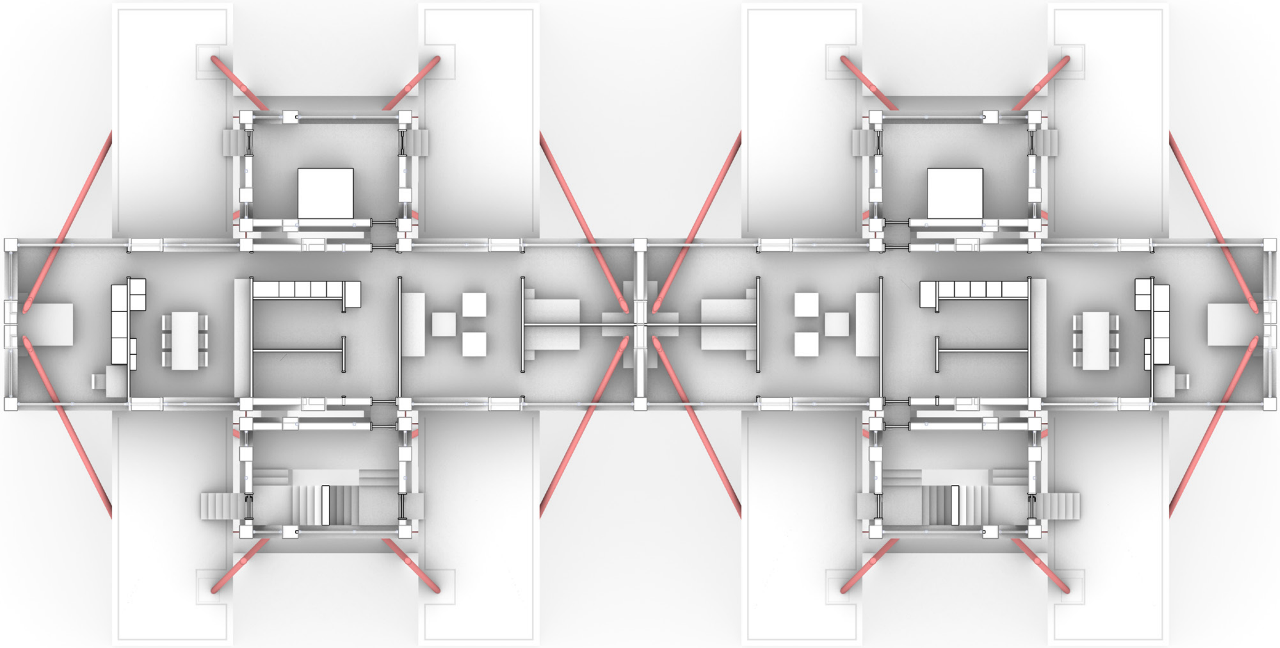


Figure 40. Plan of floor 4.

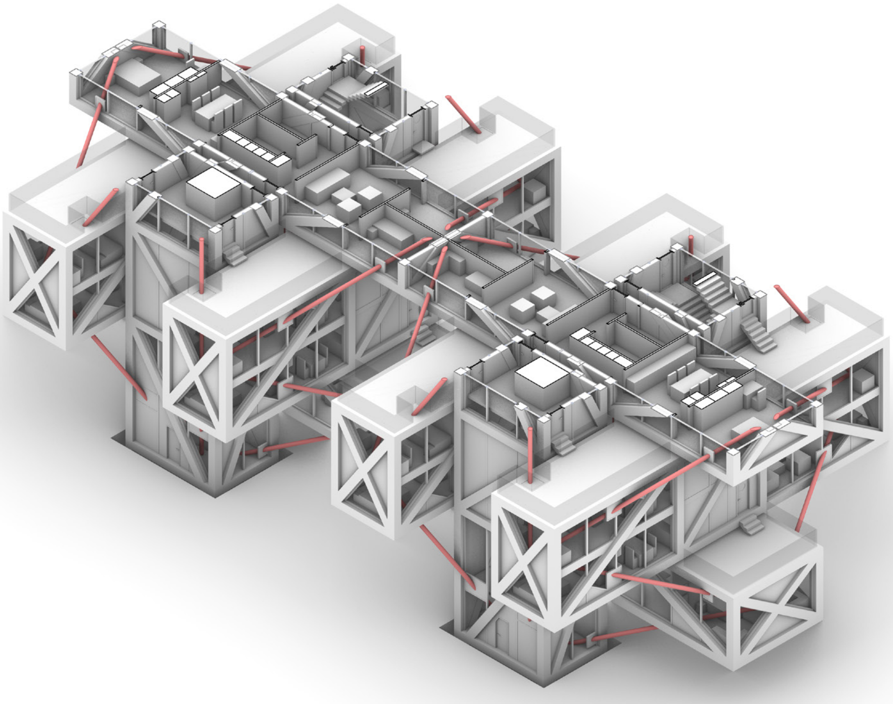


Figure 41. Isometric perspective of floor 4 plan.

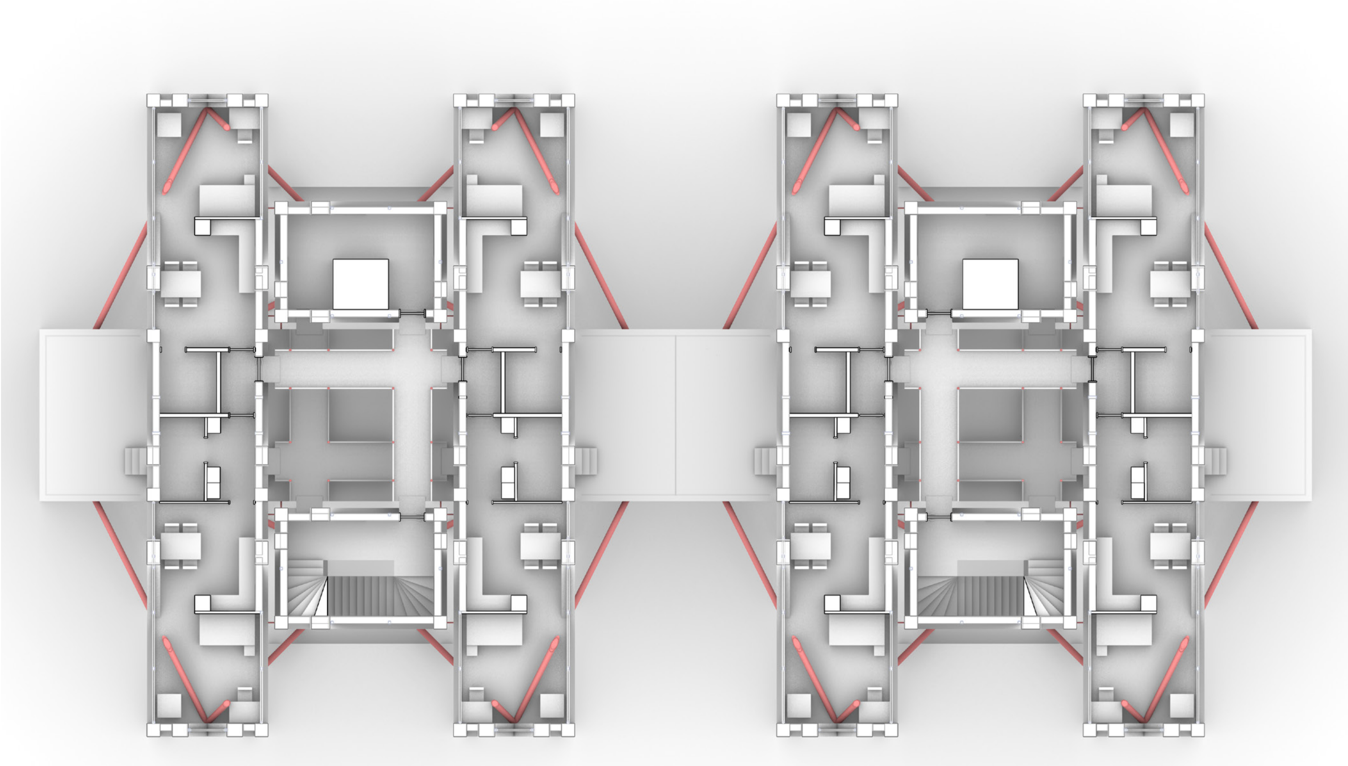


Figure 42. Plan of floor 3.

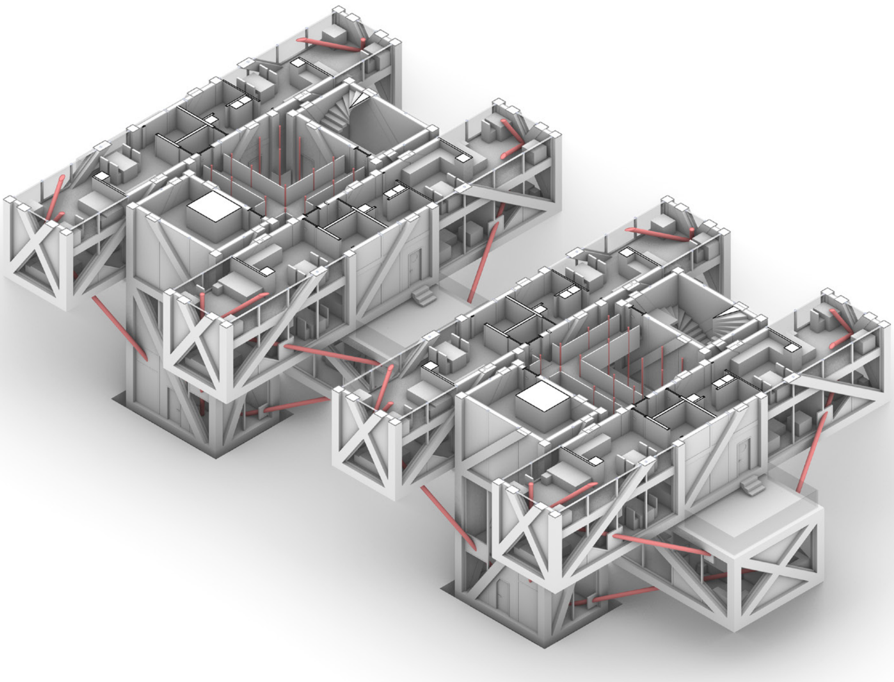


Figure 43. Isometric perspective of floor 3 plan.

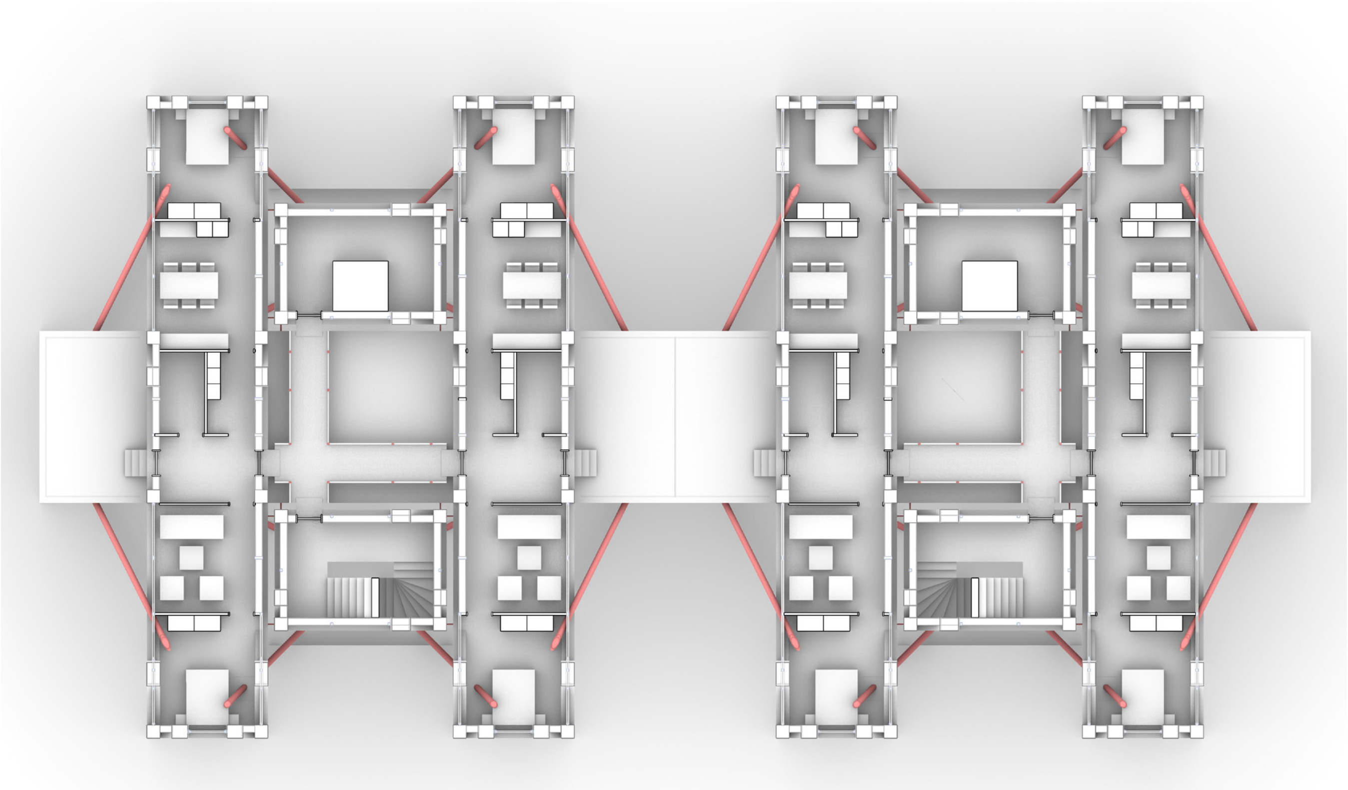


Figure 44. Plan of floor 2.

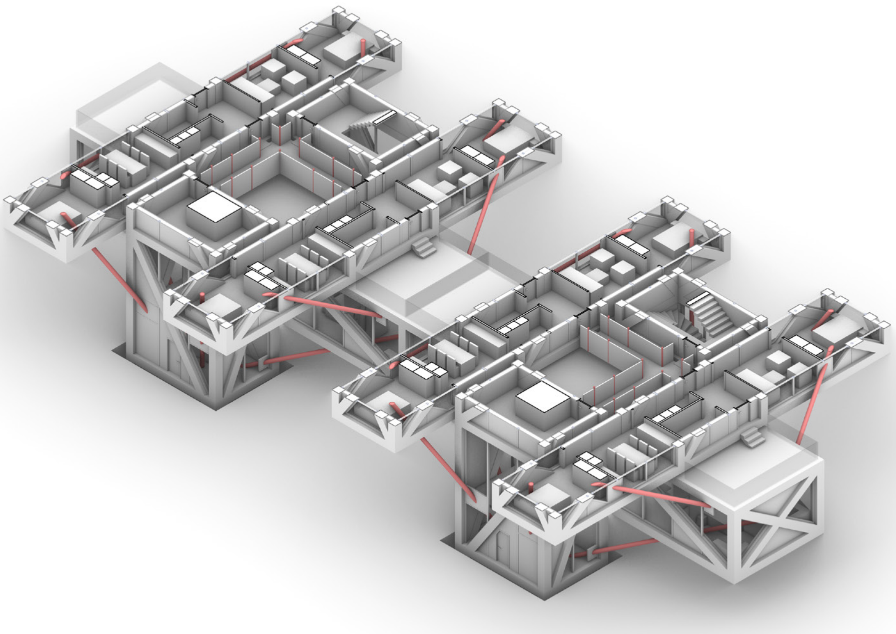


Figure 45. Isometric perspective of floor 2 plan.

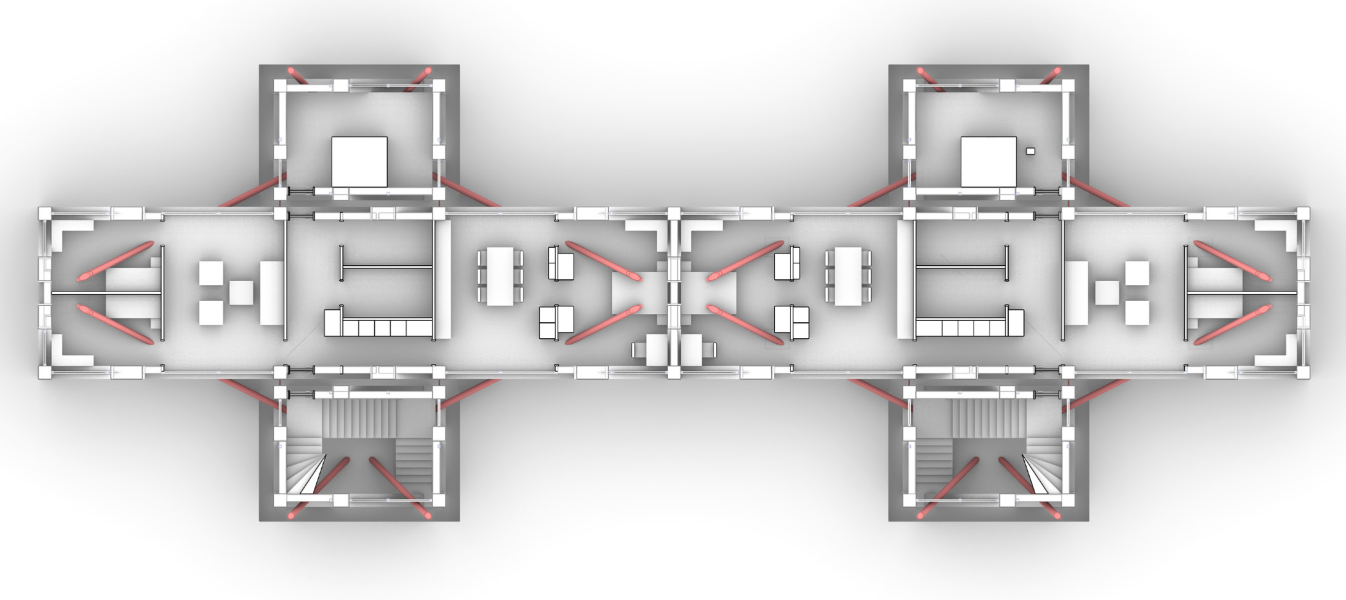


Figure 46. Plan of floor 1.

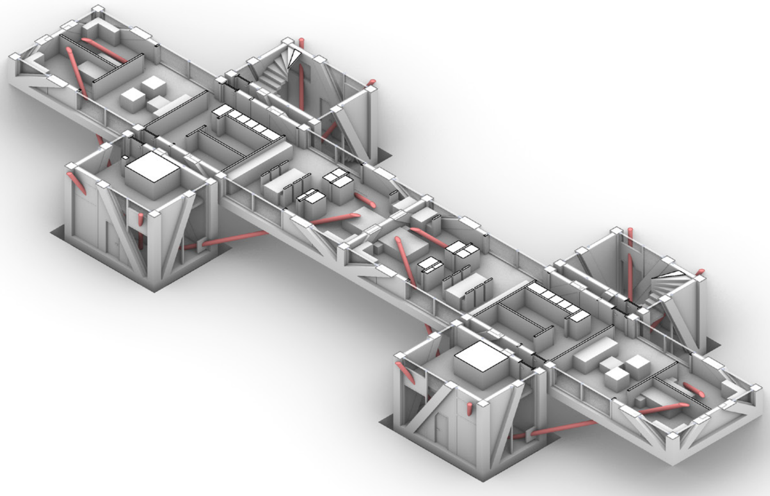


Figure 47. Isometric perspective of floor 1 plan.

Sections

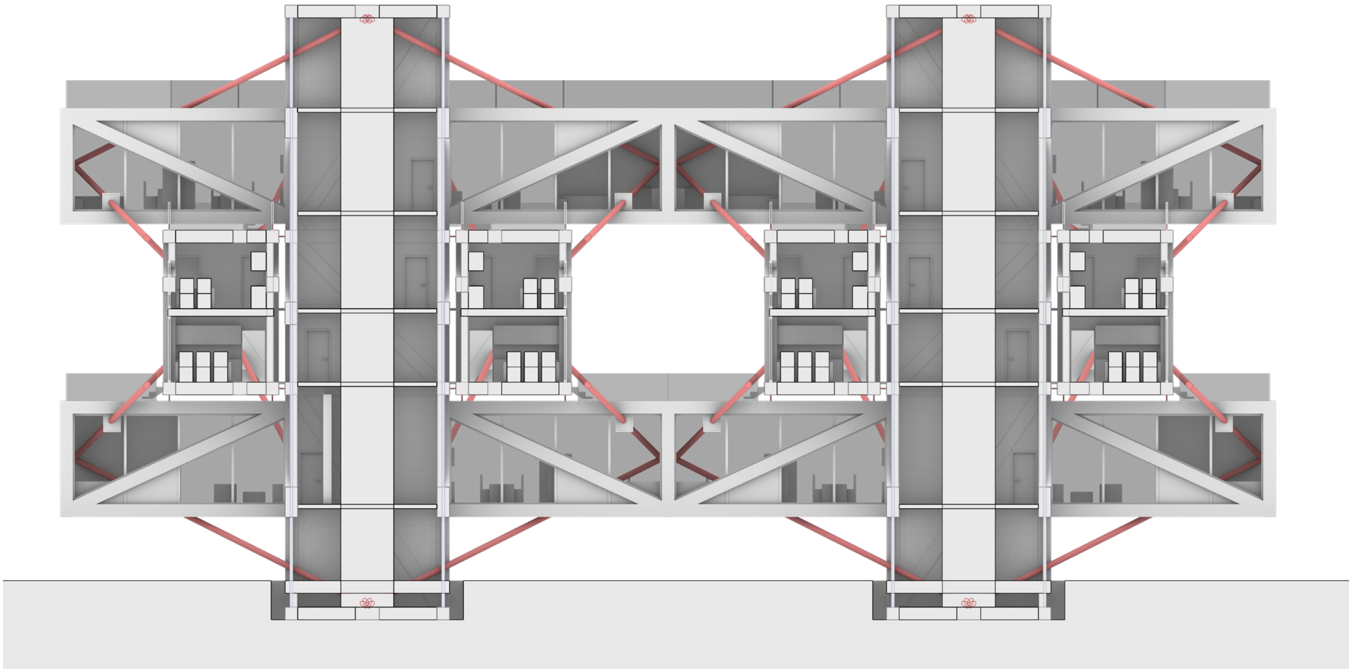


Figure 48. Section A.

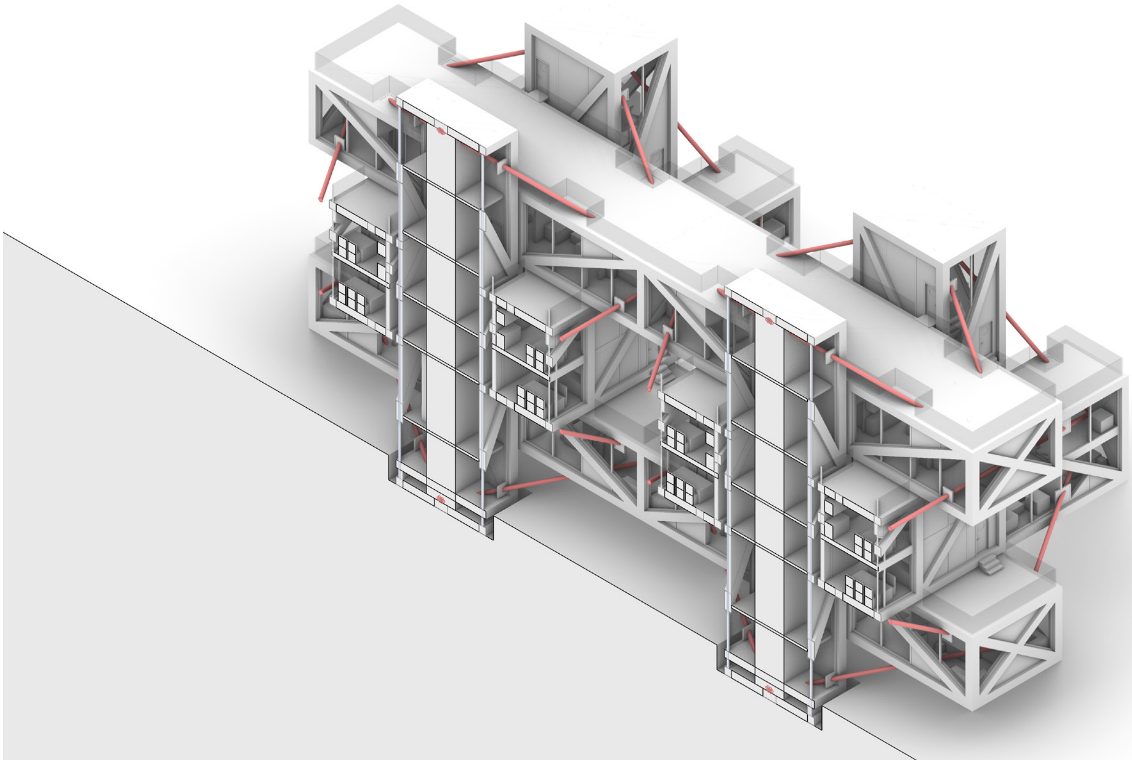


Figure 49. Isometric perspective of section A.

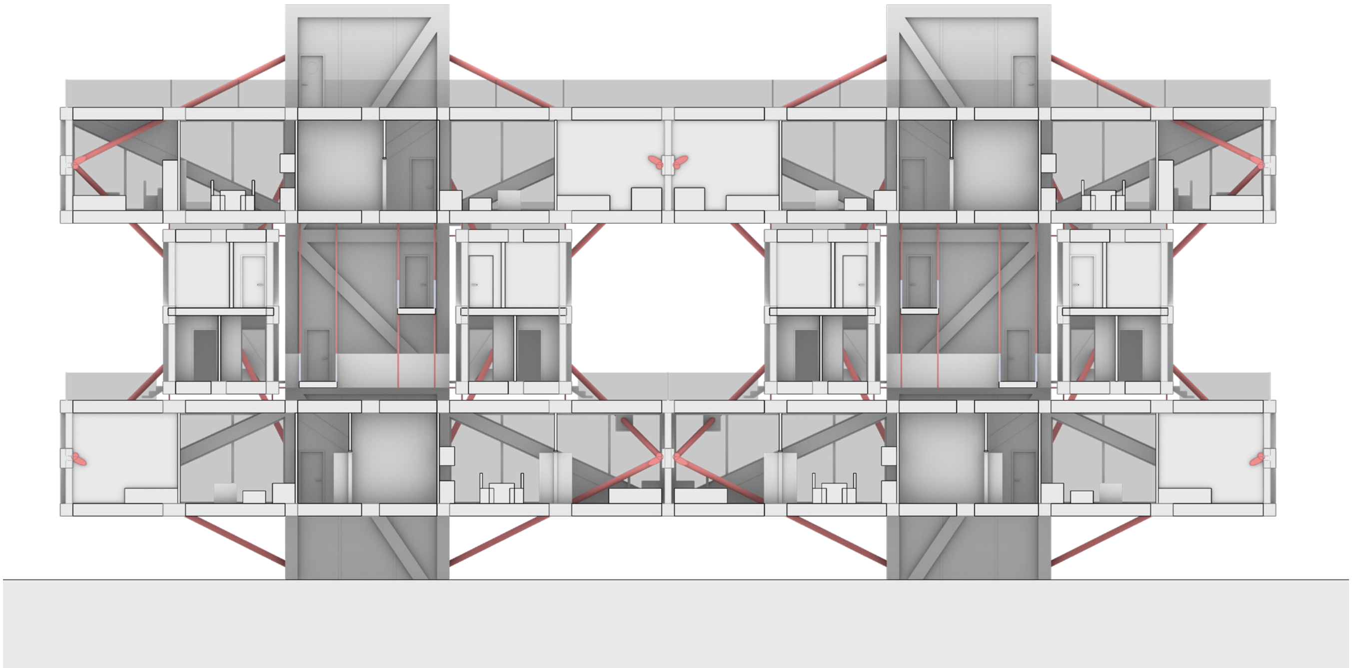


Figure 50. Section B.

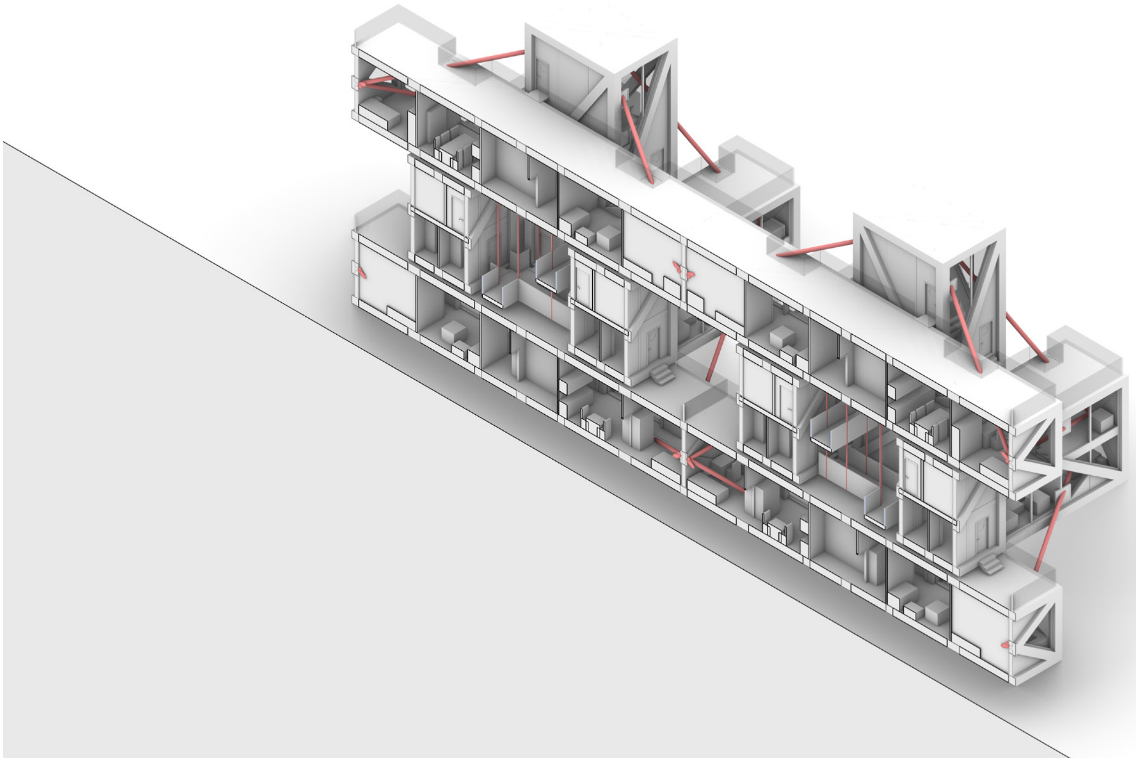


Figure 51. Isometric perspective of section B.

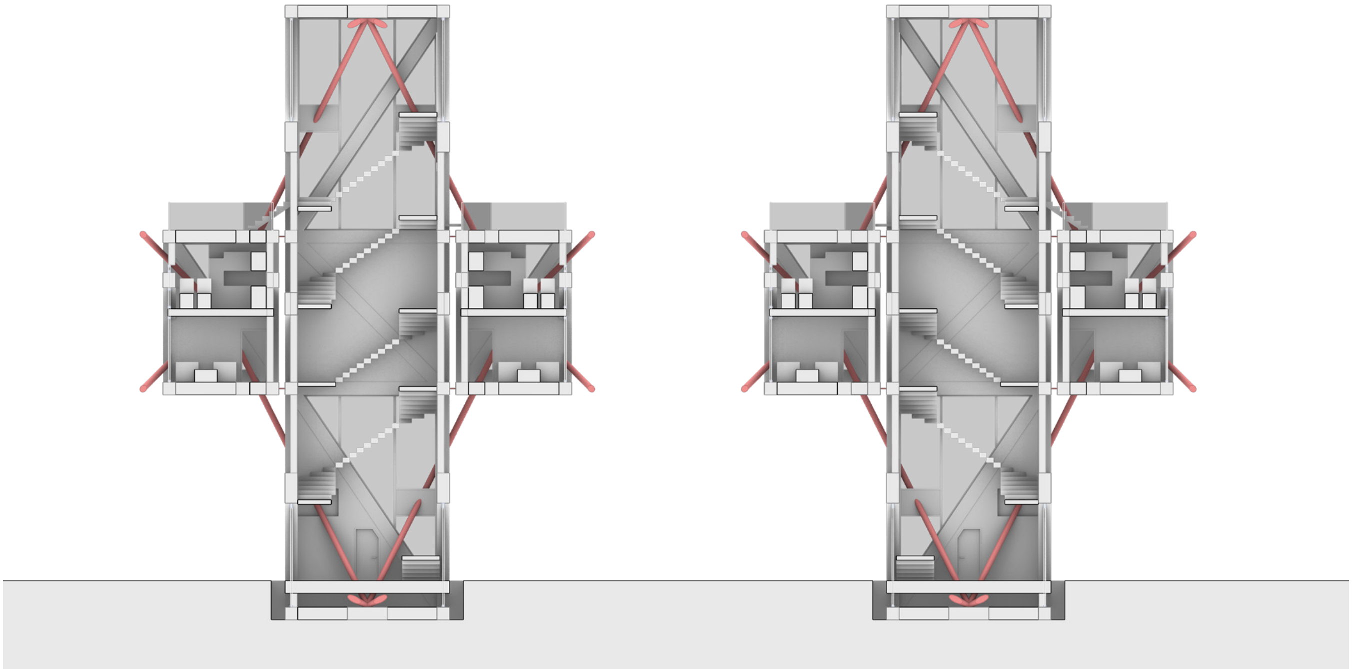


Figure 52. Section C.

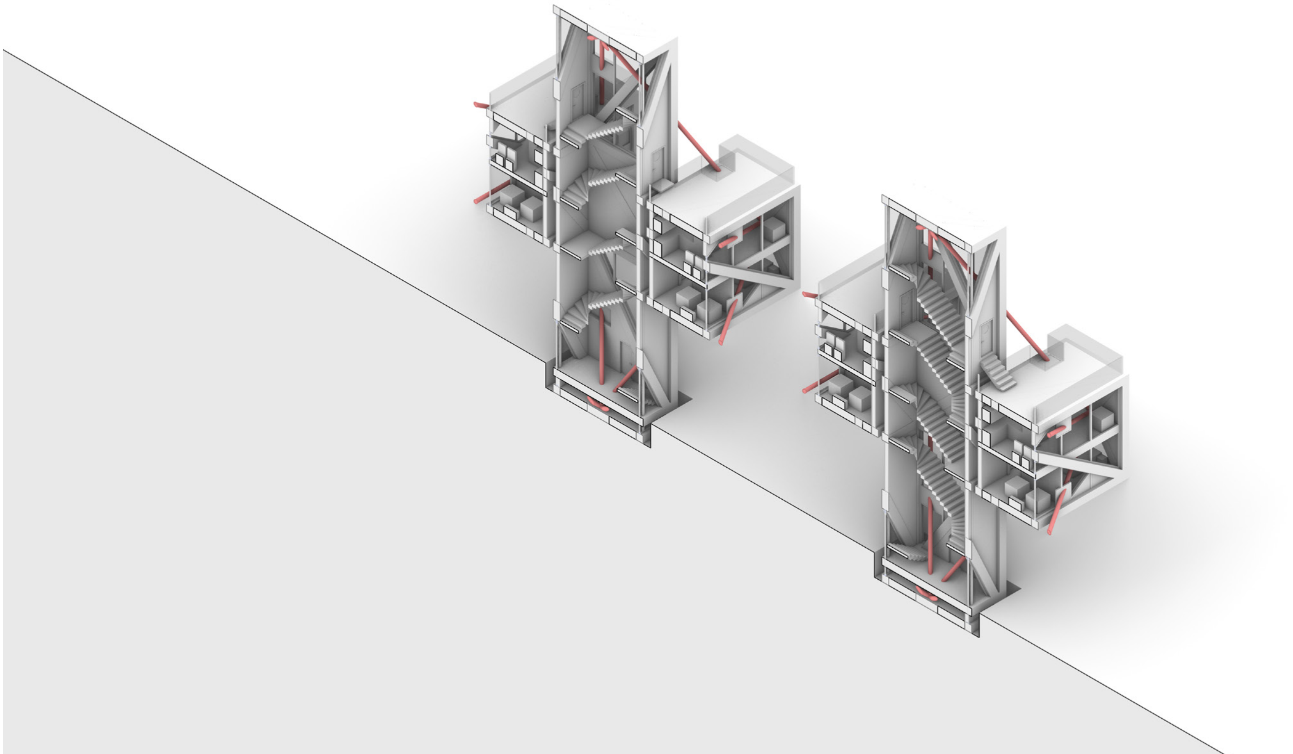


Figure 53. Isometric perspective of section C.

Intersections

The tension components can either intersect the habitable volumes, or not. There are clear advantages to dimensioning the habitable volumes such that they do not intersect them, chiefly a less complex climate shell without any special considerations for non-static connections. However, there is a substantial drawback to such an approach in the shape of space efficiency. Reducing the length of the habitable volumes and leaving the ends as pure mechanical pieces eats into the usable area without reducing the footprint of the building as seen in figure 54.

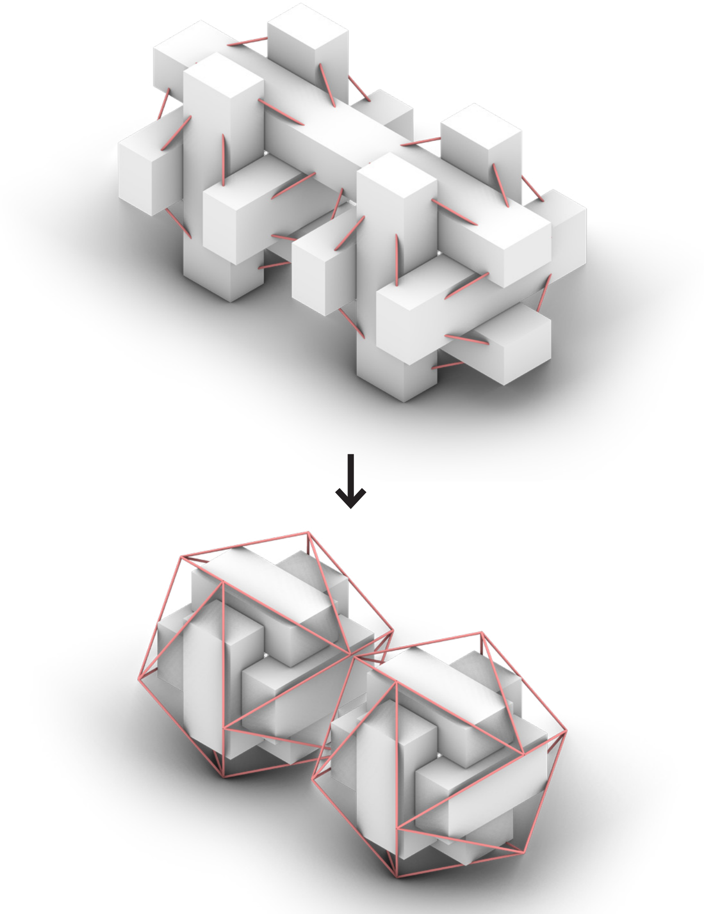


Figure 54. Isometric demonstration of loss of usable space when moving tensile connections out.

The components in Jessen’s icosahedron cannot be scaled arbitrarily. The relation between the length of a compression component and the distance to its opposite component is 2:1. This means that increasing the length of the habitable volumes can only be accomplished by uniformly scaling the system.

It seems like a better solution to accept the more complicated climate shell in the region around where the tension components intersect the habitable volumes. Testing with Kangaroo2 suggests minimal movement of the point of intersection, enabling a buffer zone of a few decimetres around the position of the tension components in rest. The purpose of this buffer zone is to keep the building watertight and provide a degree of insulation whilst being flexible. A solution akin to that seen in the flexible section of articulated busses is used in this design and is illustrated in figure 55.

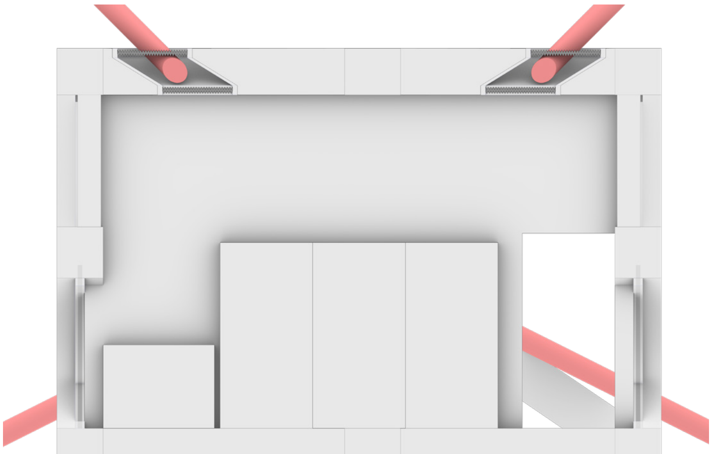


Figure 55. Section of tensile climate shell intersection.

Axial stability

An inherent property of tensegrity is the freedom for each component to rotate along its axis. Thus, for this application, they require a system to ensure their correct orientation, for safety and for comfort.

The primary means of accomplishing this is by lowering the centre of gravity of each horizontal habitable volume such that it sits directly below the axis. This stabilizes those bodies without interfering with the properties of the rest of the system. Hence, the bottom of each habitable volume should be heavy, whilst the top should be light with cavities in the ceilings an a heavy core in the floors as illustrated in figure 56. This establishes a general tendency for the habitable volumes to return to their intended positions without introducing additional rigidity to the system.

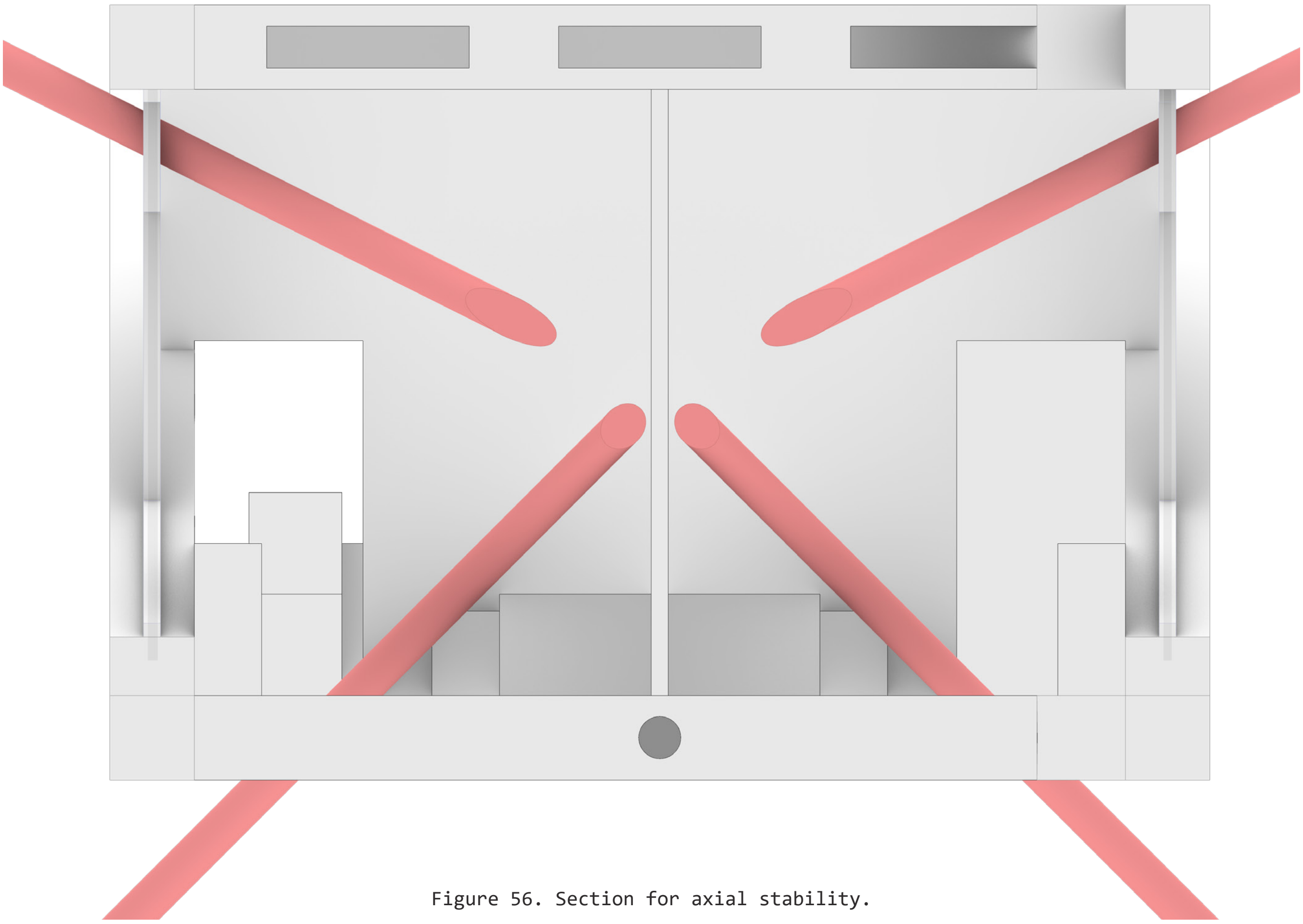


Figure 56. Section for axial stability.

As an auxiliary mechanism for ensuring the correct orientation of the habitable volumes, they are interconnected by short tension components. This may be of particular interest for the vertical volumes as their centres of gravity cannot be moved below their axes; they would otherwise only be rotationally secured by friction. These auxiliary axial stabilizers should be elastic and gradually become stiffer to counteract rotation.

Materials

The load bearing components in the habitable volumes are made out of cross-laminated timber. The construction of the floors and ceilings differ in order to facilitate a lower centre of gravity to improve the axial stability. The floors are made out of solid wood, with the possibility of adding a core of metal along their axes. The ceilings are likewise made from wood, but with cavities to make them lighter. The window frames are constructed from aluminium.

The tension components are constructed from high performance steel wire ropes fitted with polyethylene cable pipes to give them smooth surfaces as well as to enable interaction with the buffer zones of the habitable volumes. Superelastic memory alloys were considered but ultimately not chosen as their relatively low yield strength would have resulted in substantially thicker tension components.

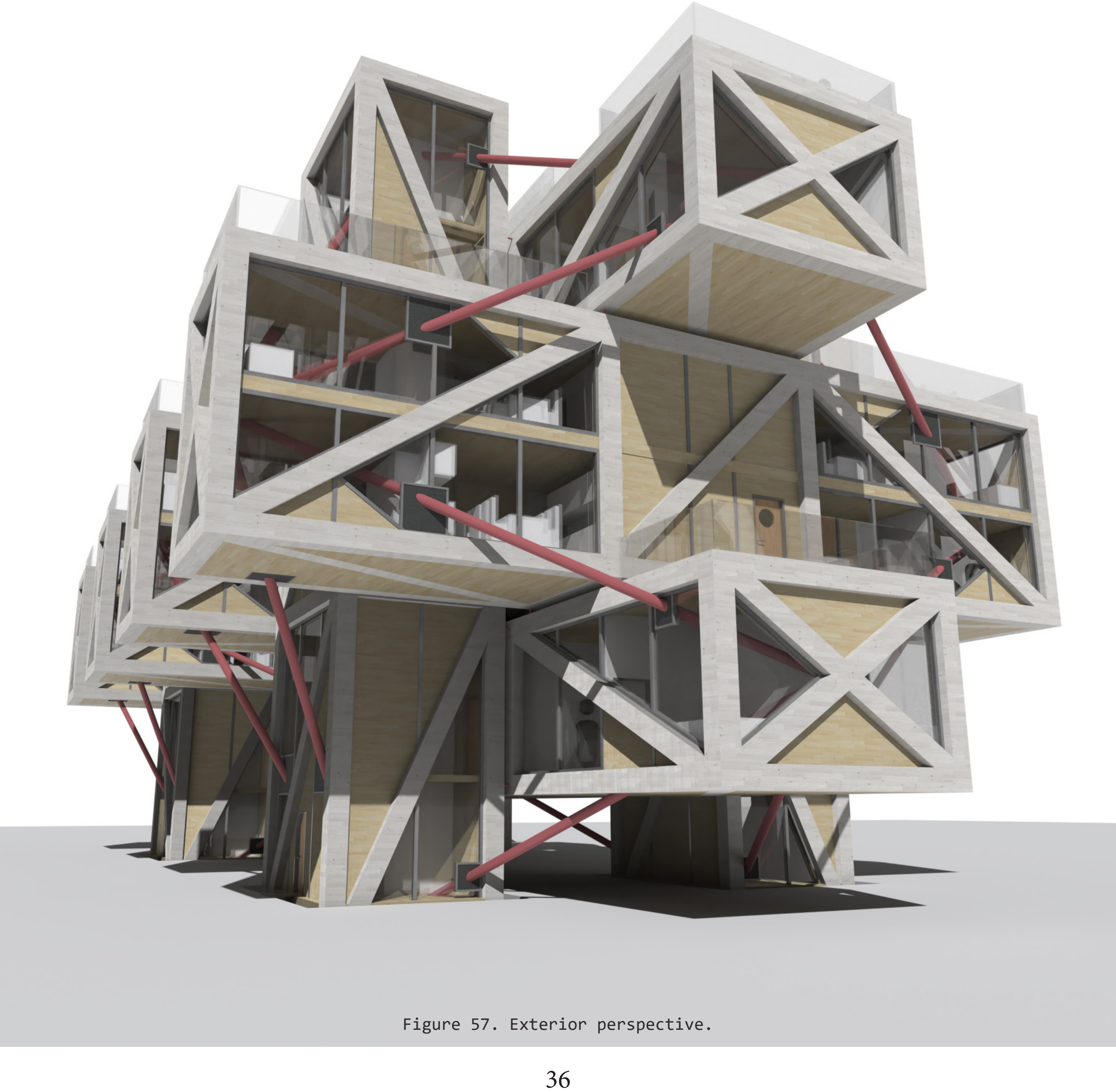


Figure 57. Exterior perspective.

Architectonic expression

As the structural logic of the building sits at the very core of the design, the shell of the habitable volume should bring attention to its structure. To that effect, they were designed as trusses, ubiquitous load bearing structures. From an architectonic point of view they help convey the idea of the habitable volumes being pragmatic and functional.

The external walls of the building were designing with openness and brightness in mind, only closing off the facade when needed for privacy. This ties into the perception of tensegrity structures as all but floating in the air, the architectonic expression matching the lightness typically associated with tensegrity. The windows are subdivided into discrete units and framed, emphasizing the symmetry of the trusses as well as establishing a rhythm in the facade,

The cable pipes are red to make them stand out from the rest of the structure visually, thus bringing attention to what may be considered the spatially most interesting features of the building. It also serves as a nod to the illustration of tension and compression as red and blue respectively. The rooms they intersect are designed around them, the cables informing the flow of specific rooms as well as the general layouts of the apartments.

The cross-laminated timber of the trusses is glazed white, contrasting against the more natural expression of the rest of the wooden elements.

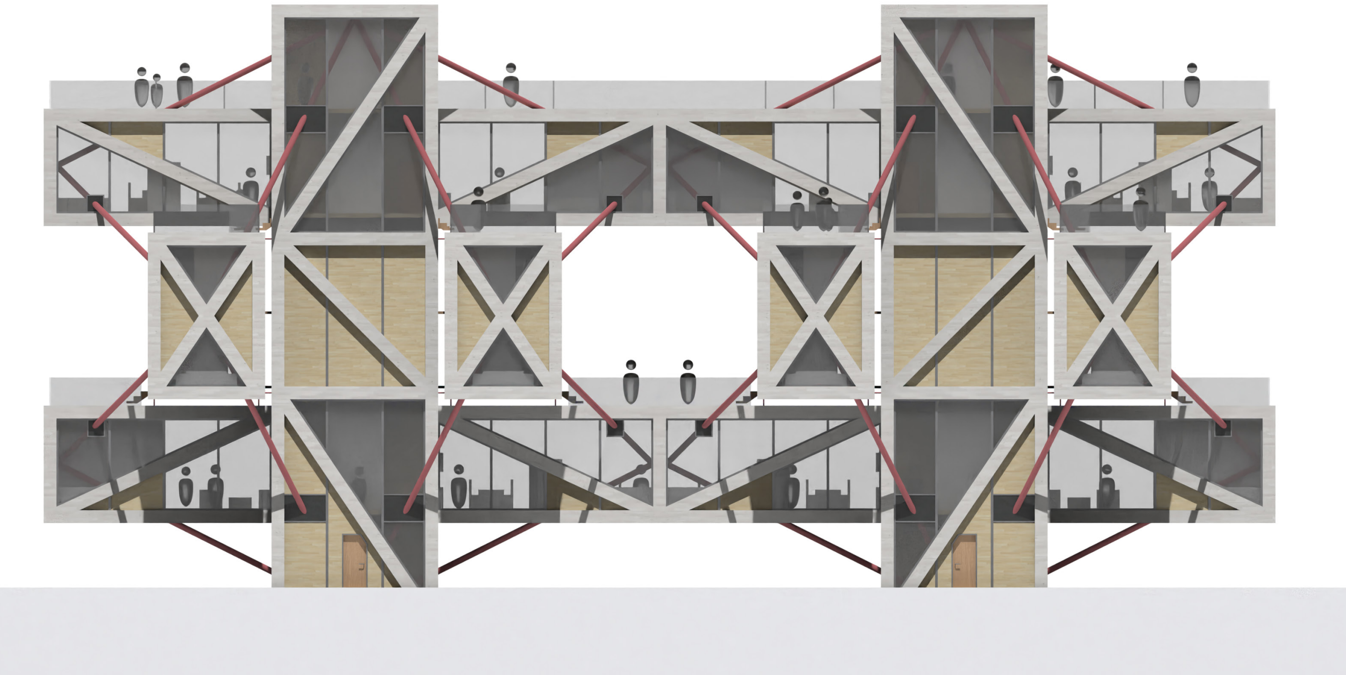


Figure 58. Facade elevation.

Perspectives

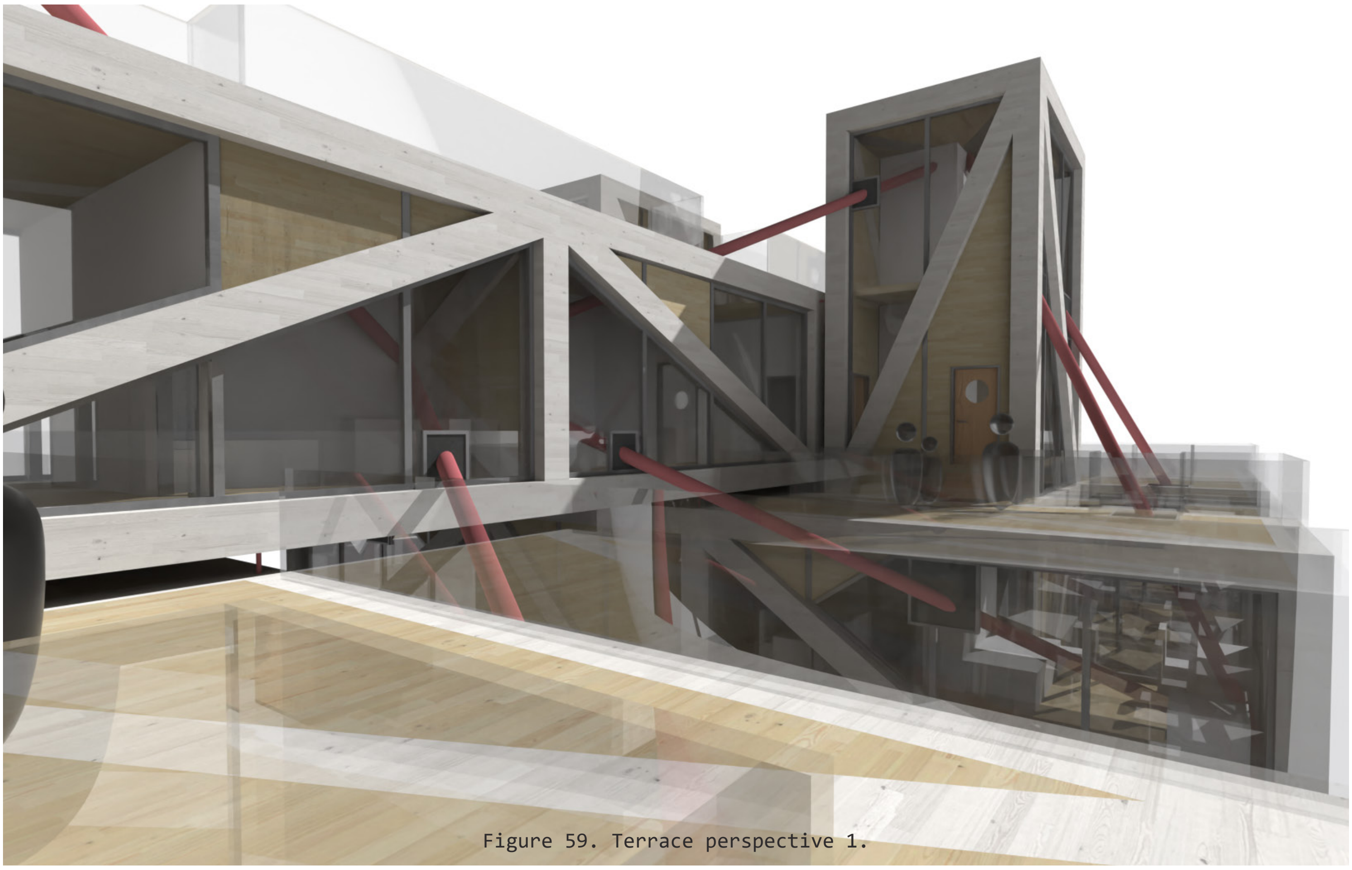


Figure 59. Terrace perspective 1.

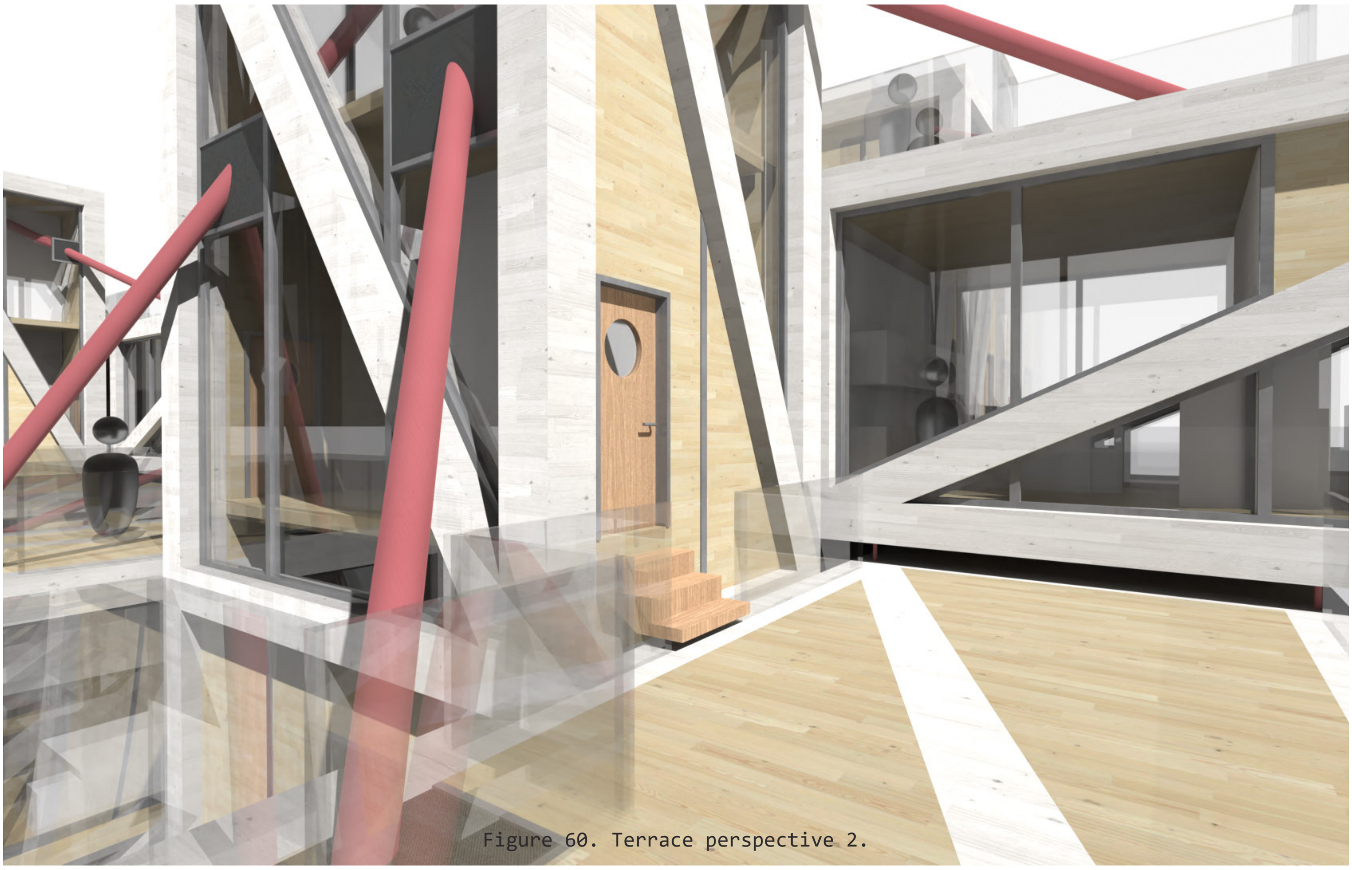


Figure 60. Terrace perspective 2.

Figure 61. Enfilade perspective.

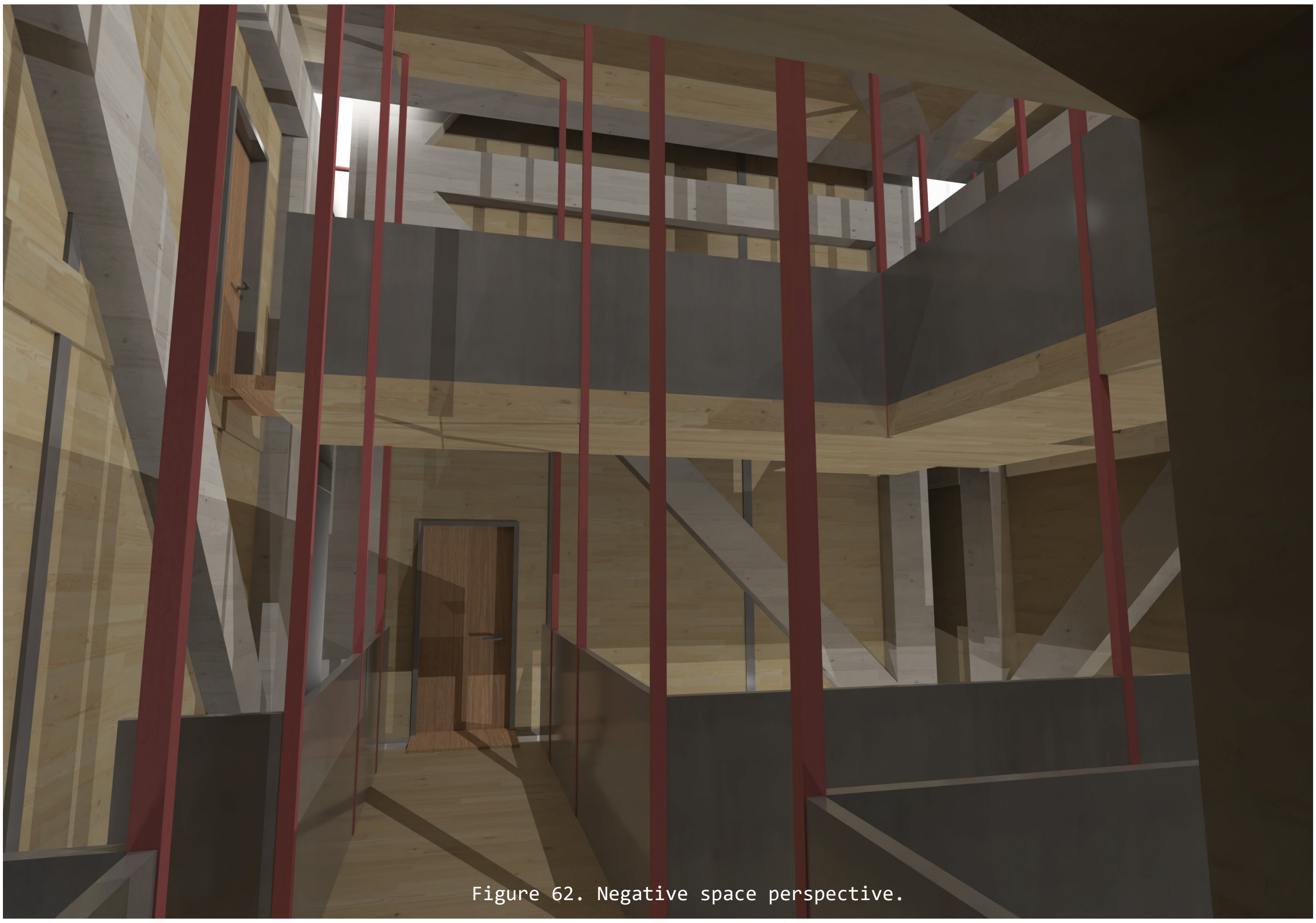


Figure 62. Negative space perspective.

Figure 63. Interior perspective kitchen.

Figure 64. Interior perspective bedroom.

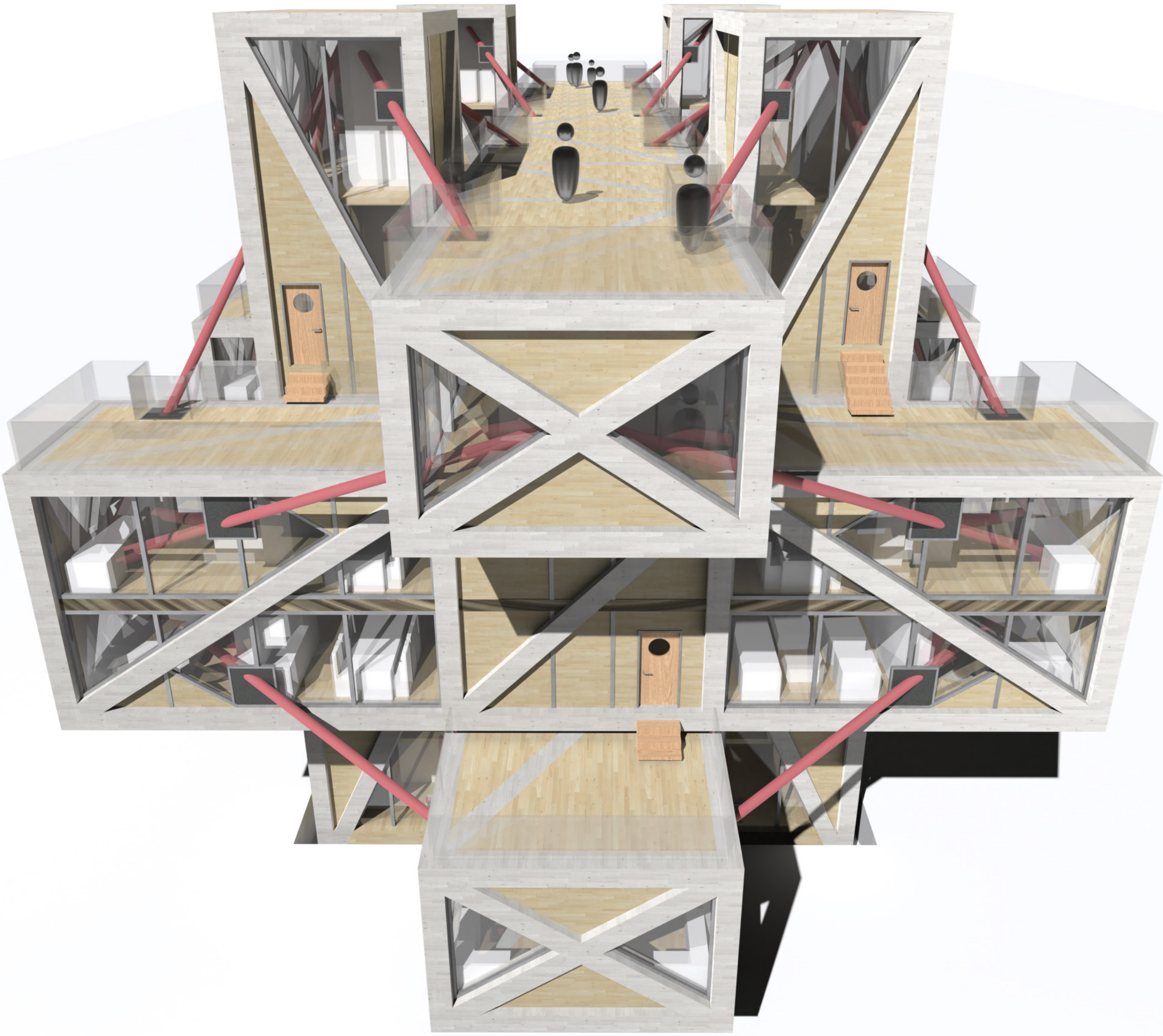


Figure 65. Exterior perspective.

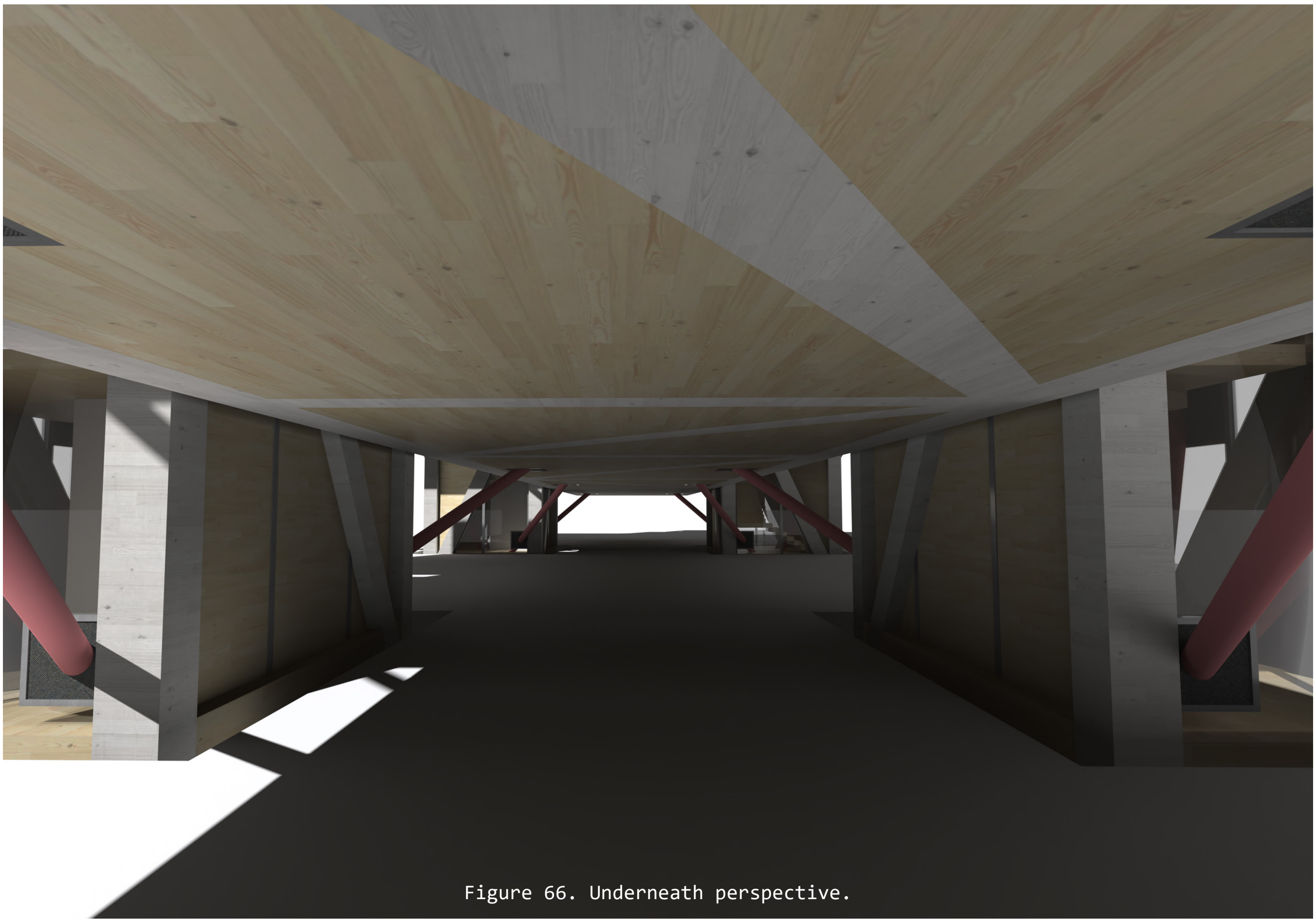


Figure 66. Underneath perspective.

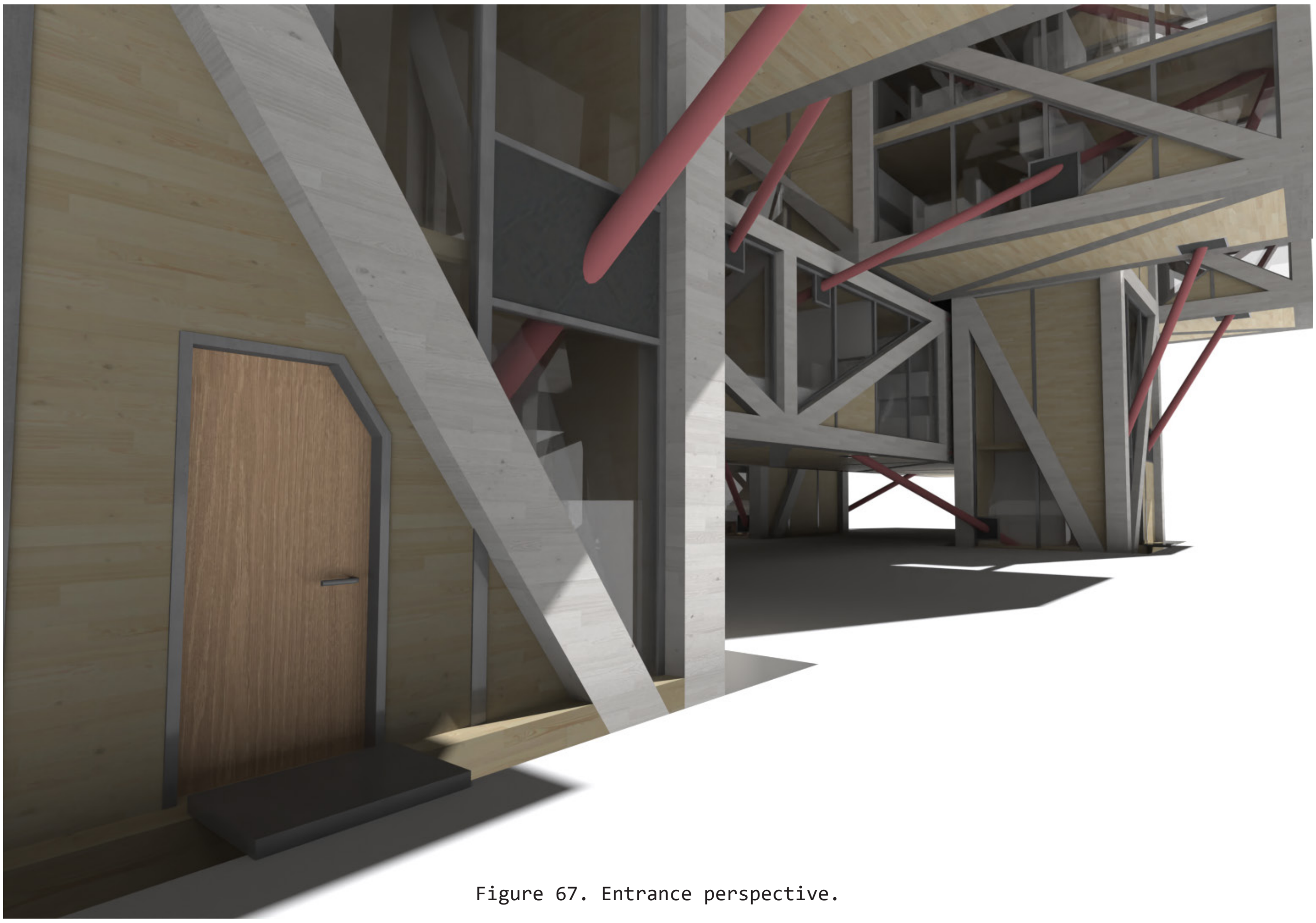


Figure 67. Entrance perspective.

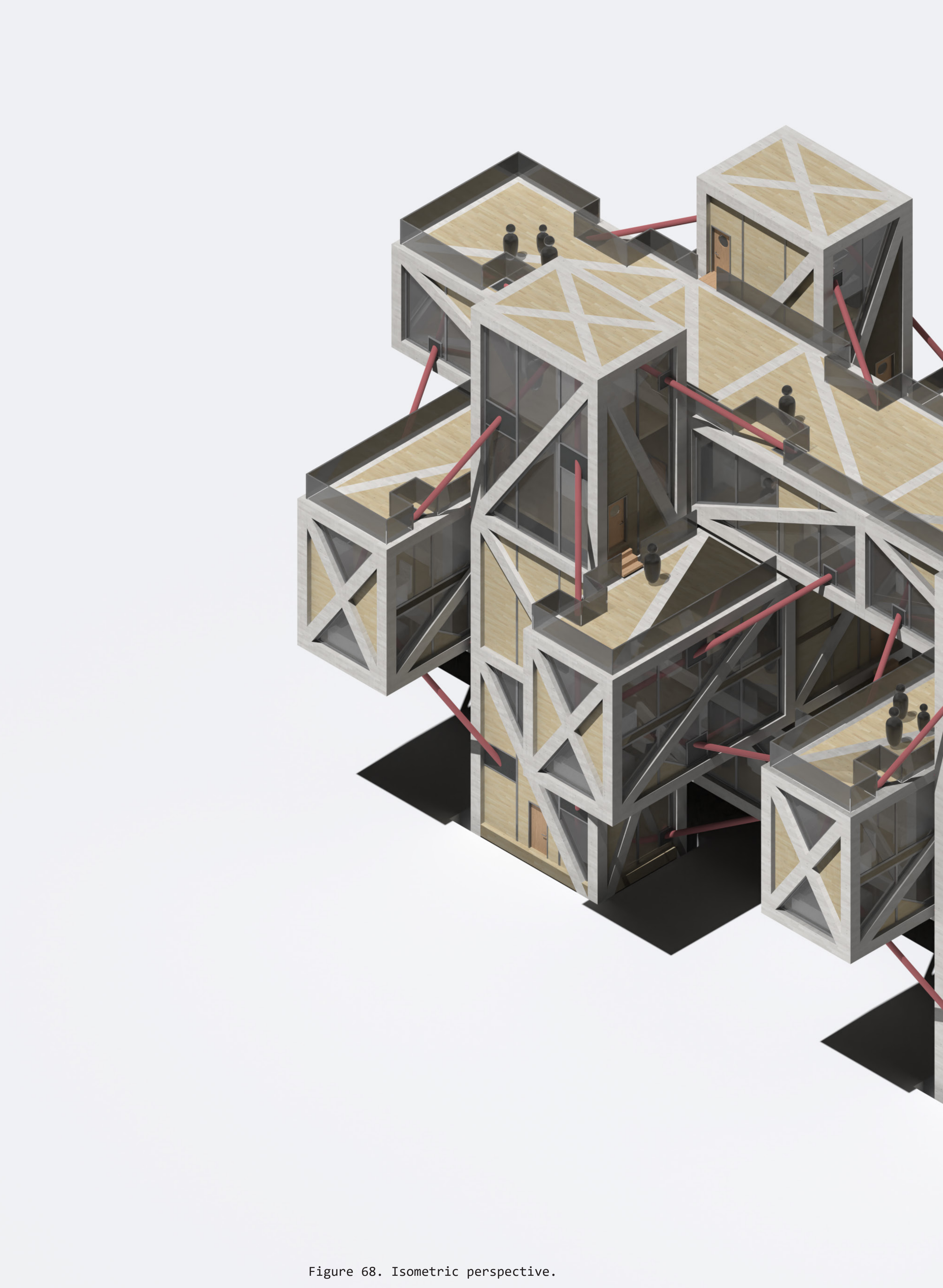
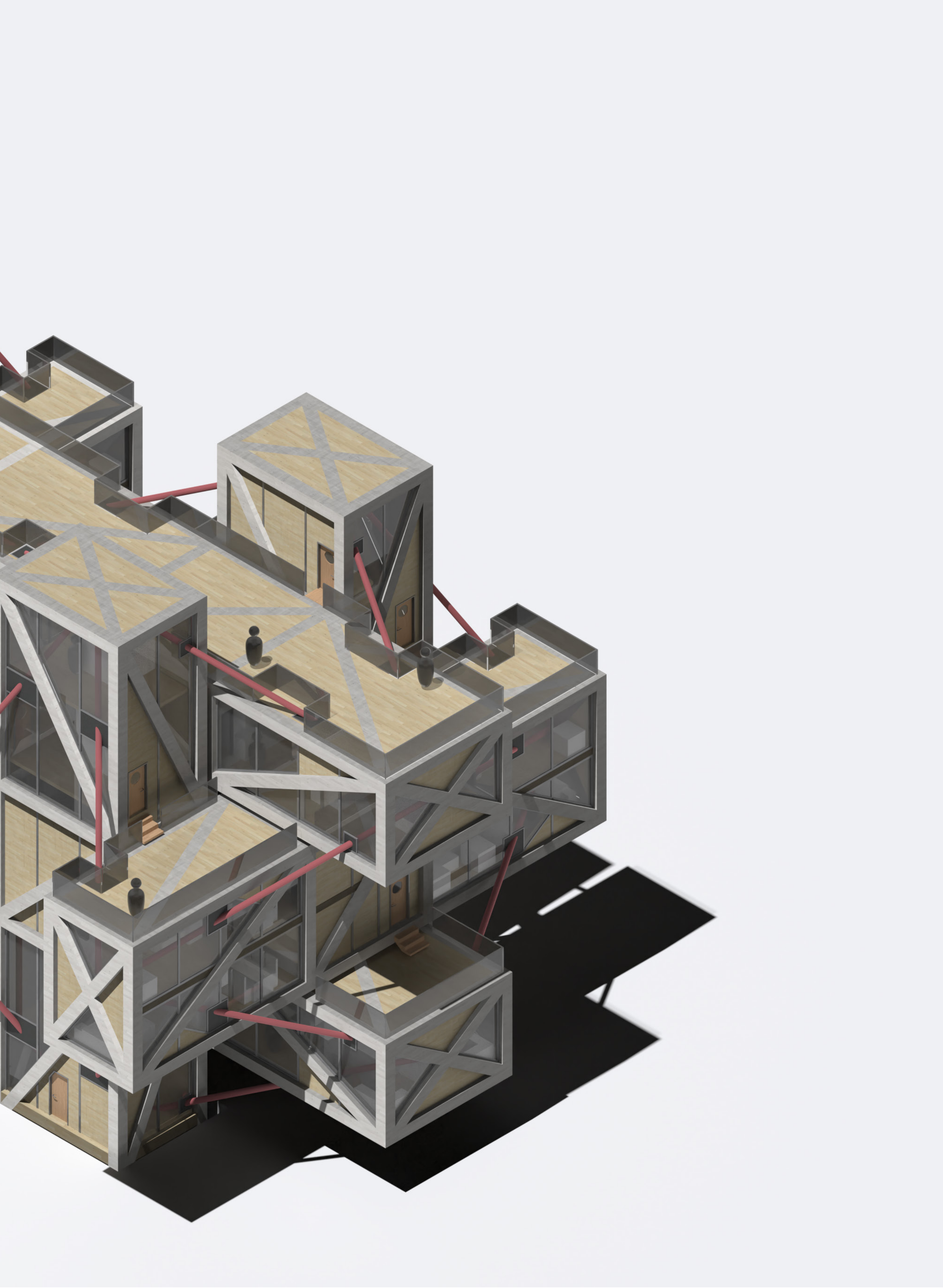


Figure 68. Isometric perspective.



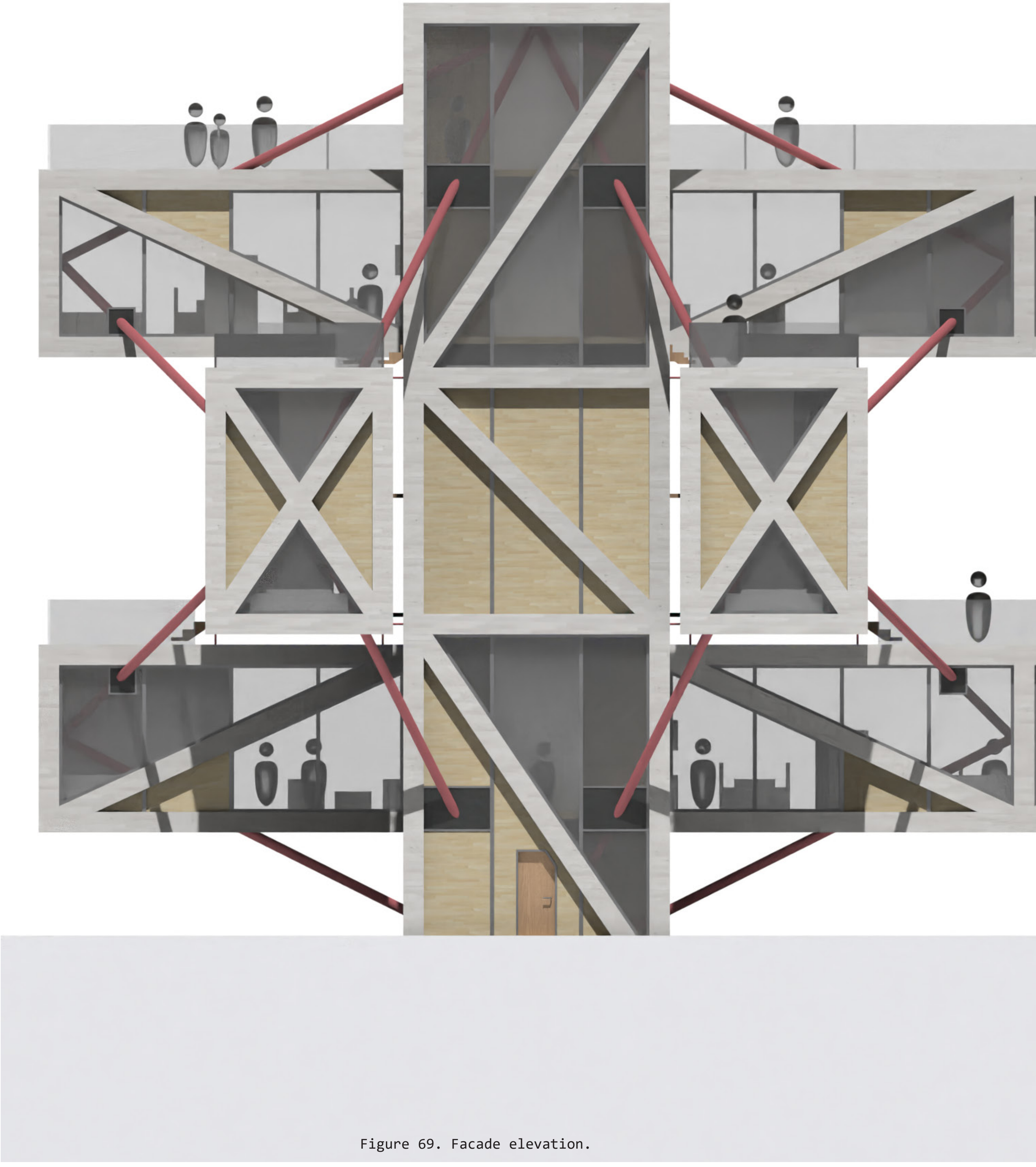
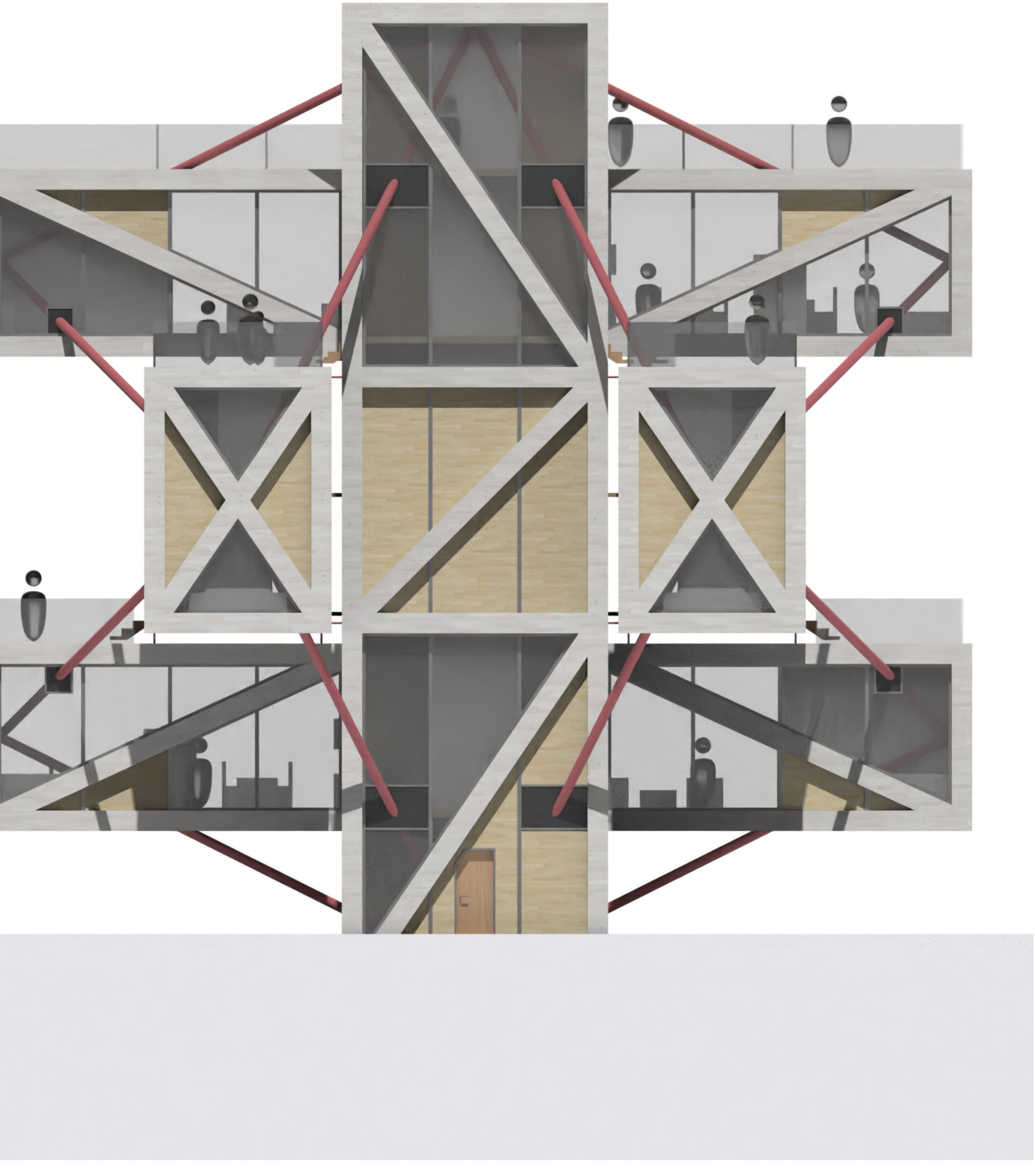


Figure 69. Facade elevation.



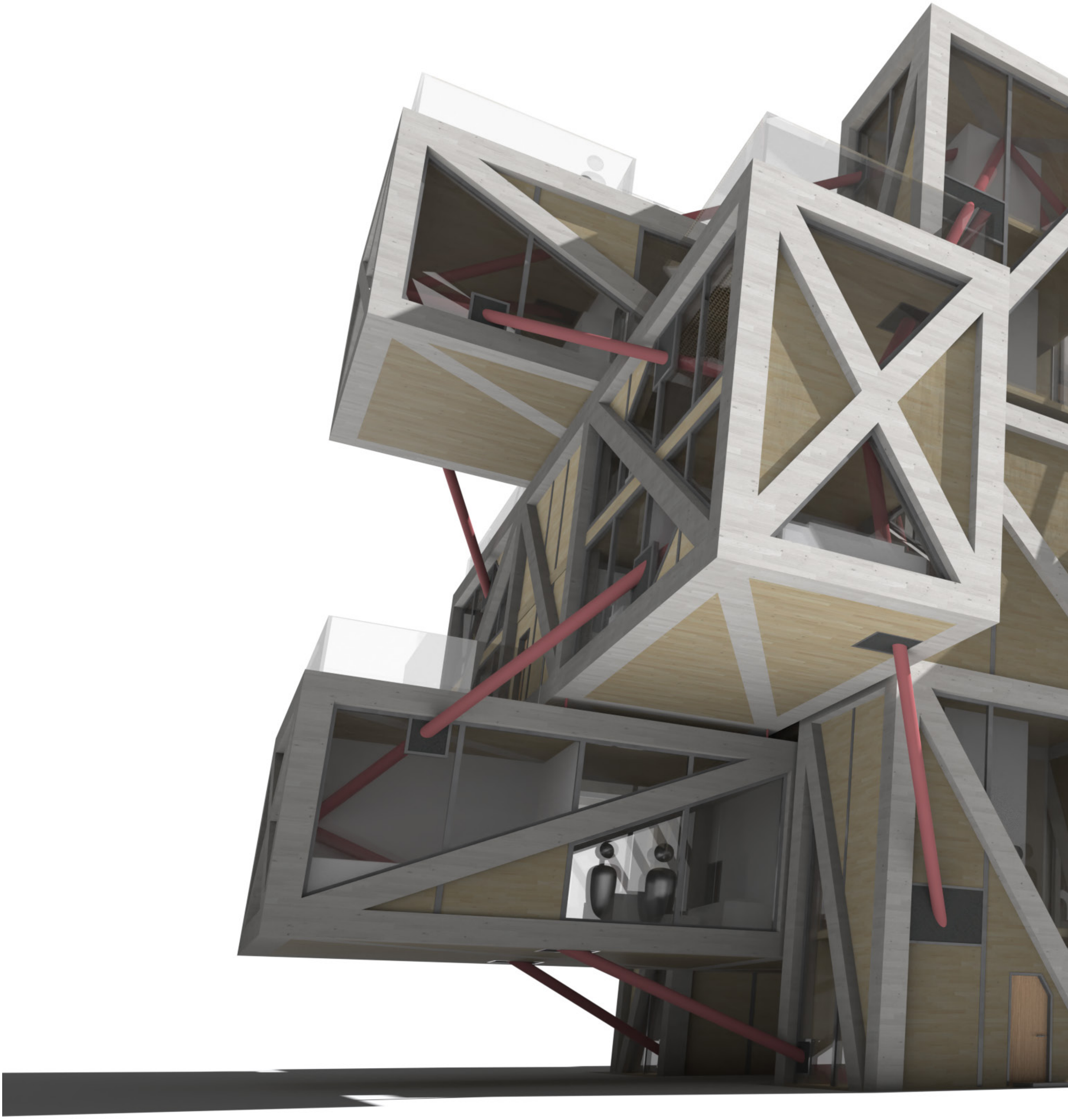
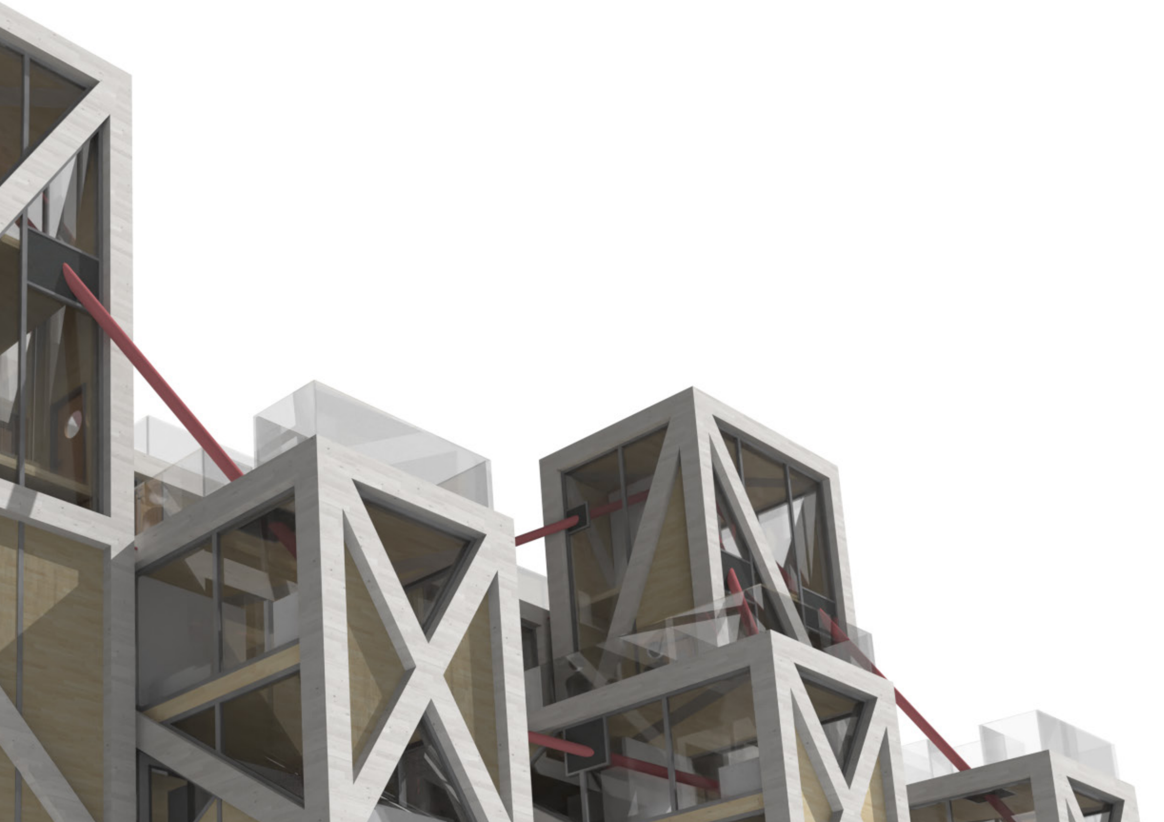


Figure 70. Exterior perspective.



Potential sites

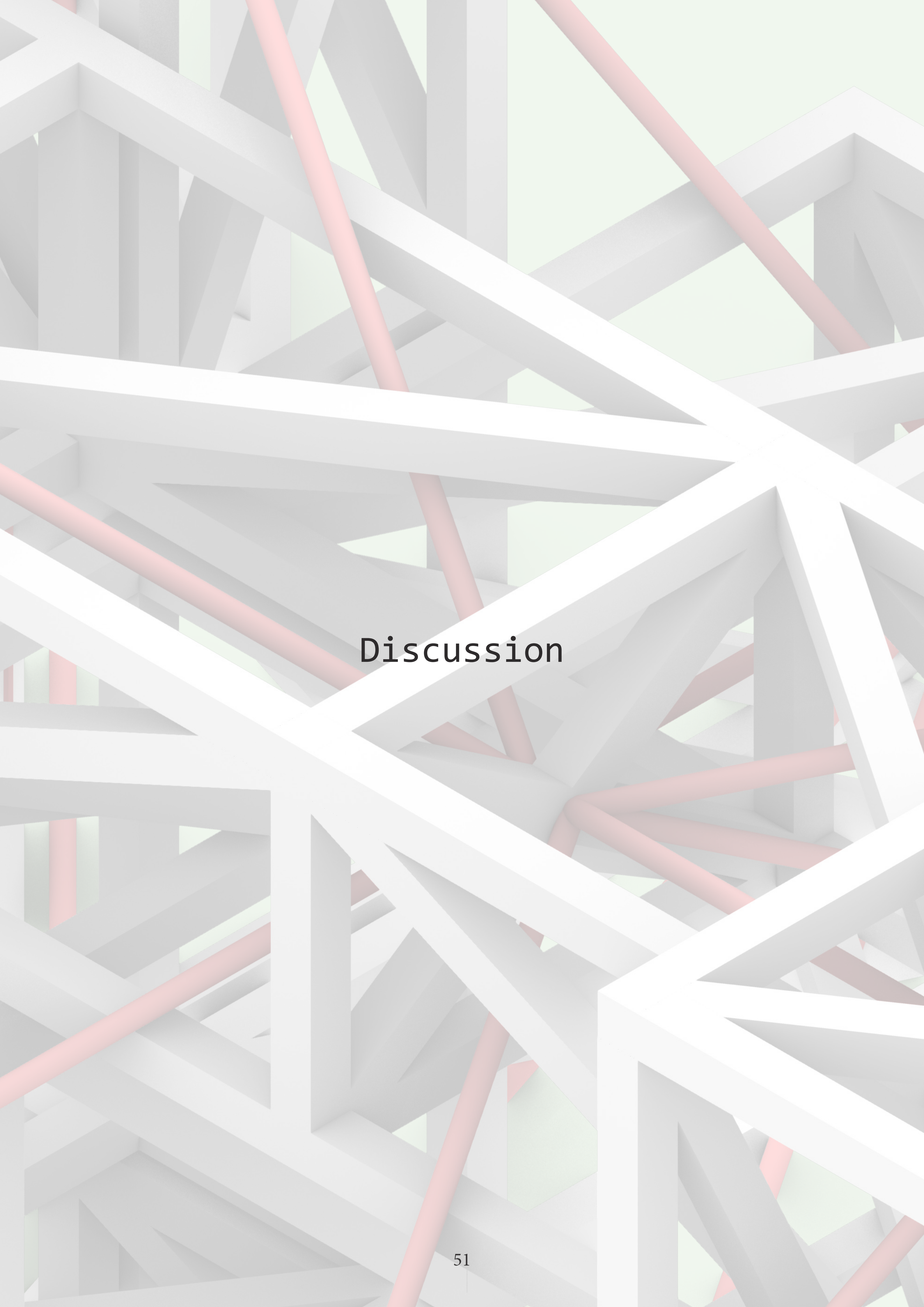
Figure 71. Locations on map.

The potential sites, California and Italy, were chosen chiefly on the basis that they are prone to earthquakes, warm, and wealthy. The latter two of these factors are particularly relevant for the concept design, as this concept design was not made with Swedish climate in mind and would likely be expensive. In contrast, earthquake-resilient tensegrity buildings are relevant to all areas which are prone to earthquakes.

The inclusion of suggested sites should be understood as visualizing the concept design in suitable contexts and providing a basis for discussing the prototype design, not as specific choices for where this design may be built.

Figure 72. Perspective of building in Italy.

Discussion



Discussion

The specific dimensioning of the tensile load bearing parts of the habitable volumes of the tensegrity systems has largely been done based on physical models, one of which can be seen in figure 5. Their dimensioning is speculative as their radius and material depends on a lot of different factors, including the mass of the habitable volumes, pre-stress relative to gravity, allowed deformation. As such, the approach is that it is better to over dimension these components and possibly get the option to adapt a visually more delicate solution in the future.

A lot of the explorations and testing done with Kangaroo2, particularly from the early stages of this thesis, have been omitted for brevity. There were a lot of bad ideas, and a lot of time was spent trying to fix bad ideas. Fundamentally, any structure that proved not to work is of far lesser interest than those that ultimately proved to be worthwhile candidates for architectonic exploration.

Something that quickly became clear during the literature study phase was the propensity for 2D representations of tensegrity structures to be difficult to decipher, particularly black and white such in printed works. With that in mind, a consistent way to represent compression and tension components has been used alongside standardized perspectives.

This tensegrity building concept design should be considered as just that, a concept for how to implement tensegrity in habitable architecture. Although it is, in the mind of the author, a very promising candidate for habitable tensegrity, this thesis does not make the claim that it is objectively the best way to accomplish it, nor that it is a completely worked through building proposal that could be built tomorrow without further development.

This concept building would likely be prohibitively expensive as a tensegrity building is something that has never been done before and, as has been explained over the previous several pages, requires a multitude of specialized solutions to function. That being said, this is not at all unusual for emerging technologies, and should not be used as an argument to write them off.

A simpler and more economical design would likely be more viable for widespread adoption, as wealth inequality exacerbates the vulnerability to earthquakes. However, demonstrating a more complex architectural application for earthquake-resilient tensegrity structures helps to propagate the concept in general, as well as strongly suggesting that simpler designs may be built en masse.

Furthermore, there are many other potential applications for tensegrity buildings. They are lightweight, strong, and flexible, suggesting use cases such as temporary disaster relief buildings which could be efficiently transported, or lightweight structures for glamping with limited damage to the ground on which they stand.

Conclusion

Conclusion

The main benefits associated with tensegrity in an earthquake scenario are its low weight as system-level elastic deformation. By distributing the lateral force subjected to the building through multiple components they can be better handled, thus alleviating the risk for component failure. Fundamentally, the setup for tensegrity is analogous to that of a building with seismic base isolation. A non-rigid connection to the ground mitigates the structural impact of an earthquake.

Spatially, the defining feature of tensegrity is its tendency to create unorthodox angles in 3D-space which often clash with traditional orthogonal architecture. This is further exacerbated by a propensity to deform which means that special care has to be taken when designing the interface between a mechanical tensegrity structure and the programme of a building.

Another defining characteristic of tensegrity systems is the thin tension components holding the more substantial compressive components in place. This can give the impression of the compression components floating in space, which strengthens the impression of visually airy structures. This is more so the case when viewing a tensegrity system from afar than when observing a small part of it up close.

In terms of usage, the defining factors for tensegrity systems are the non-conventional angles if and when they directly interact with a room, as well as the capability for system wide deformation. The latter means that any component is prone to move in relation to its siblings, which must be taken into consideration when designing these systems. Buffer zones are required between components which otherwise may have been prone to colliding.

In this thesis, the design focuses on a multifamily residential building, not only because it is a widespread type of building, but also as a means to showcase how tensegrity can be used for buildings in general. If a multifamily residential building can be built with tensegrity, so can an office building, a public building, or a school.

Constructing buildings with tensegrity as the main structural principle is viable. Such buildings could help alleviate the consequences of earthquakes, moving towards sustainability through reducing the need for reconstruction as well as by reducing the human suffering and loss of life.

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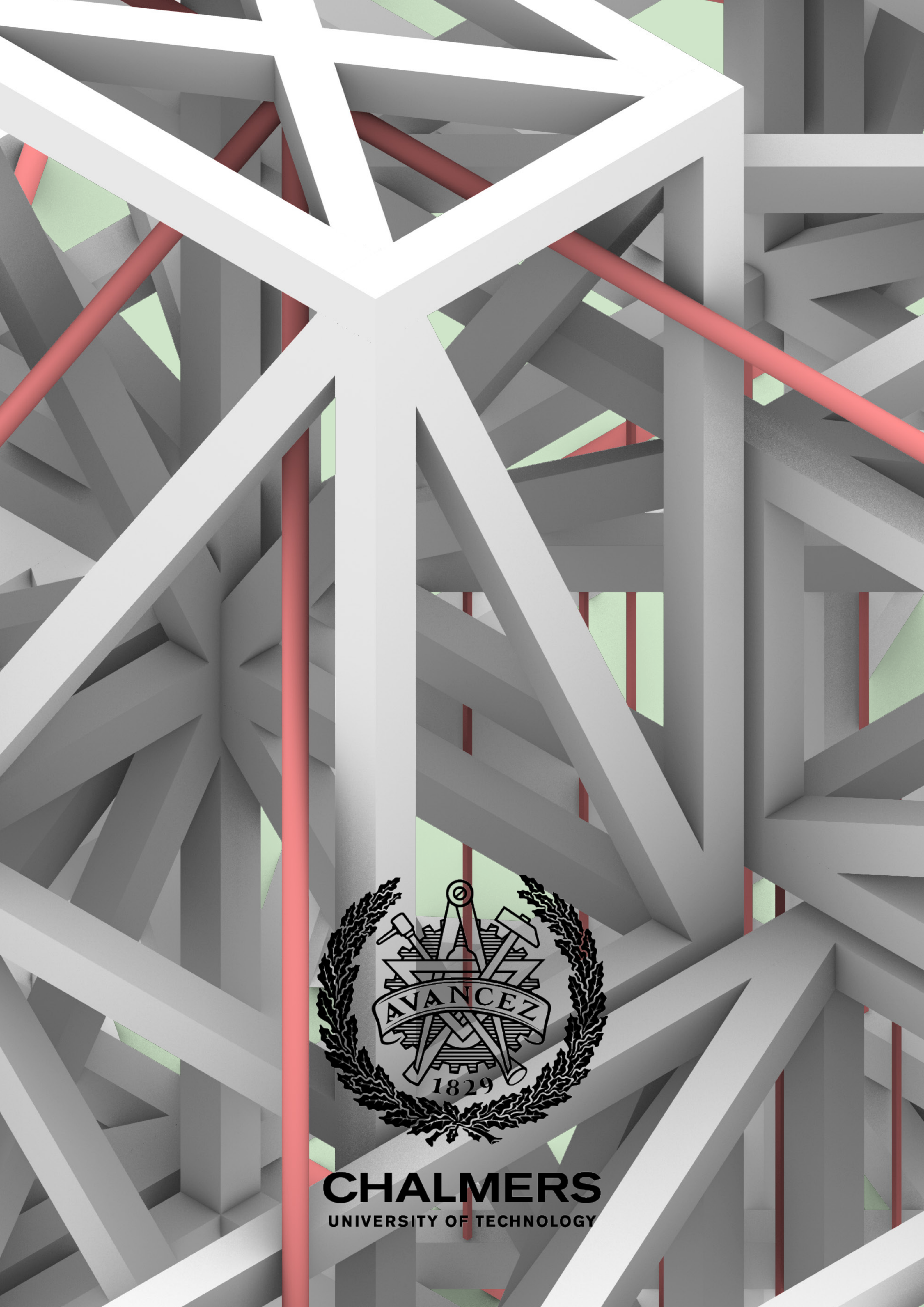

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