TOWARDS A HUMAN - FREE ARCHITECTURE?

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Abstract: This thesis concerns itself with the intelligent performance of architectural structural systems through the lens of topological optimization and additive manufacturing. The following research premised using computational bi-directional evolutionary structural optimization (BESO), is a venture into how architecture items ensure a higher degree of structural intelligence by reprioritizing material to areas of principle stress. A computational framework is realized with findings suggesting divergence from traditional orthogonal post and beam construction. The fluid non-orthogonal BESO outcomes display greater structural efficacy against parameter-based loading conditions. The question that this dissertation investigates is: **how the reprioritization of material to areas of principle stress drives the symbiosis of engineering**

performance and architectural outcome?

Preface: The recent advances in 3D printing and computational processing power are directing practitioners to fabricate non-orthogonal objects with unprecedented structural complexity[1]. Computational abilities of bi-directional evolutionary structural optimization (henceforth BESO) to simulate physics with in-built Finite Element Analysis (henceforth FEA), provides this platform for form to follow force. This dissertation is an acedemic exercise that explores structure in architecture that is directly responsive to the physical force exerted, without any construction contraints, for, it has been well established that force does not move in a linear fashion and, nor do our human made topologies,

least of all, architectural topologies respond *precisely* to the forces exerted. Naturally, building anything is limited by fabrication technology[2]. The outcome of *form following force*[3] becomes an interesting question, even for the problem of a spanning beam, when practitioners begin to, 1) consider and, 2) diverge from proprietary elements and 'flat sheet' architecture. The computational push towards physics solvers is the puritanical belief that new outcomes must use new technologies. The use of computational methods over analogue tools provide an expansion of the architectural language that preaches a dogmatic response of form following force. As of writing, 2021 architectural and engineering technology marks a point where small-scale additive manufacturing is no more expensive than analogue proprietary means. A few Large-scale projects using topol-

ogy optimization (henceforth TO) and additive manufacturing (henceforth AM), such as the 12.5m spanning MX3D bridge, printed with steel, or the concrete ceiling cast from 3D-printed form work from DFAB in Zurich, have suggested a future of bespoke, customized architectures. Large scales are marked with long printing times, a small market of printing fabricators, plagued by printing cost, time and unverified performance, making 3D printing largely uncharted territory for contractors. In thinking ahead: the near future can predict with certainty that small, medium and large scale projects will incorporate steel and concrete printing, and other composites; mycelium and clay for non-load bearing items. Assuming an efficient future of 3D printing, and using the assumption as a thought experiment for free thinking – this thesis

speculates greater performance of geometry through the computational ability to simulate physics digitally.

What **resolution** should the reader take away from reading this dissertation? What is provided is a single lens (as designers have many which they operate through) on how to generate a building or structure through colonization and re-prioritization of its parts and space. The important key words here are: generation (finding form), colonization (of available space) and reprioritization (of material). **The thesis concludes** that BESO is one tool in the practitioner's kitset; the computer and computational script works itself as a designer, side by side the human as aid, with build in artificial intelligence, the BESO tool can be viewed as a **computational sketching tool.** Resultant meshes are often un-

precise due to resolution issues, however the mesh following the direct line of force offers an indication of how to solve the structural problem, how one can go about rationalizing a structural scheme, and offers conceptual typologies that expand the scope of architect's possibilities of a given project – in essence, we achieve **a novel *structural draft*[4].**

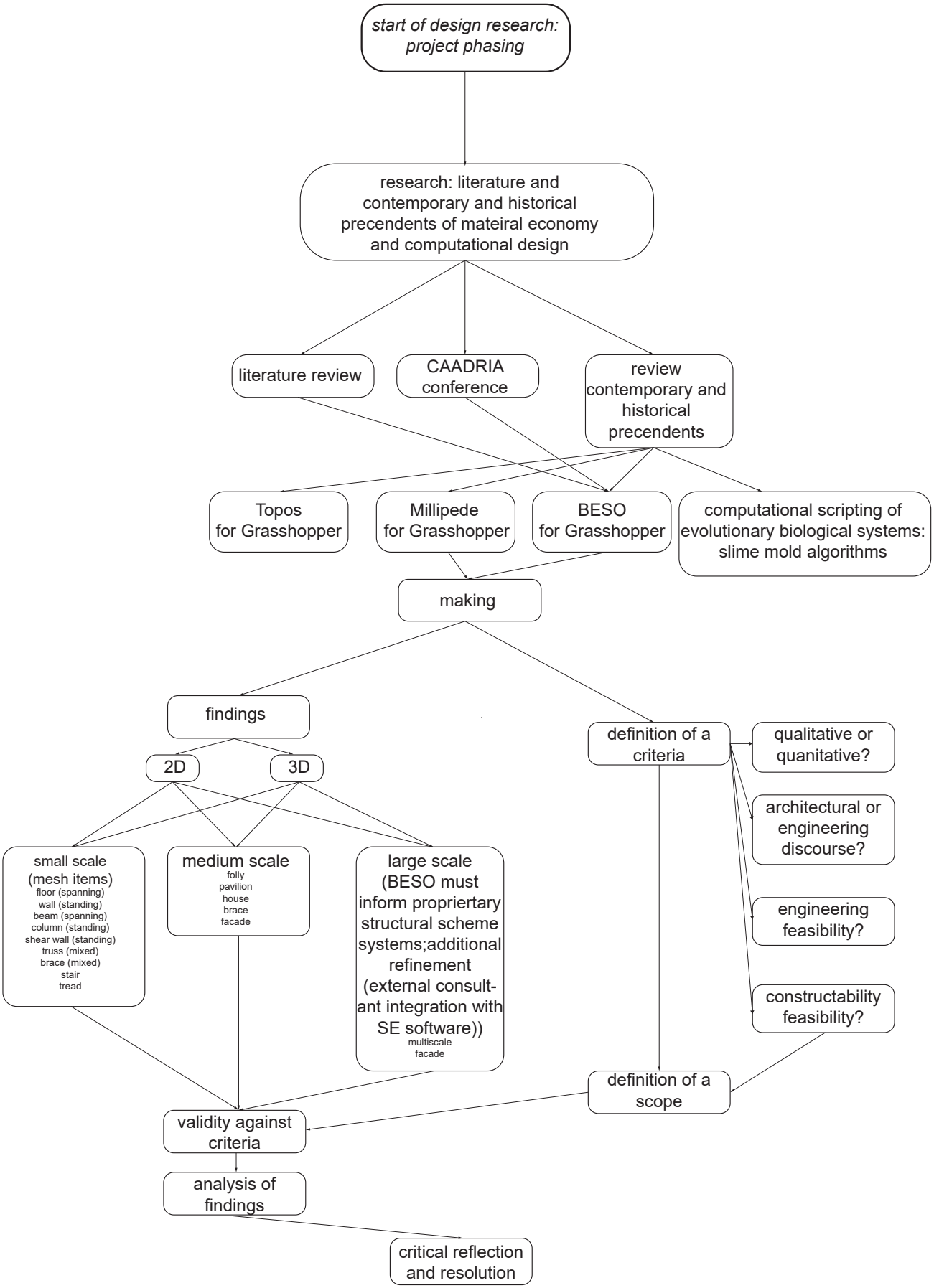
The **scope** of the thesis is speculative. Novel applications of BESO are tested on small, medium, and large scaled structures. This work is an architectural thesis and not an engineering discourse, the verification of the work, again, is strictly **qualitative and not quantitative.** The research are studies of architectural items – the floor, columns, beams, shear walls, super structures, facades – studied anatomically,

redefining the architectural language as ***standing and spanning***. The structural **scope** is limited to simplified loading conditions: Gravity loading is always implied computationally. Deadload, MEP, and live loading is simplified but accounted for in singular nondescript loading where magnitude and direction is described. Lateral loading is differentiated into: wind loading as a surface pressure of a tributary area, which increases proportionally to the height of the building, but does not consider technical phenomena such as the build-up of positive and negative pressures, vortexes, uplift suction et cetera, and seismic loads which do include self-weight inertia, but do not include building frequency. Loading conditions are kept intentionally simplistic. The scope of exercise is limited to 3 scales: S as micro elements, M as residential and pavilion

scales, and L as multistorey structural systems. Constructability and structural verification are not within the scope.

Thank you to my supervisors for their time. Thanks Tane Moleta for incentivizing novel work. Thank you, Professor Andre Brown, for seeing value in my work and providing a basis of understanding how a combination of computation and structure can drive architectural outcome. Professor Marc Aurel Schnabel, thanks for the connections. Thank you Lee Lip Jiang, Cassidy Van der Weilen, Dr Nabil Allaf, Nic Ding Wen Bao and Marny Evans. The computational domain of this thesis ethically requires referencing of precedent scripts, thus, both ideas and computational process which are borrowed from are referenced. A visual methodology is not provided here in this dissertation as the

following summarizes aptly the process undertaken. The 9-month project was structured as follows: Research from March 2021 to November. Testing from May to July. Making and recording findings from July to November. The following is broken into five chapters. Graphically the methodology can be descibed as • → **Chapter I** is an essay proposing a BESO paradigm, exploring history, reasons for optimizing, relationships to biology and history, architectures forebearers, Gesamtkunstwerk, fabrication, and a philosophy. **Chapter II** is standing items; **Chapter III** are micro items; **Chapter IV** investigates spanning items. **Chapter V** is the production of architectures that typify the work.



● **1** a graphic methodology

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TERMINOLOGY

TO (topological optimization): topology can be thought of as shape. An optimal shape within the domain of structures can be defined as performing load transfer with the minimum amount needed.

BESO (Bidirectional evolutionary structural optimization): parametric reduction and reprioritization of an object's envelope or plane volume fraction to resist imposed loading conditions based on material and other properties. BESO informs TO

FEA (Finite Element Analysis): a method of numerically solving differential equations in mathematical modelling. TO finds a geometry that fulfills a predefined criterion of FEA. BESO uses FEA to achieve the optimized topology.

ER (evolution rate): amount or rate of change per iteration

IT (iteration amount): number of iterations.

VF (volume fraction): expressed as % of initial geometry experiencing optimization and material reprioritization.

SubD (sub-design domain): separate parts of an object/envelope/plane experiencing optimization and material reprioritization.

NDD (non-design domain): predetermined constraints that are not optimized, mostly commonly a flat floor, room envelope et cetera.

Mesh: a hollow enclosed volume made from triangles or quads.

AM (Additive Manufacturing): typified by layer 3D printing.

Orthogonal: Linear geometry, typically vertical and horizontal

Non-orthogonal: curved or irregular geometry.

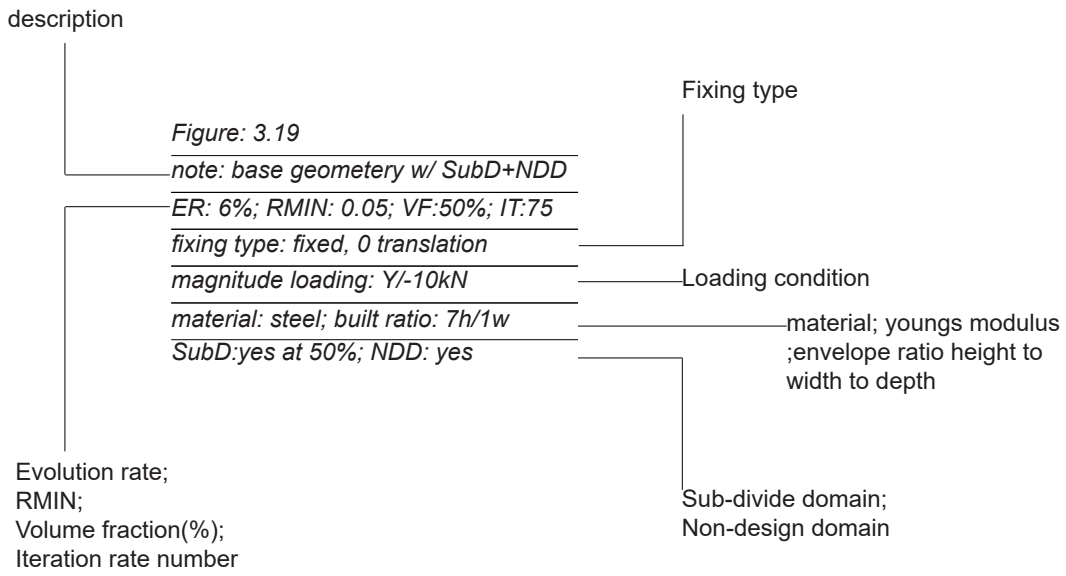
Envelope: the outside boundary condition of a 3-dimensional object.

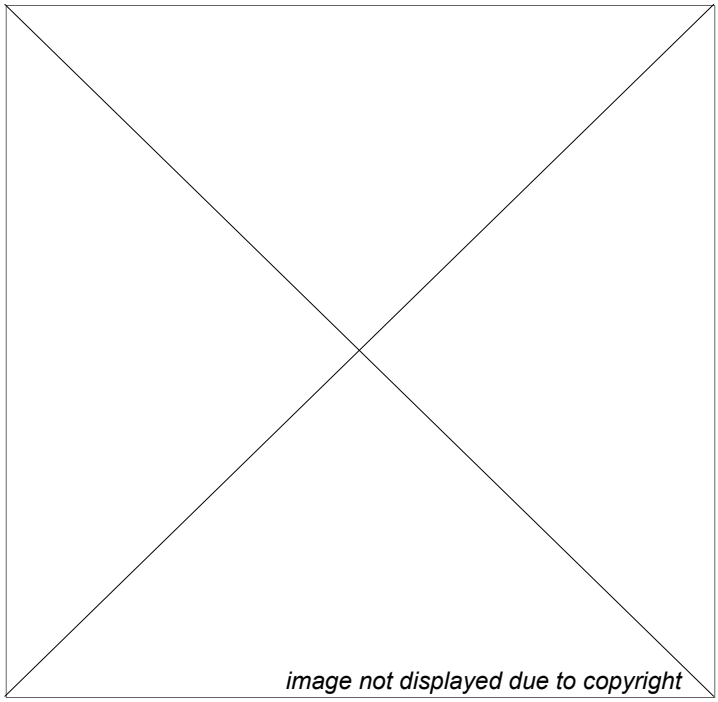
Morphogenesis: described for architecture, morphogenesis is the process an object undergoes from external stimulus. Described in orthopaedic surgeon Julian Wolff's The Law of Bone Remodelling, circa 1892 — we understand bones to reinforce themselves against loading conditions, called morphogenesis; we see different levels of

porosity and material density across a femur cross section. The process of BESO can also be attested to this definition.

Homogeneity: described for architecture, homogeneity is the continuous use of one material and form that covers multiple uses. A diagrid structure can attest to being more homogenous than a post and beam structure where diagonals work against gravity and lateral loads.

The matrix •↓ is an example of the specifications and parameters of each test.



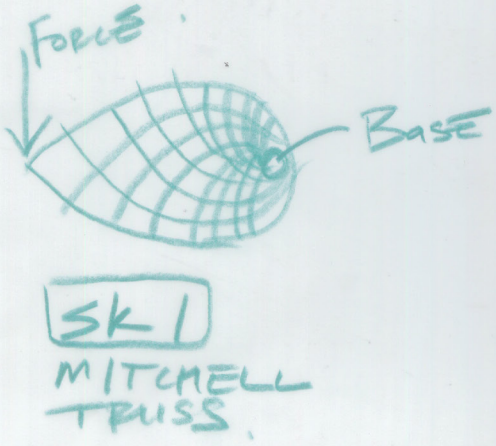


● **1.1** Kings College Chapel Cambridge.

CHAPTER I

an essay proposing a BESO paradigm

history; why optimise; biology; architectural precedents; Gesamtkunst-werk; BESO; robotic printing.



The recent advances in high resolution 3D printing and cutting-edge computational processing power have re-inspired designers and architects with the feasibility of fabricating objects with unprecedented structural complexity and material homogeneity[5]. Computational abilities to simulate physics with FEA, provides a platform for new topologies that are direct response to forces exerted, for it has been well established that force does not move in a linear fashion and, nor do our human made topologies, least of all, architectural topologies, respond *precisely* to the forces exerted. Naturally objects are limited to the limit of fabrication[6].

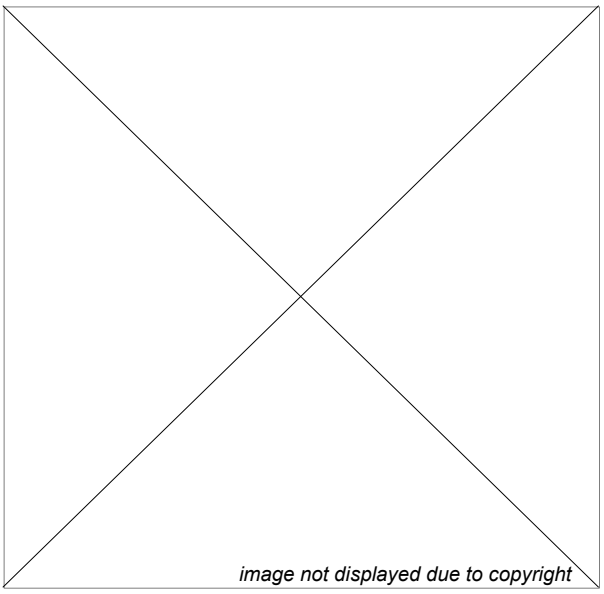
Developments in architecture continue to be inextricably tied to the evolution of structural morphology[7]. The outcome of **form following force**[8] becomes an interesting question, even for the question of a spanning beam, when practitioners begin to consider and diverge from proprietary elements. As of writing (2021), architectural and engineering technology marks a point where small-scale additive manufacturing is no more expensive than analogue proprietary means. A few Large-scale projects using topology optimization and additive manufacturing such as the 12.5m spanning MX3D bridge, printed with steel, or the concrete ceiling cast from 3D-printed form work from DFAB in Zurich, have suggested a future of bespoke, customized architectures. However, large scales are marked with long printing times and a minute market of printing fabricators — the constraints tied to the Zeitgeist.

TO, naturally observed in nature, is also mathematically described in structural engineering. Computationally represented, it is a subtractive process that performs Finite Element Analysis through loads and supports defined in a voxel domain space and finds the optimal paths of force transference from loads to supports. These paths of load transfer are the optimized topologies[9]. TO reorganizes an objects shape to discover an optimal geometry that fulfills a predefined criterion of FEA[10]. Historically, Australian Anthony Mitchell published a seminal paper on structural optimisation — one year before Einstein's 1905 miracle year — developing a framework of observing optimal structural forms[11]. Robert Hooke's earlier discourse of funicular compressive structures would provide inspiration for both Gaudi, Poleni and all interested in the uses of optimisation through the suggestion that analogue models using a hanging '*flexible line'* would, when inverted, *'stand the rigid arch". Poleni's* 1748 solution

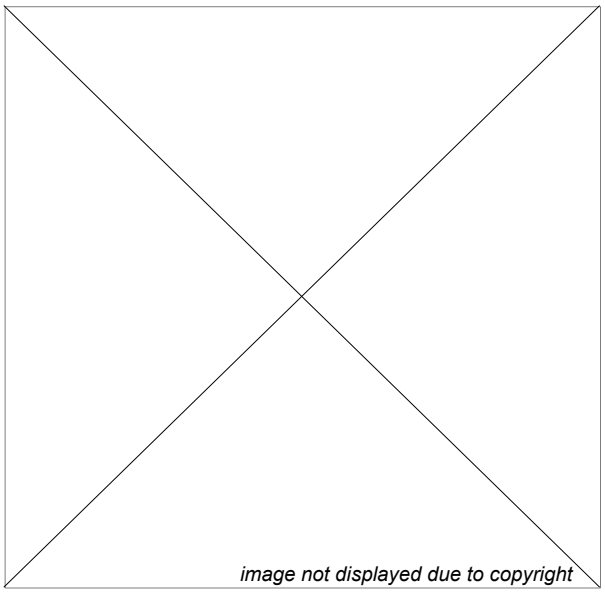
for St Peter's Basilica in Rome reinterpreted Hooke's work, turning an academic exercise in a physical exercise by hanging weights along a slack line to indicate the proposed curvature of the spanning dome[12].

Why optimise? The reason for optimisation could be said in jest that material economy incentivises more creative problem solving[13]; structures become more interesting with porosity. Engineer Heinz Isler highlighted the importance of light-weighting as structures are more effective with less weight. Others would suggest performance, parts consolidation, and sustainability in a world which finds itself politically, socially, and environmentally obliged to take more sustainable measures, where construction accounts for 39% of the embodied carbon emission globally; this carbon emitting material mostly being structural[14], from waste, non-durable architectures, formwork, materiality, and processes. It should be noted that the building industry creates 50% of waste in New Zealand.[15] Perhaps this question, *why optimise?* can be answered regarding economics: material is expensive with inflation, but form is cheap[16] — **or by the afforded freedom of design scope.** In the sector of aeronautical travel, the fiscal and engineering benefit of volume reduction and material reprioritisation for an overhead luggage bracket is considerable over a 30-year lifetime, carrying one kilogram is equivalent to a $100,000 of fuel[17]. When topological optimisation tools are considered over an entire system, we see drastic changes to topology and — we see ease of simulating, reiterating, and fast-tracking early design decision making; we see more intelligent design. Chapter II will describe intelligent design.

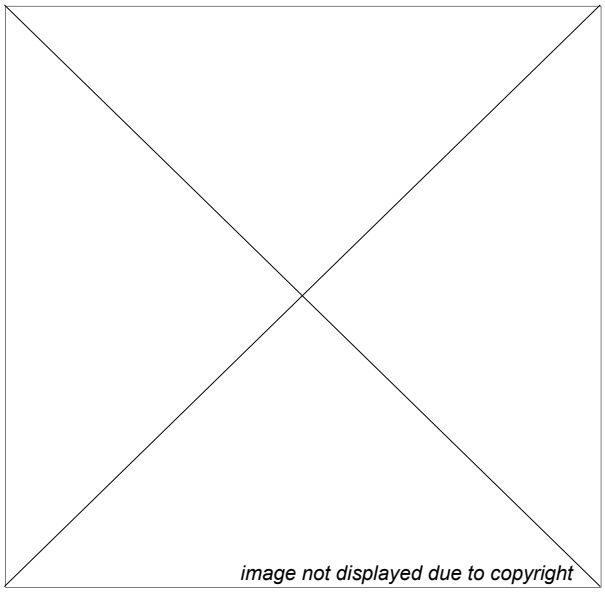
Intelligent form is evident in biological systems such as bones, trees and arthropod exoskeletons. Described in orthopaedic surgeon Julian Wolff's The Law of Bone Remodelling, circa 1892 — we understand bones to reinforce themselves against loading conditions, called morphogenesis; we see different levels of porosity and material density across a femur cross section. Anatomist F. Meyer and structural engineer G. Culmann found similarities between calculations of stress directions using graphic statics and the bone architecture of the human femur, shown in figures *1.2, 1.3 and 1.4• →.* Conversely, Toyota notes the typical automobile consists of 30,000 parts with differing raw materials and manufacturing processes. Commercial floors can be broken into a drop ceiling, hiding services, primary structures, secondary structures, reinforcing, mesh in a topping slab,



● **1.2** *Morphogensis of the femur bone in response to loading conditions.*



● **1.3** *3 sections of the proximal femur showing trabecular tectonics; the middle schematic drawing by Meyer (1967), adapted from Advic shows point of no stress; the right schematic shows Culmann's graphic statics adapted from Advic (2019), showing compressive and tensile forces.*



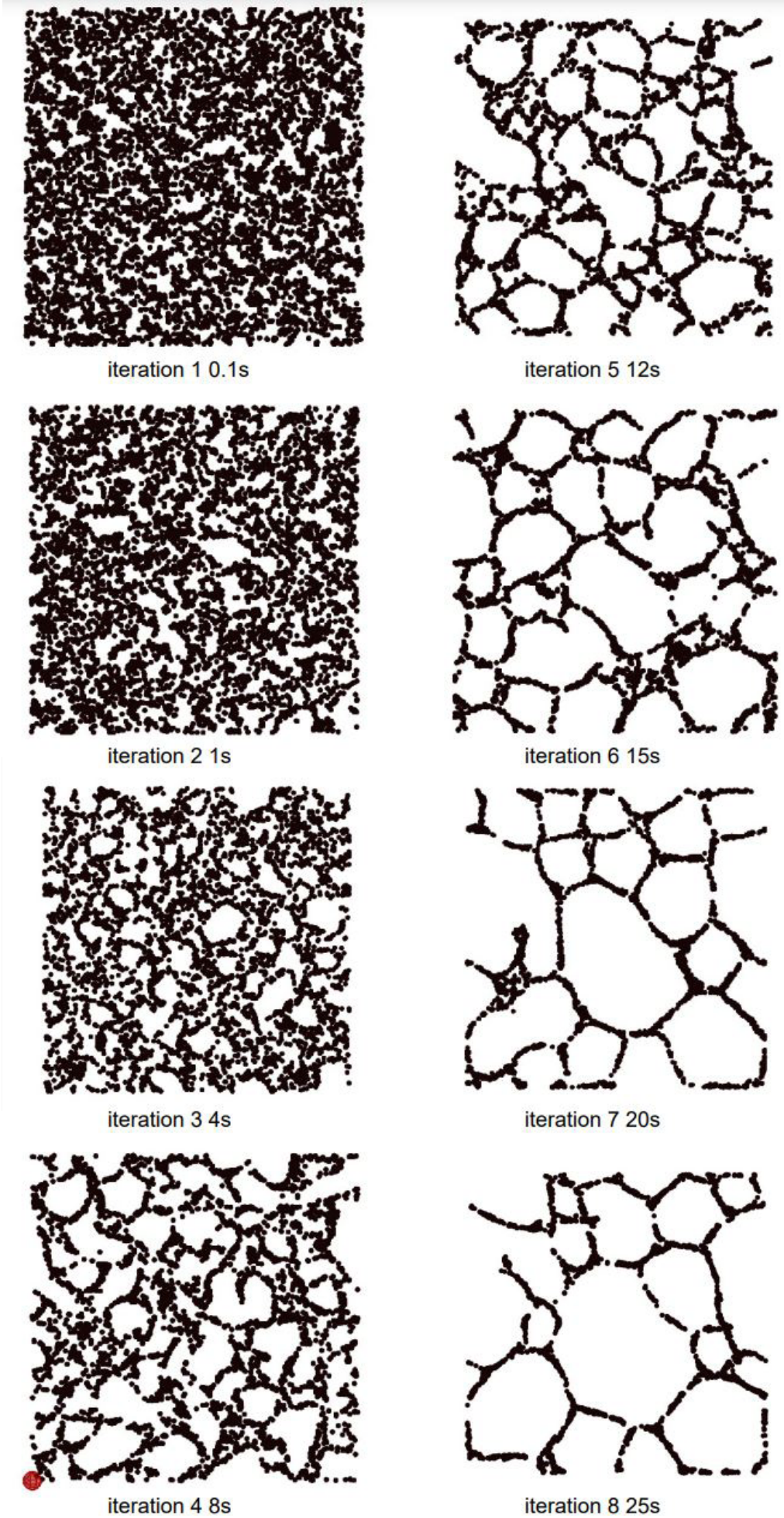
● **1.4** *Member, shape, topology optimisation and a correlation between the warren trusses effective geometery for force distribution and that of a Vultures metacarpal wing bone.*

screed, and the desired finish. The juxtaposition is clear: natural systems use very few materials[18], their components optimize over time to given loadings, whereas human technologies are an assembly of items, pre-designed, pre-planned, mechanic. *If bone is the answer, what is the question?* [19]

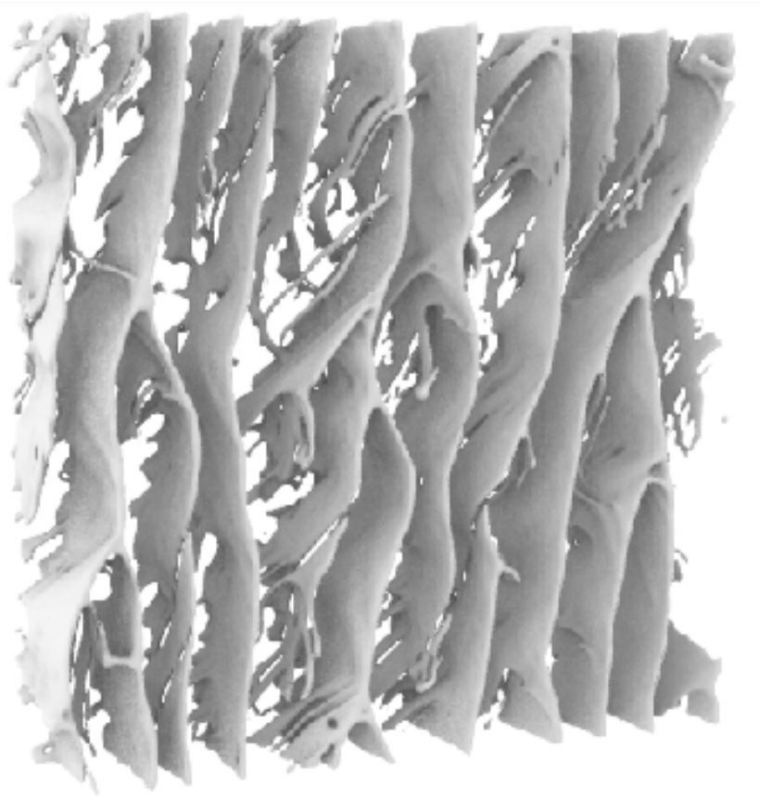
1.4 • ← displays the 1849 patented Warren Truss which works both in compression and tension depending on the location of the object traveling across the trussed bridge; this patent was an improvement of material economy by activating members to complete more than one task, over previous bridge patents of the 1840's such as the Pratt or Howe truss structures which had specific members working in either compression or tension. The Warren truss is a naturally occurring structure in nature with the metacarpal bone of a vulture display similar topology. Furthermore, *1.5,1.6,1.7*• → show slime mould algorithms describing the path finding and decentralised behaviours of the phenomenal organism itself [20], and display proof of computational abilities to simulate natural phenomena.

The intent is not necessarily to replicate nature, but more, to take lessons from natural systems to achieve greater homogeneity over assemblies of parts. This is done by specifically describing architecture that follows forces rather than predicated notions of functionality that are the result of construction technique. **It is a morphogenesis discovery of structural configuration and homogeneous marriage of parts.** The intention is to design a process so we do not prejudice nor know the final outcome making 'a leap for architectural aesthetics'[21]. TO defines makes architecture a parametric process: define points, boundary, reduction rate et cetera, and the computer will utilize its own intelligence to resolve a solution. This result is more complex than a human can draw and conceive. The process is also not labourous as the process is generation on a computer.

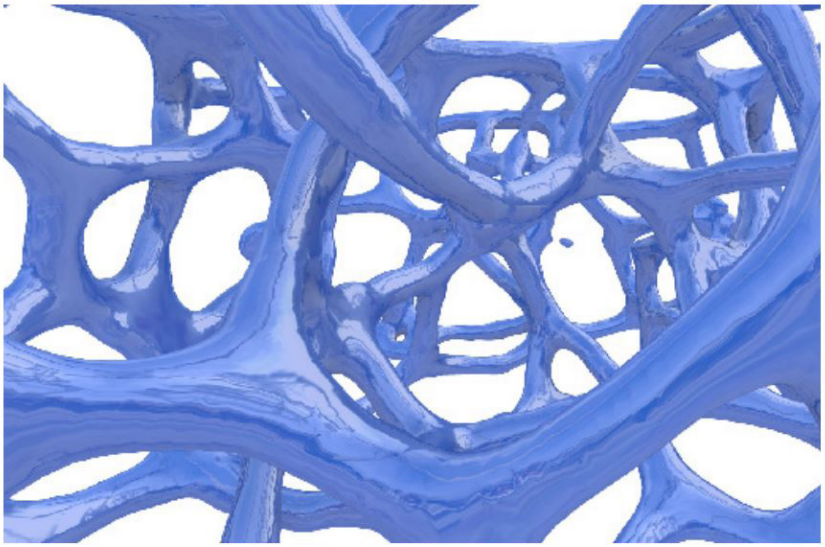
In discussing **architectural precedents**, the machine modern age is understood by its use of proprietary items; the most fervent purveyors being the modernists; Gropius, van der Rohe, Le Corbusier (to name a select few) — archetypically described by the (rather very European) Domino House *1.8*• ← whose free plan spatial organization proves that the alteration and articulation of structure and access to new materials (reinforced concrete, curtain wall sludge glass)[10] **is a structural framework which has reduced modernism to a mod-**



● **1.5** *slime mould algorithms in 2 and 3 dimensions describing the path finding and decentralised behaviours of the phenomenal organism itself, and computational proof abilities to simulate natural phenomena.*



● 1.6



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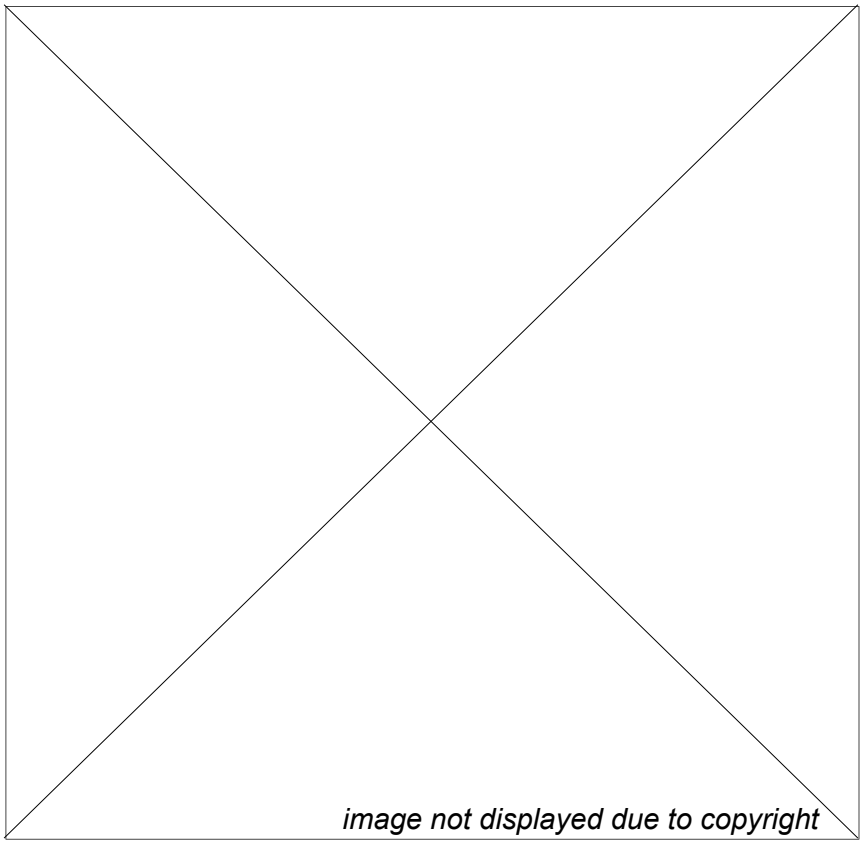
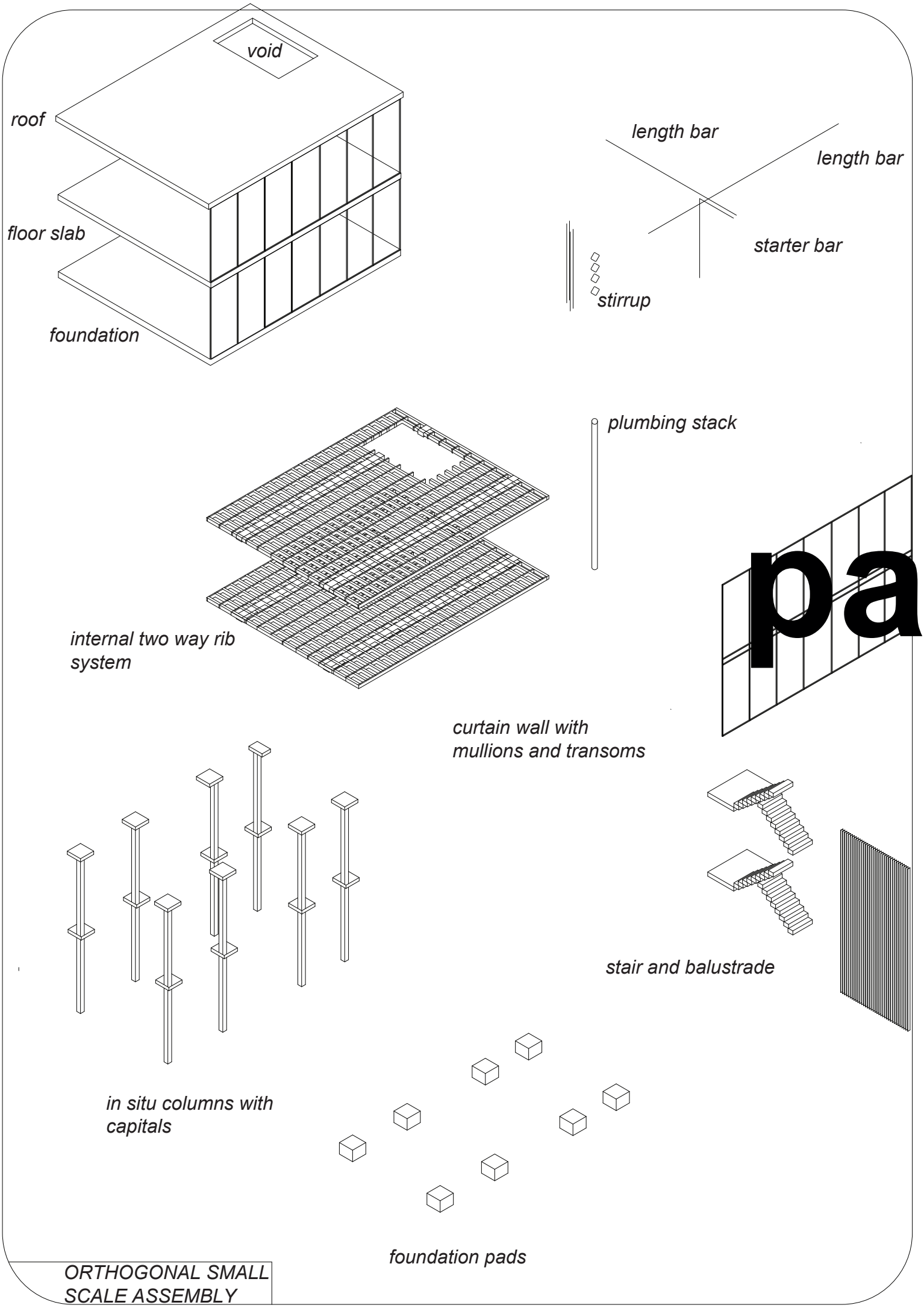


● **1.8** *Le Corbusiers Maison domino, a structral framework which has reduced modernism to a modern aesthetic which proioritises aesthetic over structural function.*

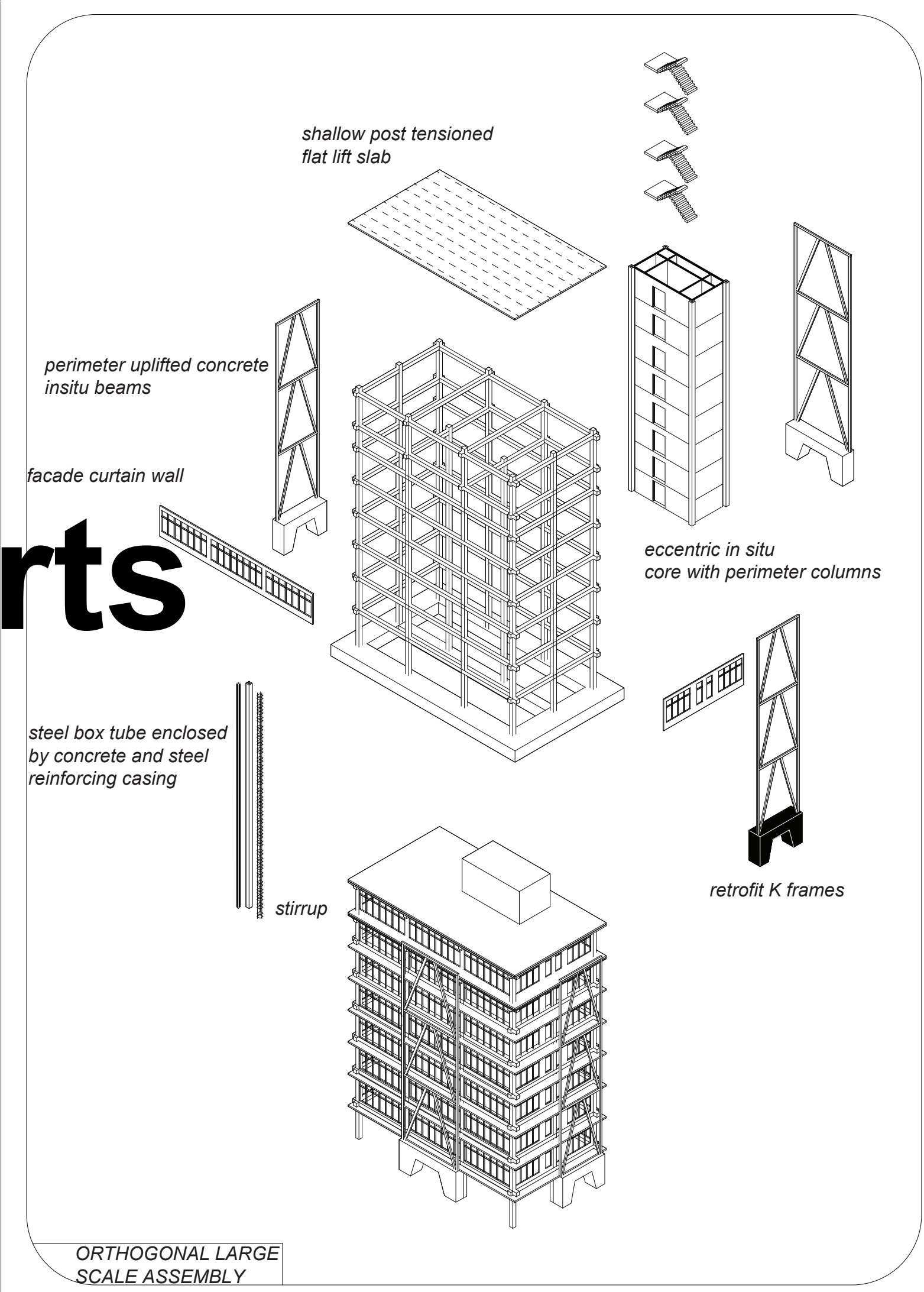
ern aesthetic which prioritises aesthetic over structural function and expression. *T*he new technologies, and a culmination of other nuanced socio-economic factors of the early 20th century, incentivised an attack on ornament by the modernists. Typically buildings consist of orthogonal beams and columns rigidity fixed, to negotiate gravity and the bending moment created; shear walls are used to negotiate shear forces created by multi directional lateral forces, seismic and wind. The domino house is not as architecturally honest as some would presume (although this is not its primary function). It is important to comment on how the vertical columns provide limited lateral bracing, and to achieve a moment frame with the slabs, significant reinforcing would be required to achieve stiffness.

Our methodology of resolving architecture, symptomatic from the capitalist machine *efficiency,* is to use forgo expression of structures as an architectural solution, instead opting for proprietary items, because they are cheap(er). Contemporary practice has also established a clear barrier between engineer and architect, adverse to previous generations where the architect was also the engineer, the psychologist a philosopher. Architects are generally consumed by programme and shape where engineers are focused on 'mathematic firmatas'[22]. This divide between practitioners has resulted in a higher degree of speciality, affecting the alliance of ornament and structure. There lies a certain richness when structure is used as architecture[13]. The diagrams • → dissect the exported modernist style: S scale being the Maison Domino, and the L scale, as the R house, a building based of the exported colonial modernist principles which Chapter II will later cover.

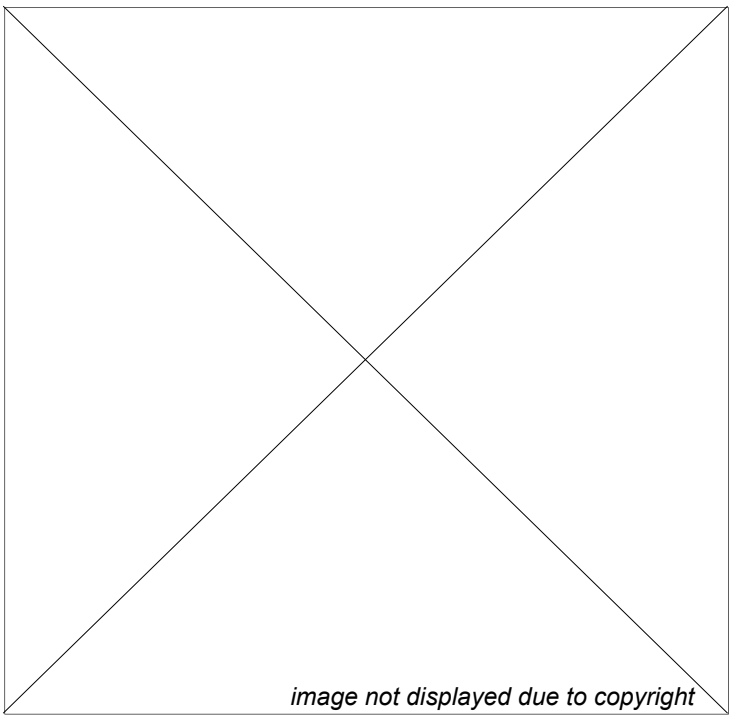
What have great precedents done? Jorn Utzorn's Sydney Opera House is a 20th Century precedent that showcases analogue optimisation. In later chapters we will discuss similarities between the simulated spanning results with BESO and the Opera House's bending moment concourse beams 1.11 • → designed by engineering firm Arup to span an impressive 49 meters[23]. Achieved through a changing profile: at the ends the concrete profile resembles a U shape compared to the mid span which profile resembles a T. We see parallels to Peter Rice's Gerberette's at Paris' Pompidou 1.10 • → in which the customised profiles change relative the extent of bending moment or shear calculated to exist under loading; this is done by changing the



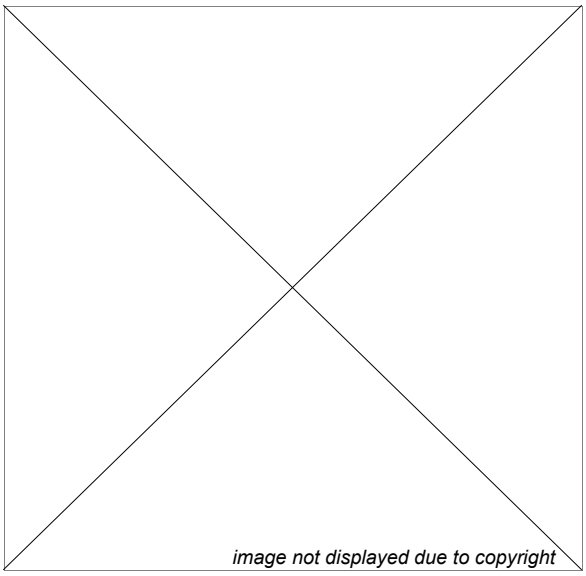
ORTHOGONAL SMALL SCALE ASSEMBLY



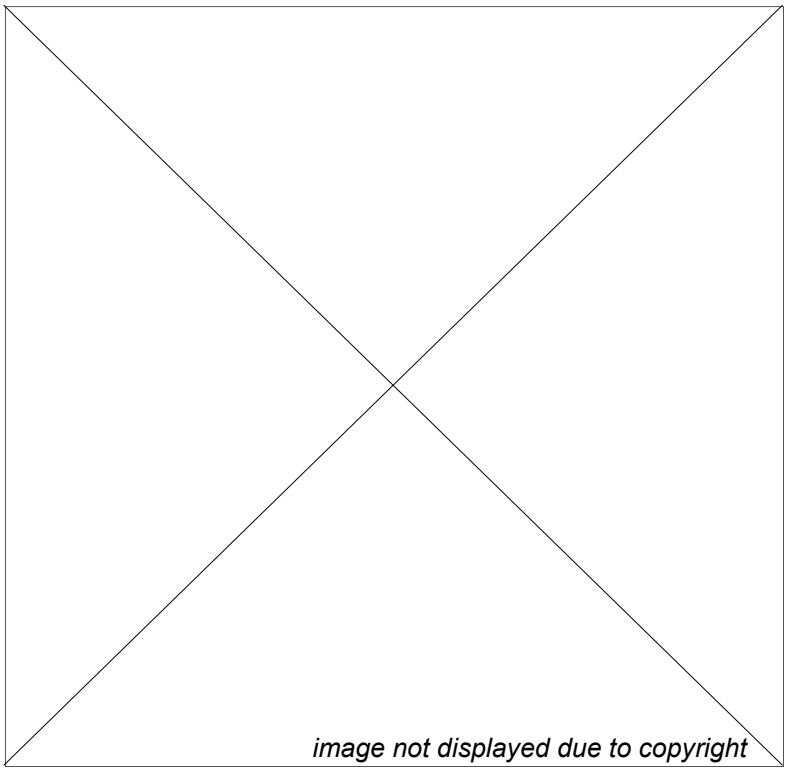
ORTHOGONAL LARGE
SCALE ASSEMBLY



● **1.11** *Arups concourse concrete beams spanning 49m .*



● **1.10** *Peter Rice's Gerberrette's at the Paris Pomp*

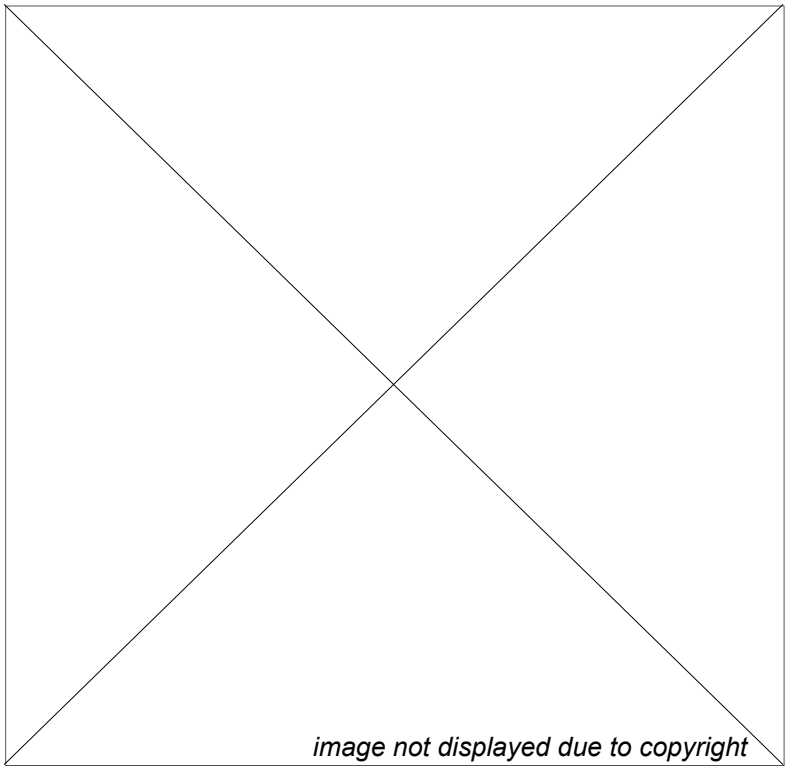


● **1.9** *Frei Otto documented a Texan monolith operating in pure compression in Gestalt Finden.*

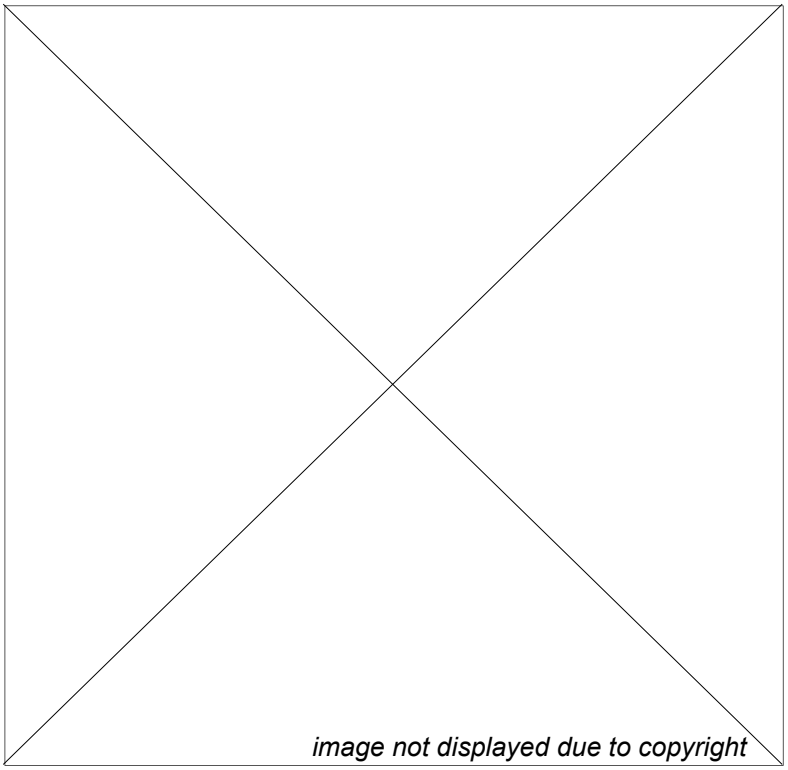
extents of webbing to take shear force and flange to take bending moment[24]. The profile of both beams resembles bending moment and shear diagrams. It is also no coincidence that both gerberette and concourse beam were cast items, liquid steel in the case of the Gerberette, and concrete for Utzorn — both moulded to liberate oneself from 'the standard industrial language'[25]. Frei Otto and Bodo Rasch's documentation of funicular monoliths existing in nature 1.9 • ← in manifesto styled book, *Gestalt Finden*, finding form, correlates to Arup's work, for the spanning monolith maintains its shape as material that is not actively engaged in compression decays away thus, Otto's flaneur observation of the spanning Texan monolith.

Robert Milliart's bridge design will inspire chapter IV. The Schwandbach bridge near Hinterfultigen, 1933, 1.13 • → was a synthesis of a compressive bottom chord arch, vertical struts which up prop the deck – all being tied together, unified to effectively carry load, like a truss. Every item is a part of the load carrying necessity, rather than the deck being superfluous which allowed the bottom chord usually heavy and cumbersome, to be light [26]. Tried as an entire system, the form responds with elegance. Milliart's Mushroom floor for the Giesshuebel warehouse in Zurich, 1910, 1.14 • → meant the exposed column capitals could sit connect to the concrete slab without beams increasing usable space. Chapter II, an anatomical study of the standing, and III, the anatomical study of the spanning — the findings will suggest that the combination of an arching floor, and the integration of columns into the floor and beam system will improve a multitude of issues: service room distribution, fire rating, lettable space, material and cost reduction. Form and structure are considered together, not 'because of an a priori architectural concept'[27]. Nature's structural taxonomy is extremely efficient, implementing natural geometric strength with material efficiency: folding, vaulting, ribs, inflation, pneumatics (humans are pneumatic), to disclose a few.

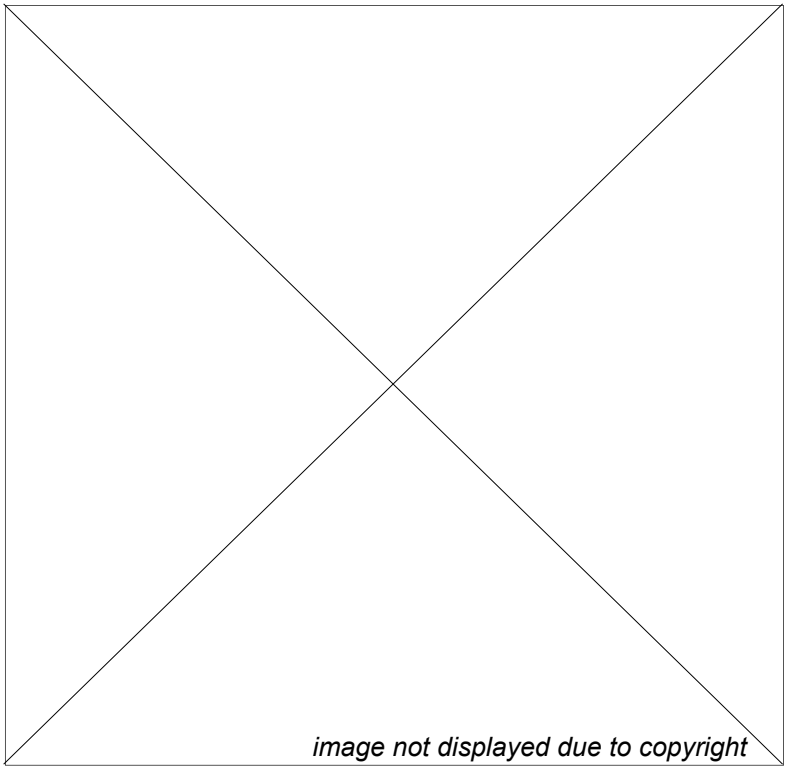
A sacristy of material in architectural history has incentivised geometry to perform more efficiently. BESO forces material economy (it is the lens of BESO). **Material economy** became essential when Mussolini's fascismo banned the importation and use of reinforcing in concrete construction in 1939[28]. The resulting change in concrete construction for practitioners like Engineer Nervi and his contemporaries forced new solutions such as funicular concrete arch solutions to negotiate an inability to resist tension through pure compression geometry



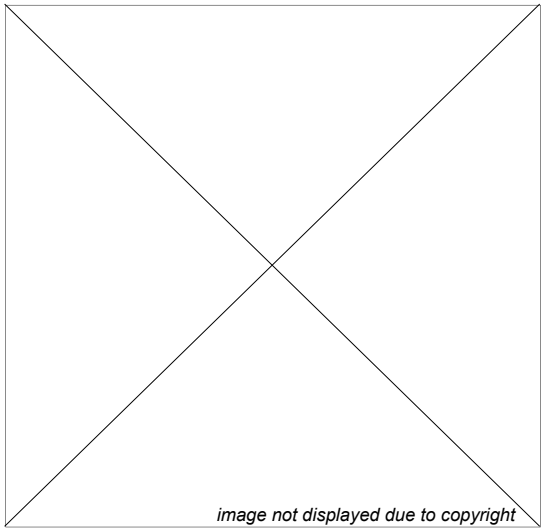
● **1.12** *Robert Milliart Salginatobel Bridge compression bridge,1929.*

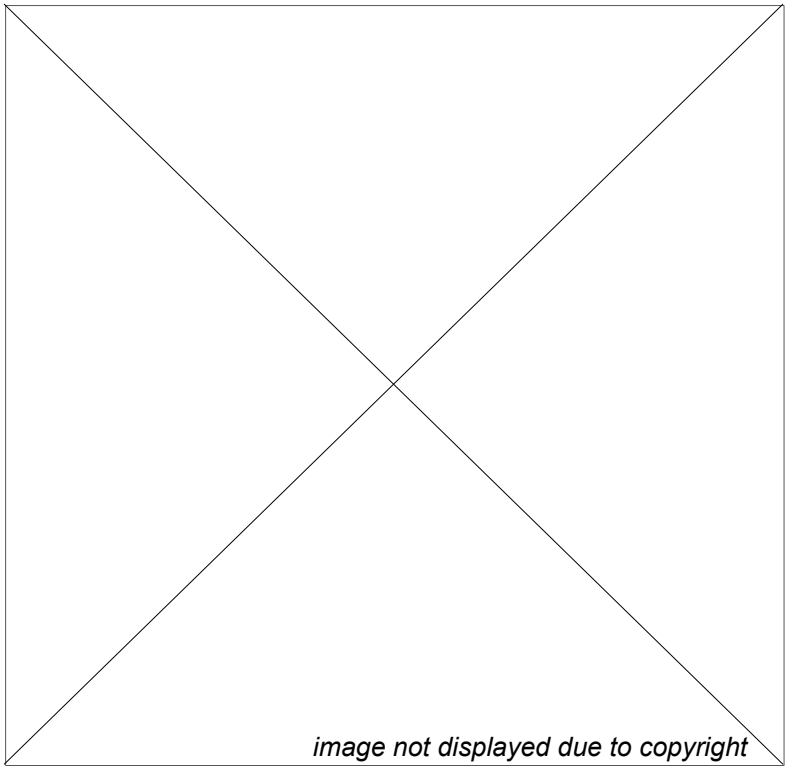


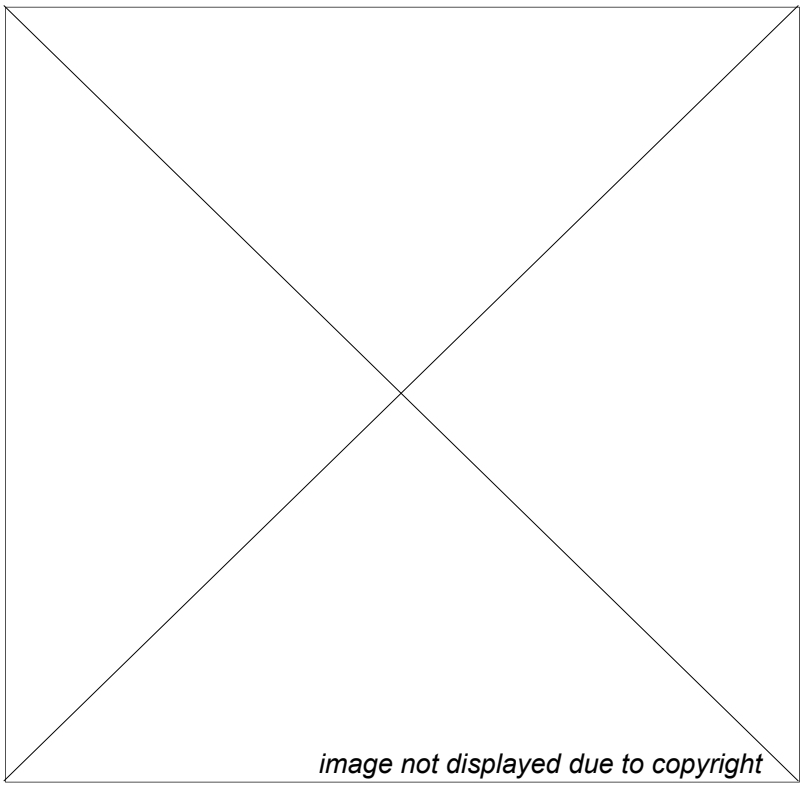
● **1.13** *The Schwandbach bridge near Hinterfultigen, 1933*



● **1.14** *Milliart's Mushroom floor for the Giesshuebel warehouse in Zurich, 1910*





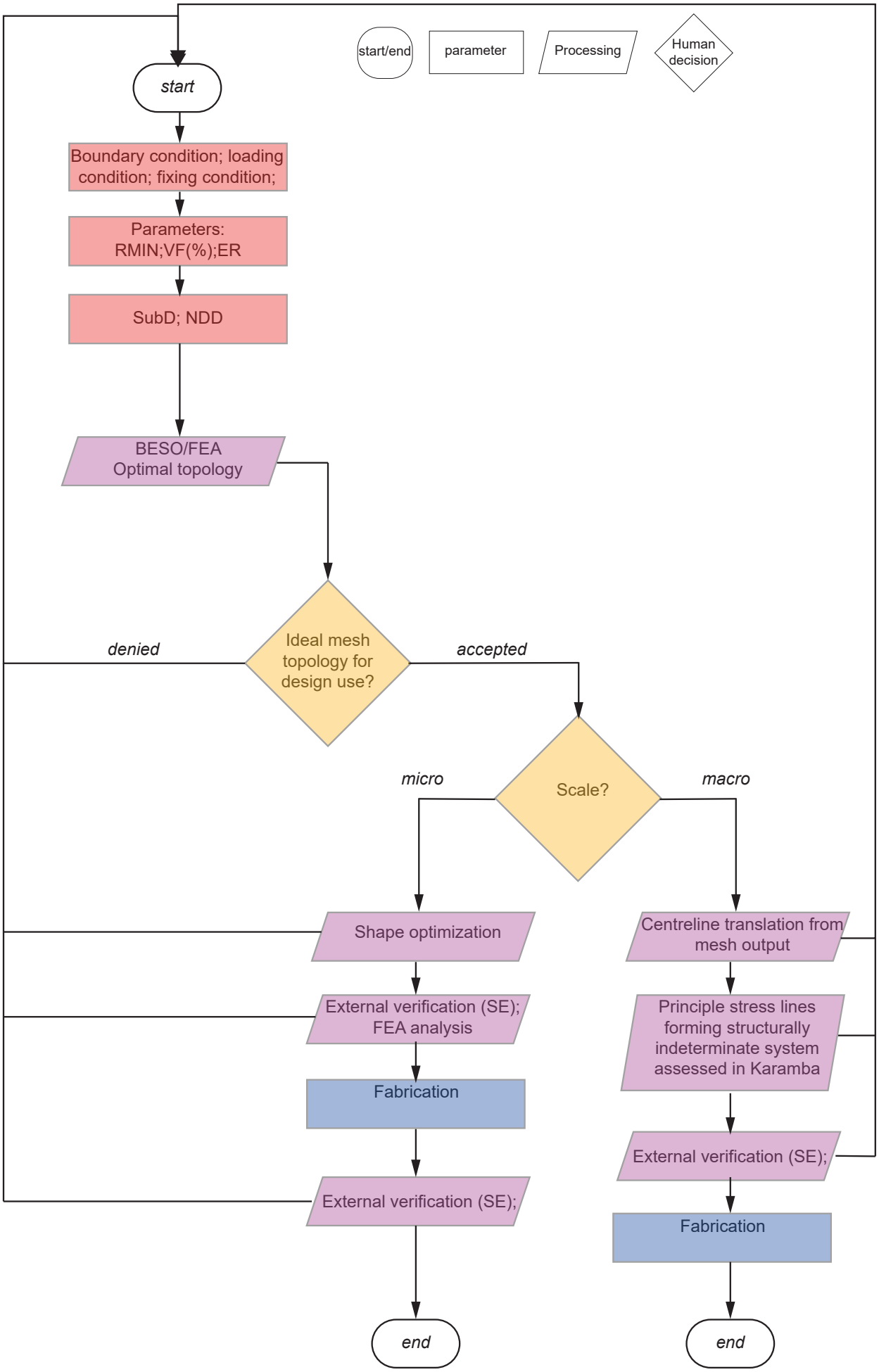


- **1.14** *Orveito aircraft hangers 1935.*
  1.15 *Gatti Wool Factory. Nervi. 1952.*
  1.16 *Akutagawa River Side Building in Takatsuki Japan 2004.*

(later findings in chapter 4 will conclude similar results). Exemplified in a series of 8, 36 wide x 100-meter-long spanning aircraft hangers constructed from compression arch-vault in-situ concrete with no steel reinforcing (Nervi has been so proud of his engineering feat, that, following the retreating Germans demolition of the war aided structures from the advancing Americans – Nervi had wanted to crawl under the structures and die with them![29]). Another methodology incentivised by restrictions was composite concrete terracotta tiles and high-grade plaster grouting, known as Senza Impiego di Ferro (S.I.F), applied to the underside and topside of concrete slabs to provide tensile strength. The Tobacco factory floor system and the Gatti Wool factory *figure* 1.15 • ←, using the Nervi system of movable formwork, was another example of moving away from tradition means of orthogonal construction by using fluid isostatic ribs which align to the principle bending moment stress trajectories making geometry work more cleverly and harder. An employee of Nervi, Arcangeli, used classical plate theory deriving that a 2d plane subjected to normal forces developed two families of curves tangential to the bending moment trajectories[30]. Thus, if the ribs follow the isostatics, the structural performance was found to be the same as a volume without volume reduction. In a 3-dmensional sense BESO works the same, but deducing critical stress trajectories in 3-dimensional space[31]. Nervi's association to Engineer Danuso suggests that analogue form finding was used with photoelastic stress visualisation, where clear glass is stressed, and the cracking is exposed to a polarised light to reveal colours of material stress distribution and principle stress.

Nervi's slabs were a study specific to a micro element within a building, questioning typical slab plate theory. Commercial scale buildings in the last decade have become more structurally efficient considering a macro scaled diagrid structure: the diagonal members placed around the periphery of the structures being neither a column nor a beam, nor a brace or strut, ensures gravity and lateral loading conditions are resolved and continuous and uninterrupted, flowing down to the ground. Inherently, columns wish to participate in lateral resistance, and a brace wishes to participate in gravity transfer; in a diagrid, the structures are neither vertical or horizontal, allowing a more efficient structure as members perform all tasks (remember the domino house) [32].

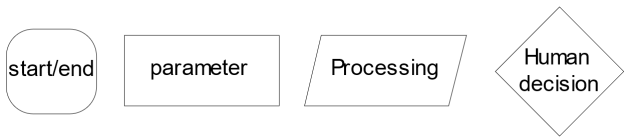
Moving to the 21st century, Takatsuki, Japan – computational



1.17
computational schematic

morphogen ESO in the architectural sphere was first achieved with the Akutagawa River Side building *figure 1.16* • ←. EESO (Extended evolutionary structural optimisation, a variant of BESO) was used to achieve a load bearing facade structural configuration. Live, dead and earthquake loads were simulated with the construction being made out of reinforced concrete and later verified through Elastoplastic numerical analysis based on deflections and cracking patterns[33].

TO can be done through multiple solver processes: Solid isotropic material penalisation (SIMP), Bendsøe and Sigmund, 2003; soft kill option (SKO); Computer aided optimisation (CAO)[34]; the homogenization method (Bendsøe and Kikuchi, 1988), the evolutionary structural optimization (ESO) , Xie and Steven,1994; and the medium solver of this thesis: BESO through the Ameba plug-in for the scripting addition Grasshopper, an algorithmic node based interface, to the free-form modelling software Rhino (bi-directional evolutionary structural optimization, Huang and Xie, 2008) [35]. Additional stress line analysis solver millipede is used in Chapter IV. All work is in Grasshopper for Rhino. The basic procedure of BESO is described right by the computation schematic. The key to the schematic is here • ←:

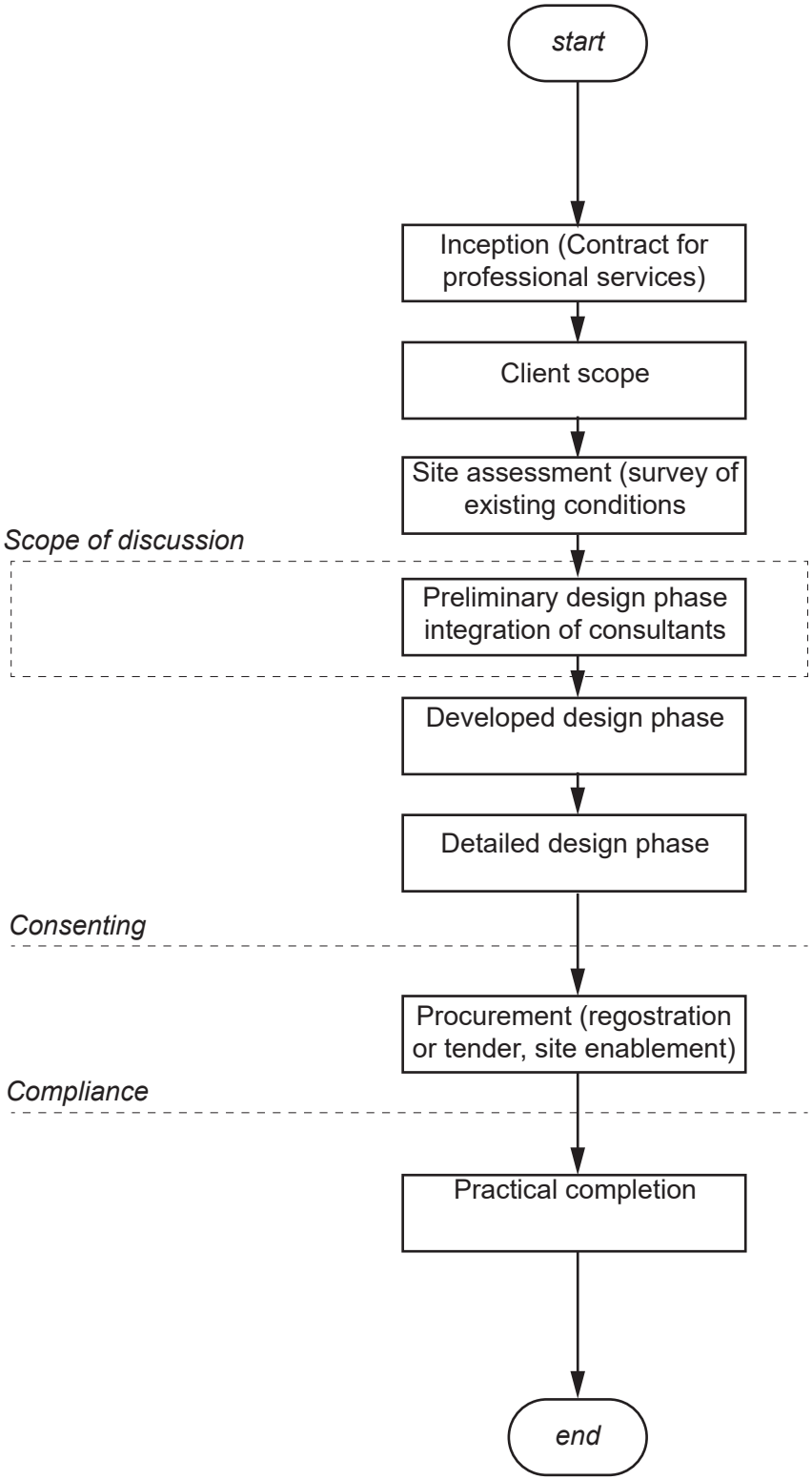


The detail of loading conditions is rather limited, given the architectural nature and not an engineering discourse. Verification is also limited given the BESO. The **loading conditions** are listed as:

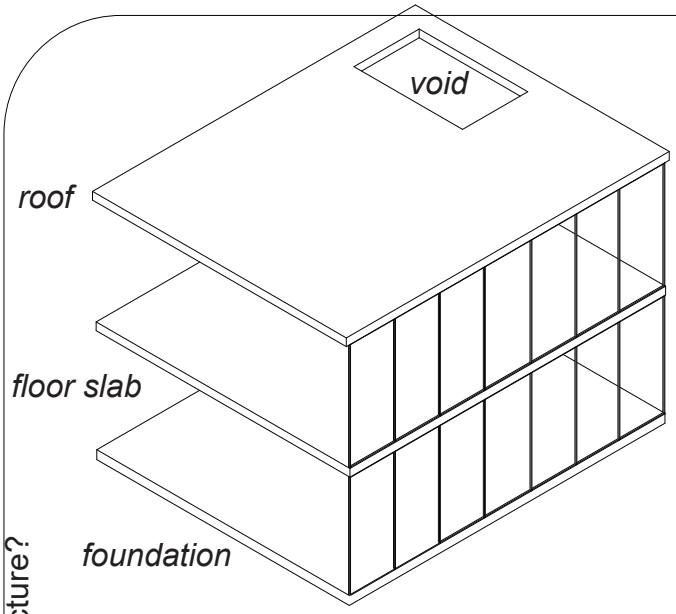
1. The structural **scope** is limited to simplified loading conditions: Gravity loading is always implied computationally, deadload, MEP, and live loading is simplified but accounted for in singular nondescript loading where only magnitude (direction) is described.
2. Lateral loading is differentiated into: wind loading as a surface pressure of a tributary area, but do not consider wind conditions such as the build-up of positive and negative pressures, uplift suction – and seismic loads which do include self-weight inertia, but do not include building frequency.

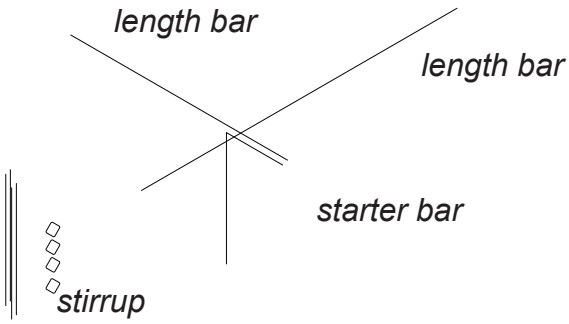
In rounding out this essay, the future 3D printed typologies are possible with the 6 axis 3D printing which currently has a multitude of

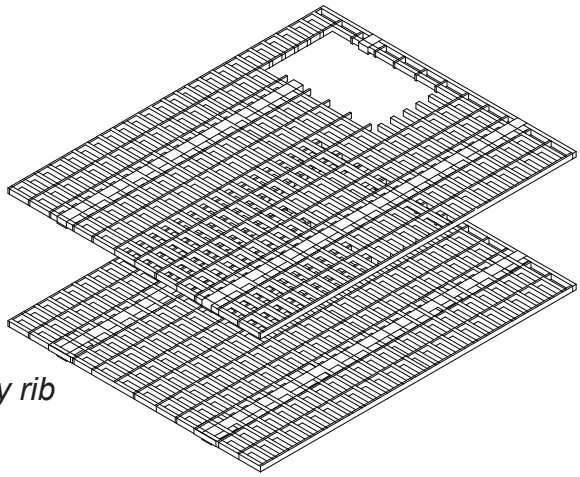
materials from steel (typified by MX3D bridge spanning 12.5m over an Amsterdam Canal), concrete, clay and plastic. Current companies are constantly improving the scope of printing ability, improving scale, printing speed (it should be noted the bridge took 6 months, hardly fast!). Companies COBOD boast a large printing area space of 10m high x 45m x 12m; ETH HIB lab in Zurich having multiple robots simultaneously print within one space, in controlled environments internally, and others playing with wireless arch additive manufacturing to print reinforcing[36]; others exploring mediums such as mycelium or concrete with steel shillings to achieve tension resistance over tradition streel reinforcing bars. The shilling density changes in location of the item, thus compressive areas seek less reinforcing whereas tensile areas seek more density. Such fabrication methods depend on which element. For spanning items, in-situ formwork is required, thus non orthogonal formwork would be required to some degree given a non-orthogonal geometry, formwork such as GFRC. Such findings were proven by Professor Mike West at Calgary University whose work with bending moment resisting beams required singular reinforcing bars under stress loading[37].



1.18
the scope of this thesis lies within the preliminary dsign phase

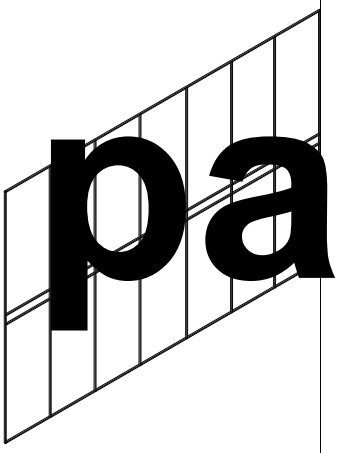




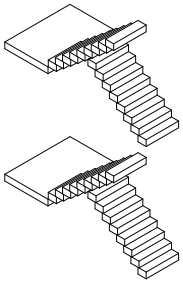


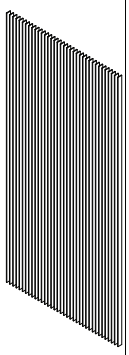
internal two way rib system

plumbing stack

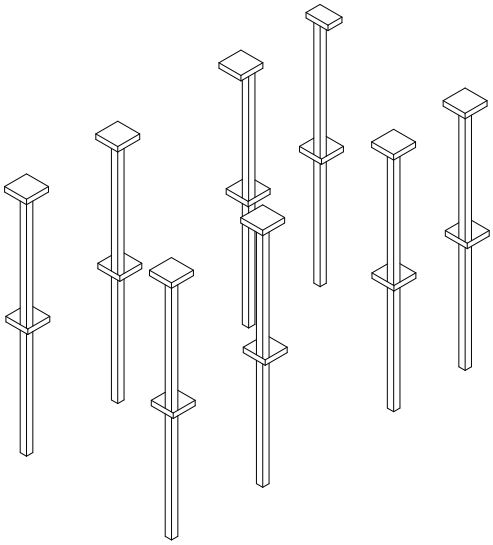


curtain wall with mullions and transoms

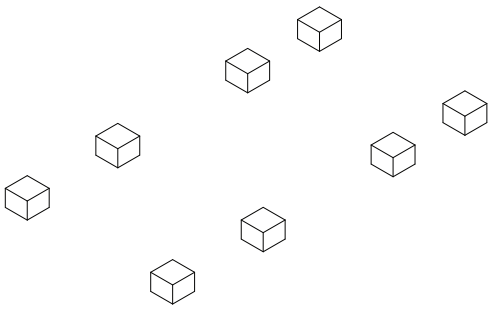




stair and balustrade

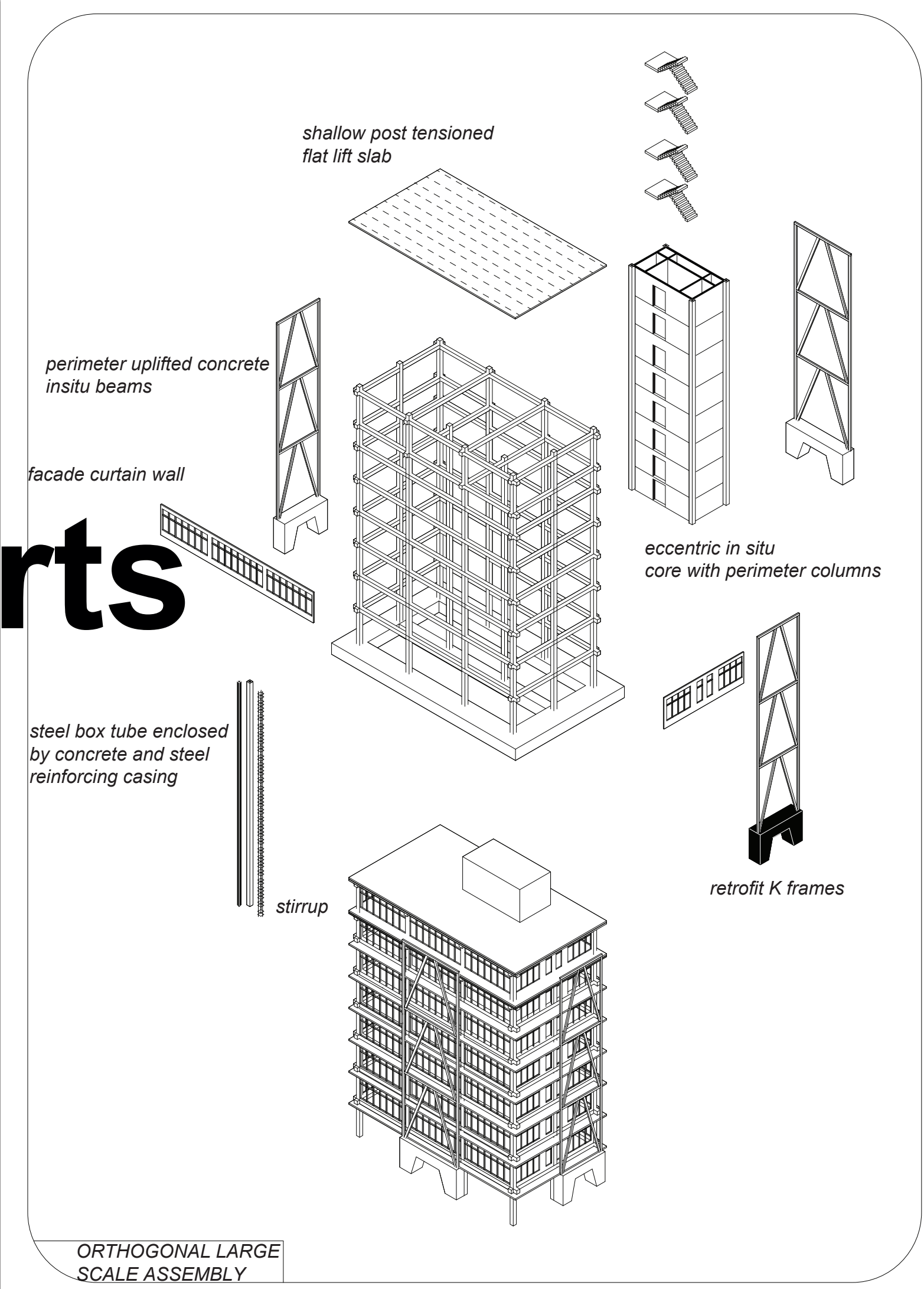


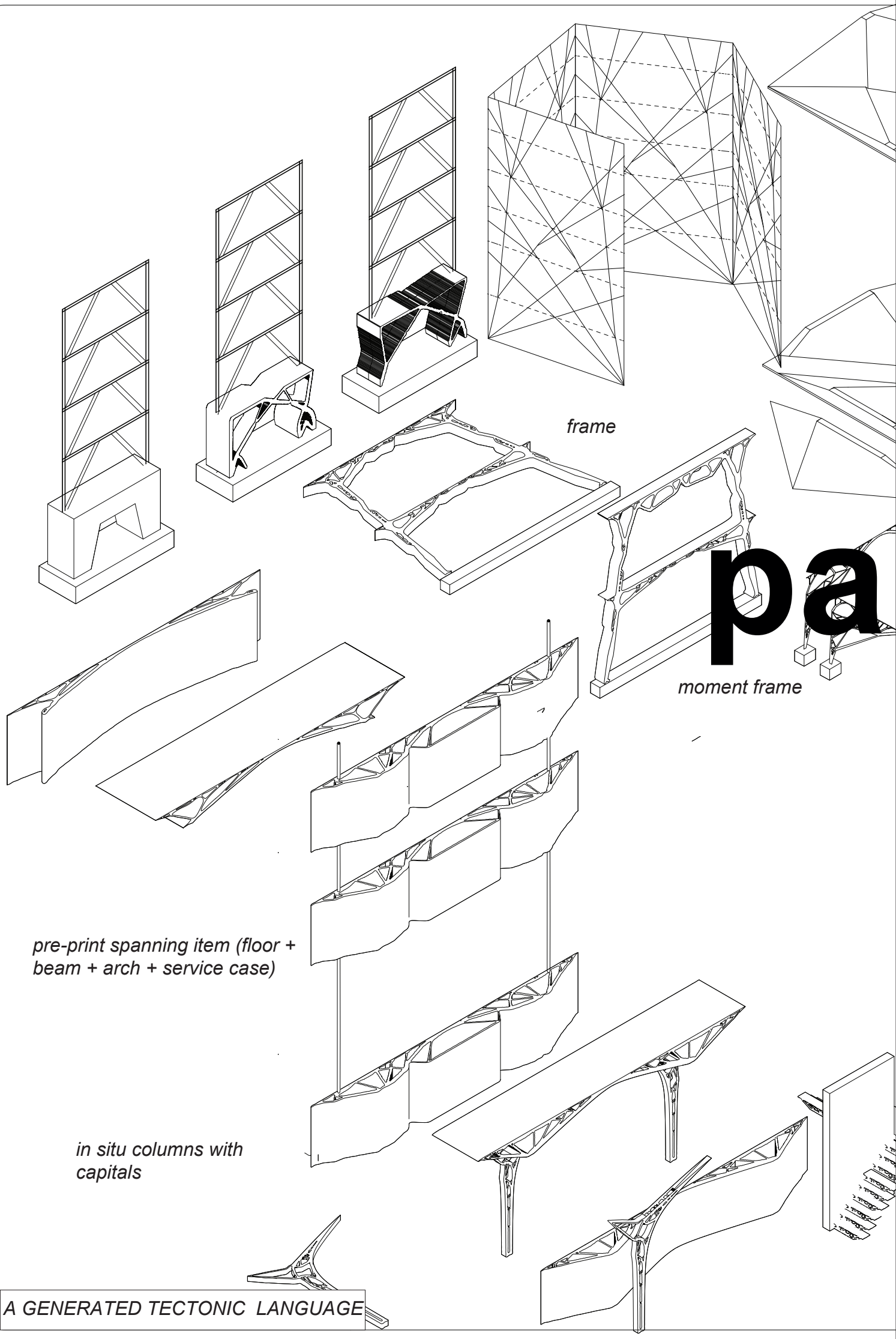
in situ columns with capitals



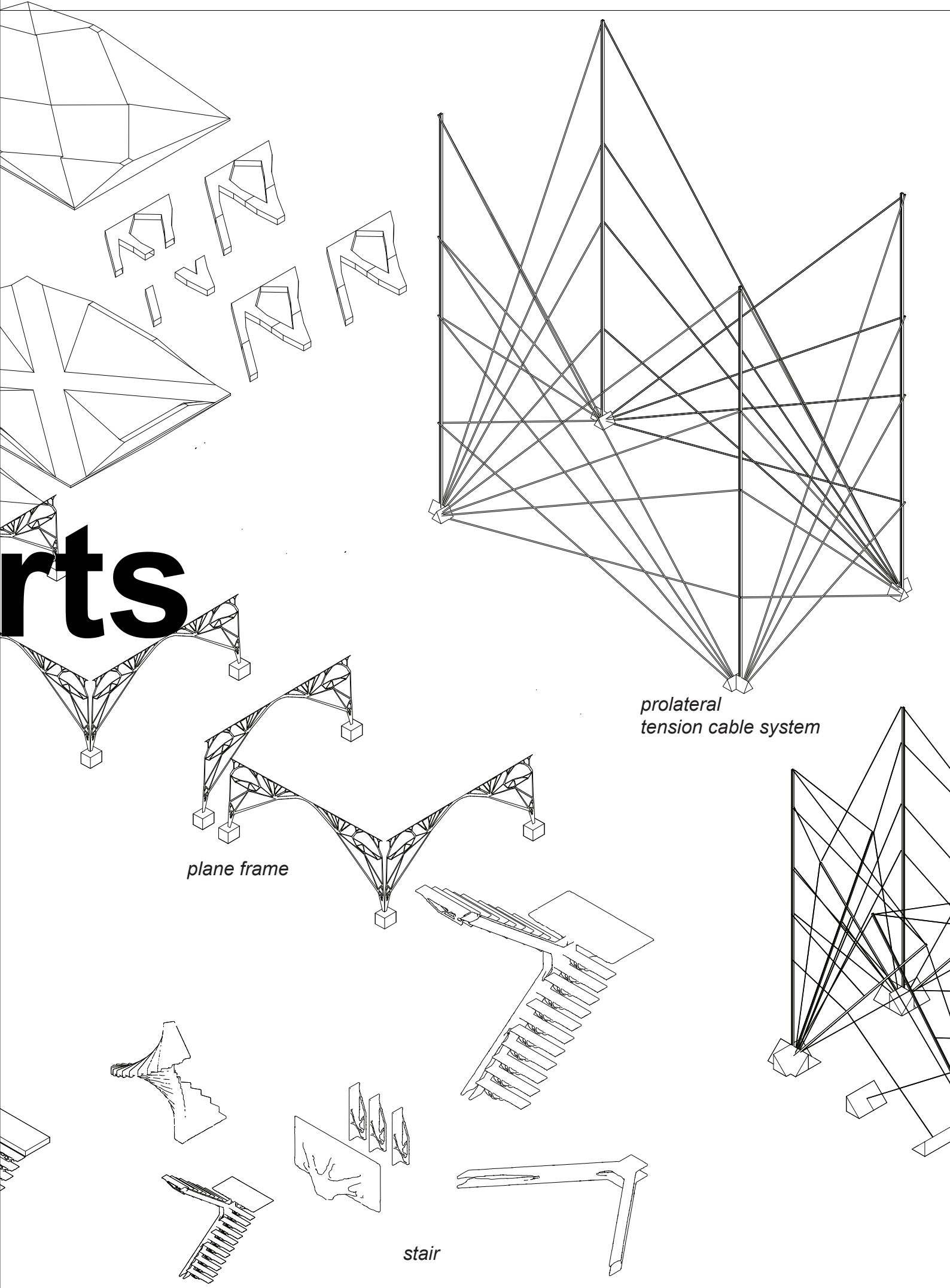
foundation pads

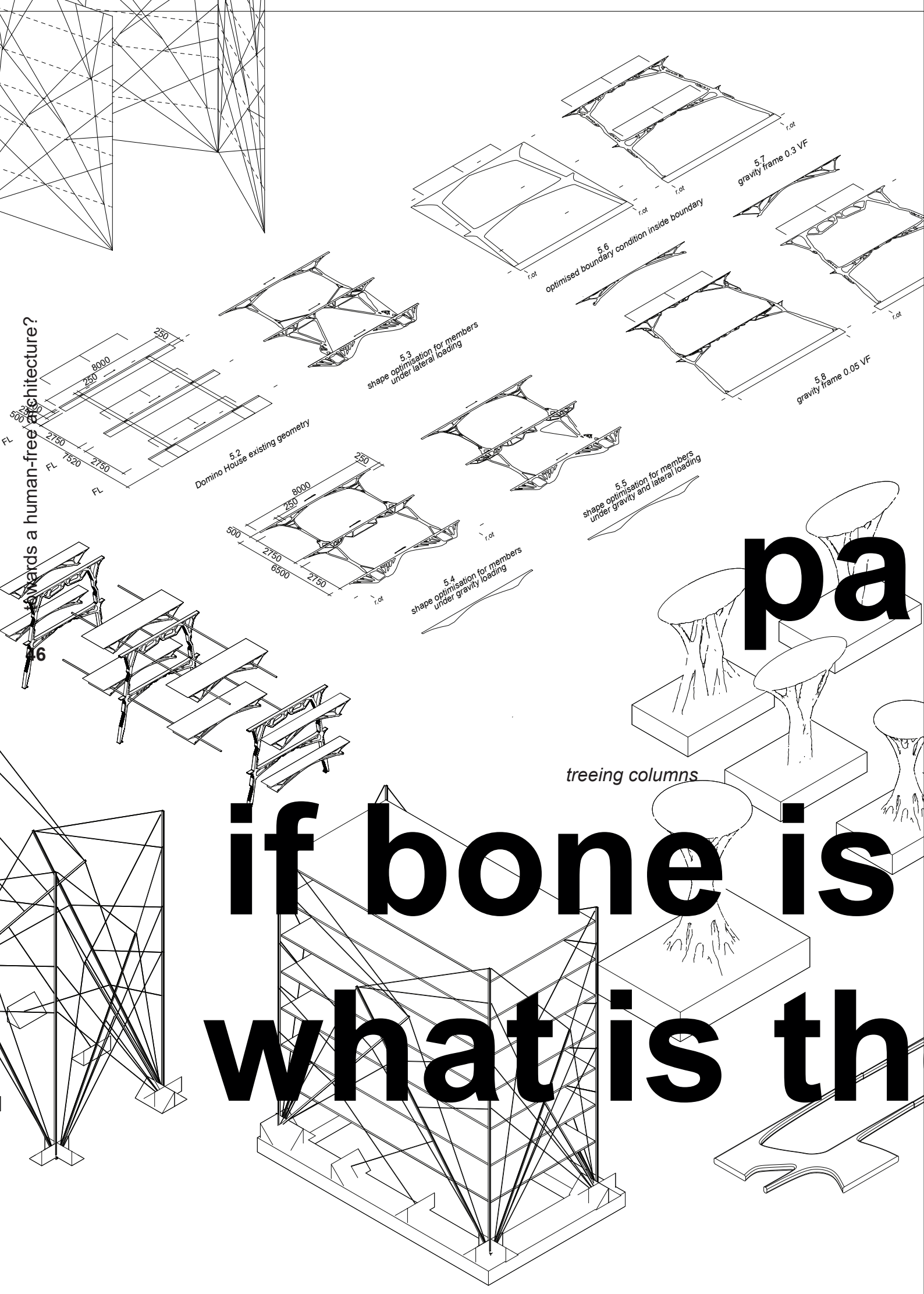
ORTHOGONAL SMALL SCALE ASSEMBLY


shallow post tensioned
flat lift slab
perimeter uplifted concrete
insitu beams
facade curtain wall
rts
eccentric in situ
core with perimeter columns
steel box tube enclosed
by concrete and steel
reinforcing casing
stirrup
retrofit K frames
ORTHOGONAL LARGE
SCALE ASSEMBLY



A GENERATED TECTONIC LANGUAGE


rts
prolateral
tension cable system
plane frame
stair

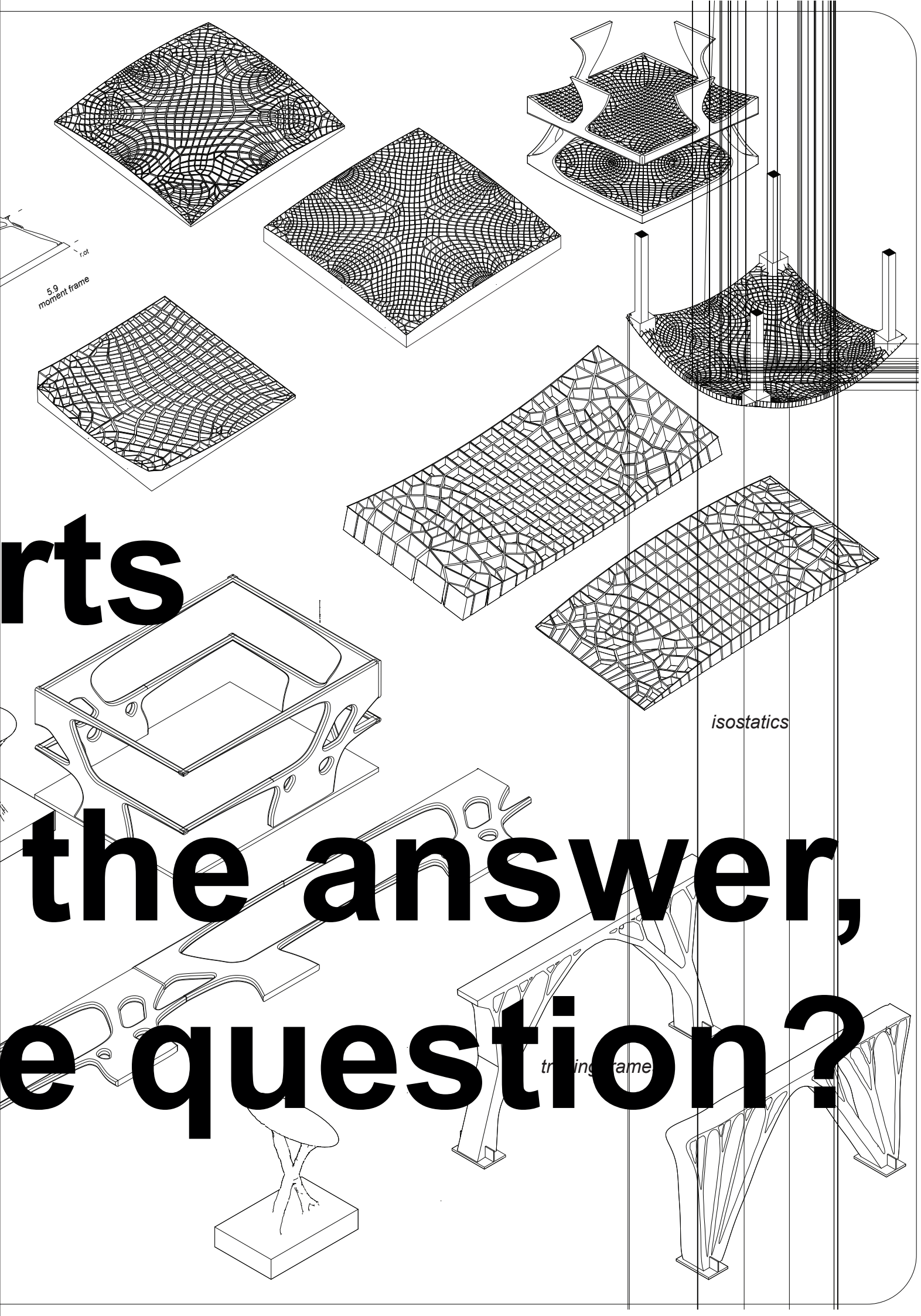


pa

treeing columns

if bone is

what is th



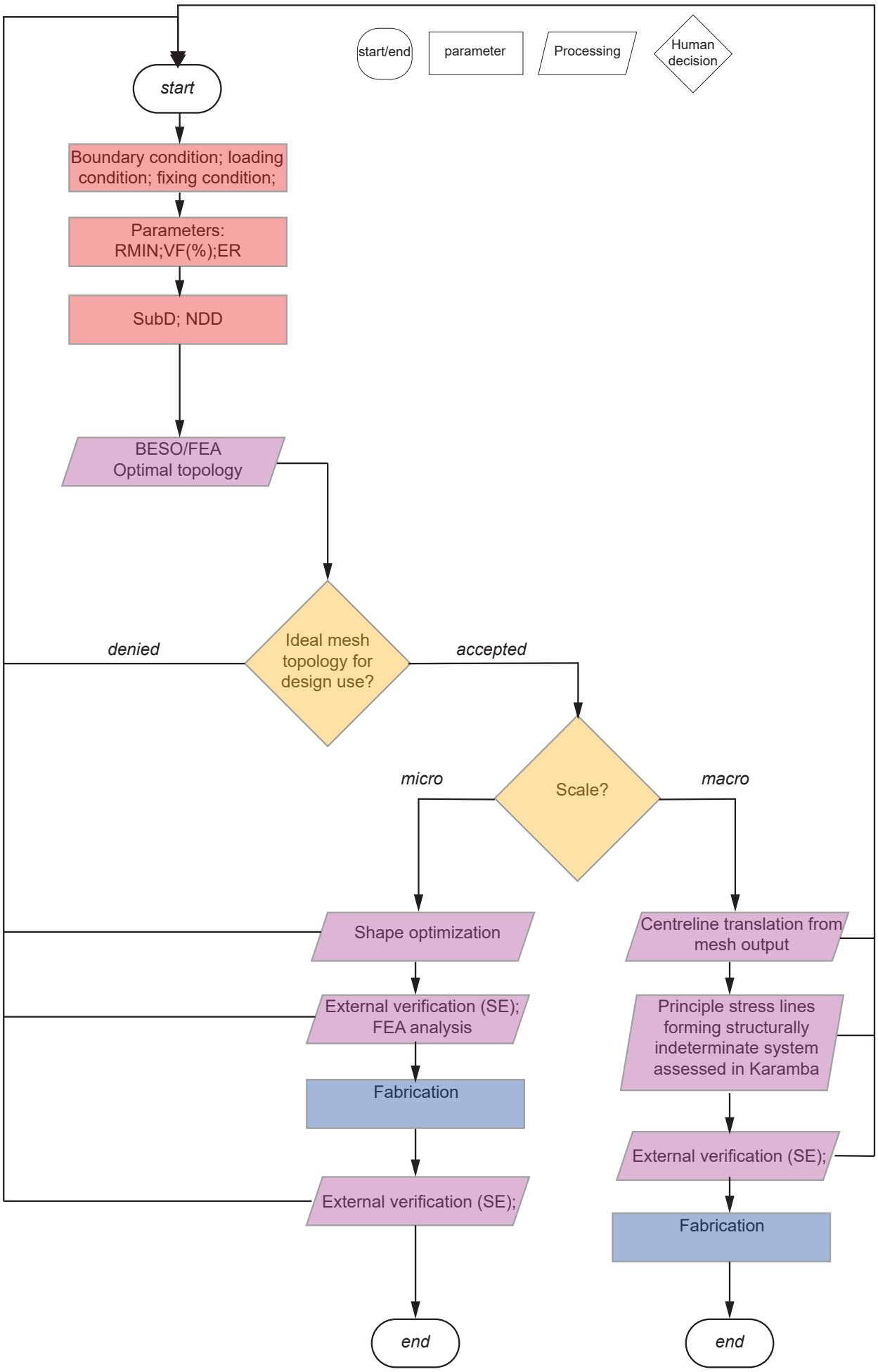
rts

the answer,

e question?

CHAPTER II

generation of standing items



2.0
computational schematic

Chapter II is concerned with standing items. BESO applied to an envelope (3 dimensional) or plane (2 dimensional) generates a structural *scheme* responsive to the envelope or plane. In other words, if a façade is concave, the resulting structural topology incorporates the curvature. This is seen in 2D studies 2.1 - 2.28• → with varying floors, loadings, building ratios, and in 3D with 2.26• →. It is important to note the term scheme mentioned previously, as a scheme is a computation aid to the architect and engineer that shows how loading could be transferred to the ground. 2.0• ← computational schematic illustrates the process undertaken. Refer to the matrix under each figure for testing specifications. Note the material properties, building ratios (over dimensions), BESO parameters, reduction rate et cetera. The resultants are superstructure of **standing and spanning items**.

The first step in the design of multistorey building, after general F.A.R, height restrictions, is to determine the preliminary structural scheme[38]. This is when the building is 'rationalized' in a conservative sense. The structural grids are generally logical and orthogonal, considering the programme, for example office layouts will acknowledge a 1.5m column interval. With this the design capacity, scope, and aesthetic are pre-determined. The determined structural grid is an extreme burden to change, and thus is often not[39]. Multiple loading responses are added together. Wind seen in 2.1• → , and live and dead load 2.2• → add together to become 2.4• →. Once an overall scheme and relationships are established, FEA can be tested. When **SubD** is used within the script as a parameter 2.18• →, a superstructure shares its material evenly over the plane, rather than when there lies no SubD of volume fraction 2.20• →, mass tends to exist at the base, with less at the top of the plane; the SubD allows each section to be optimized evenly at the set VF, rather than more material at

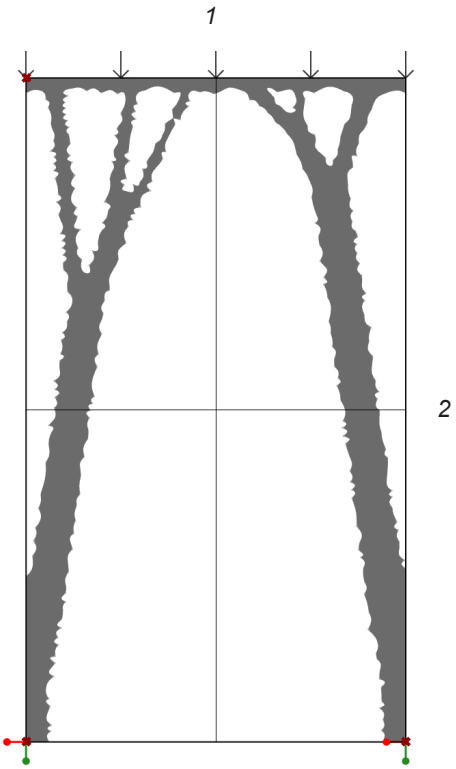


Figure: 2.1 flat plane with no floors

iteration rate: 31

ER: 6%; RMIN: 0.05; VF:10%

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 1h/2w

SubD:no; NDD: no

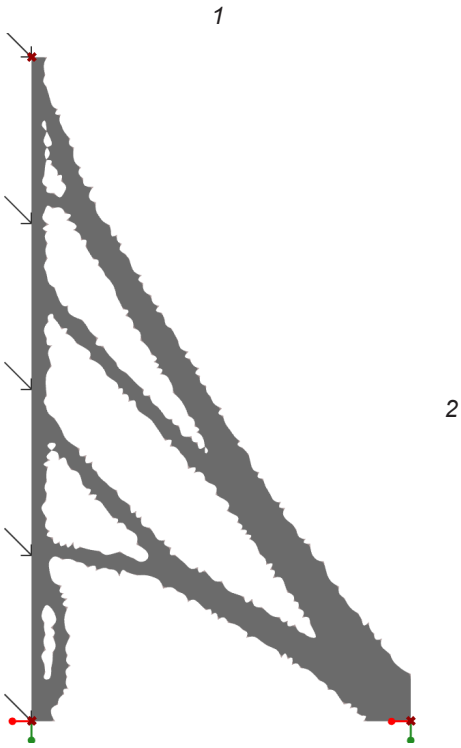


Figure: 2.2 flat plane with no floors

iteration rate: 31

ER: 6%; RMIN: 0.05; VF:10%

fixing type: fixed, 0 translation

magnitude loading: Y and X /-10kN

material: steel; built ratio: 1h/2w

SubD:no; NDD: no

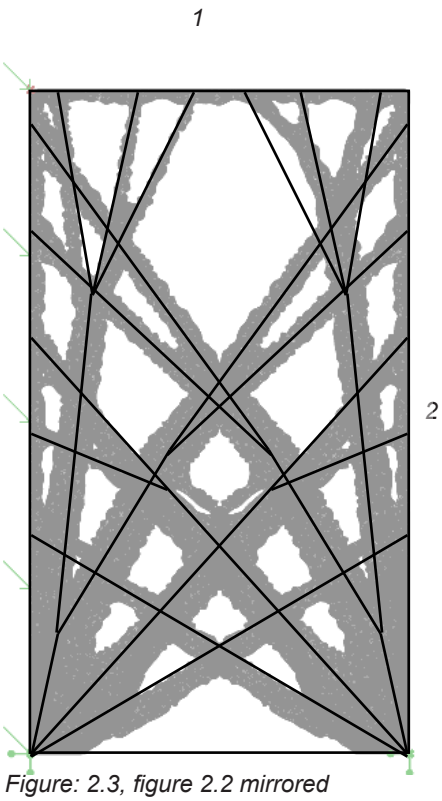


Figure: 2.3, figure 2.2 mirrored

iteration rate: 31

ER: 6%; RMIN: 0.05; VF:10%

fixing type: fixed, 0 translation

magnitude loading: Y and x /-10kN

material: steel; built ratio: 1h/2w

SubD:no; NDD: no

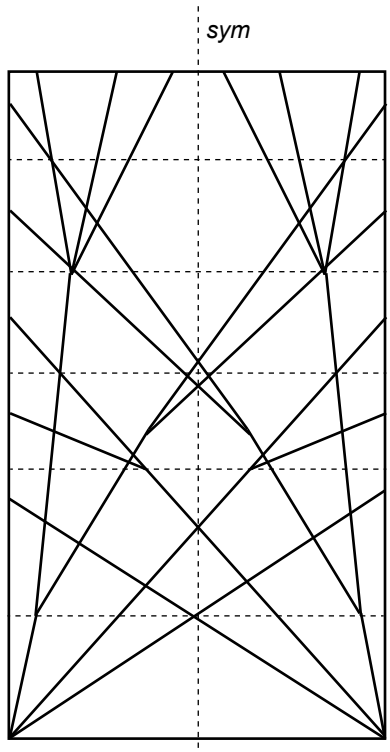


Figure: 2.4, line conversion of 2.3

iteration rate: 31

ER: 6%; RMIN: 0.05; VF:10%

fixing type: fixed, 0 translation

magnitude loading: Y and x /-10kN

material: steel; built ratio: 1h/2w

SubD:no; NDD: no

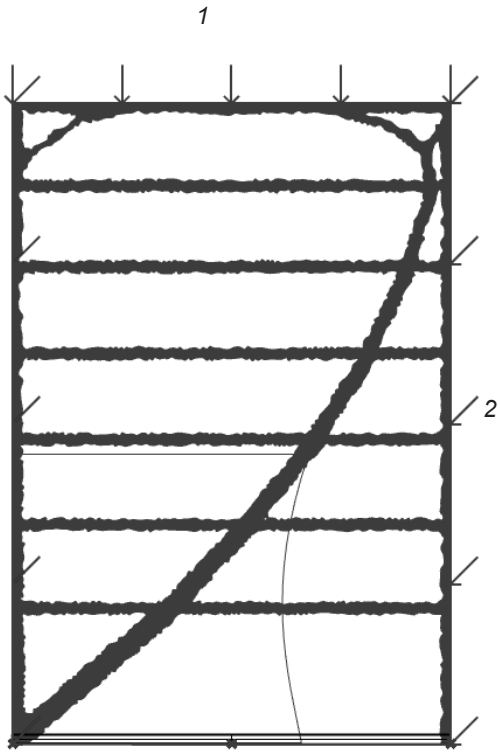


Figure: 2.5 flat plane with floor ND-
iteration rate: 76
ER: 6%; RMIN: 0.05; VF:10%
fixing type: fixed, 0 translation
magnitude loading: Y and X /-10kN
material: steel; built ratio: 1h/2w
SubD:no; NDD: yes, floors

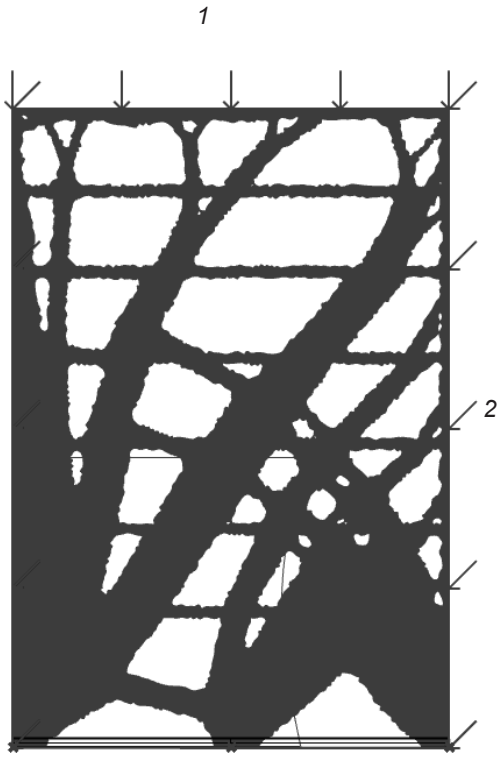


Figure: 2.6 flat plane w/ floor NDD
iteration rate: 56
ER: 6%; RMIN: 0.05; VF:40%
fixing type: fixed, 0 translation
magnitude loading: Z /-10kN
material: steel; built ratio: 1h/2w
SubD:no; NDD: yes, floors

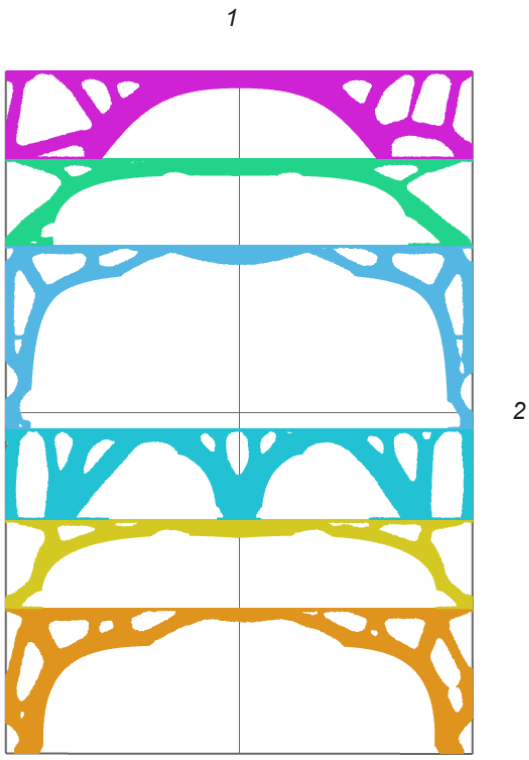


Figure: 2.7 flat plane w/ floor NDD
iteration rate: varying
ER: 6%; RMIN: 0.05; VF:10%
fixing type: fixed, 0 translation
magnitude loading: Z /-10kN
material: steel; built ratio: 1h/2w
SubD:no; NDD: yes, floors

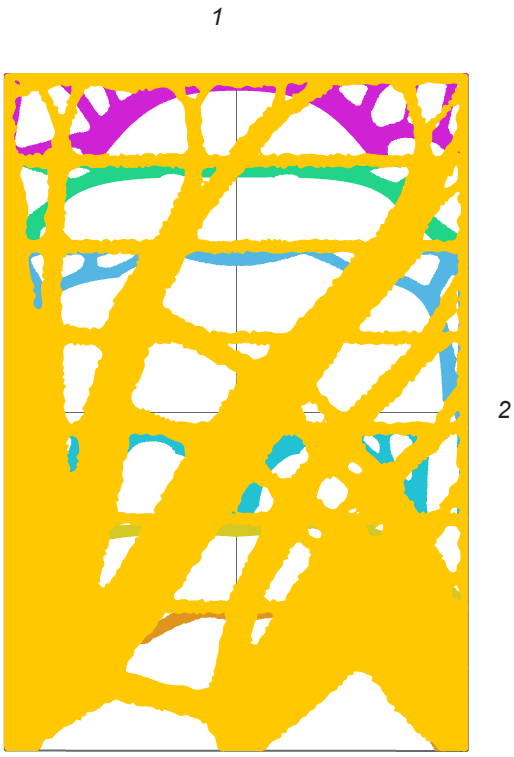


Figure: 2.8 addition of items
iteration rate: varying
ER: 6%; RMIN: 0.05; VF:10%
fixing type: fixed, 0 translation
magnitude loading: Z /-10kN
material: steel; built ratio: 1h/2w
SubD:no; NDD: yes, floors

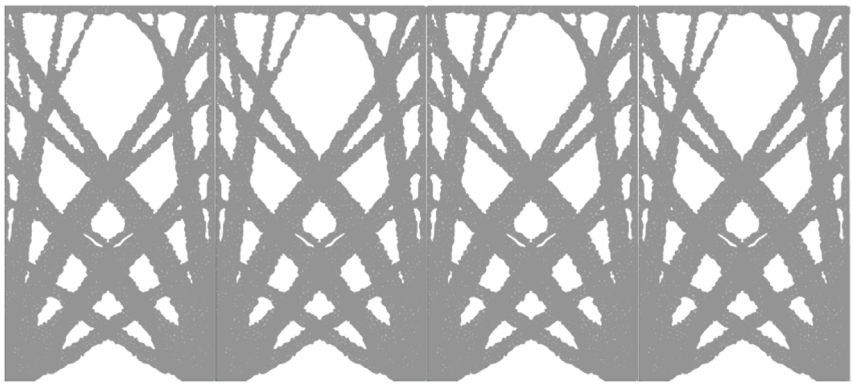
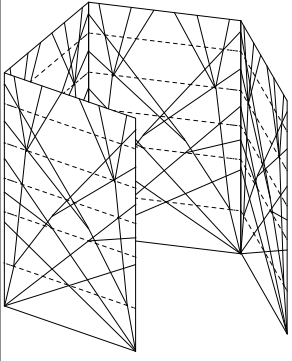


figure 2.3.1
patten logic adapted from Ito Studio model on Omotensando Building Tokyo (2020),



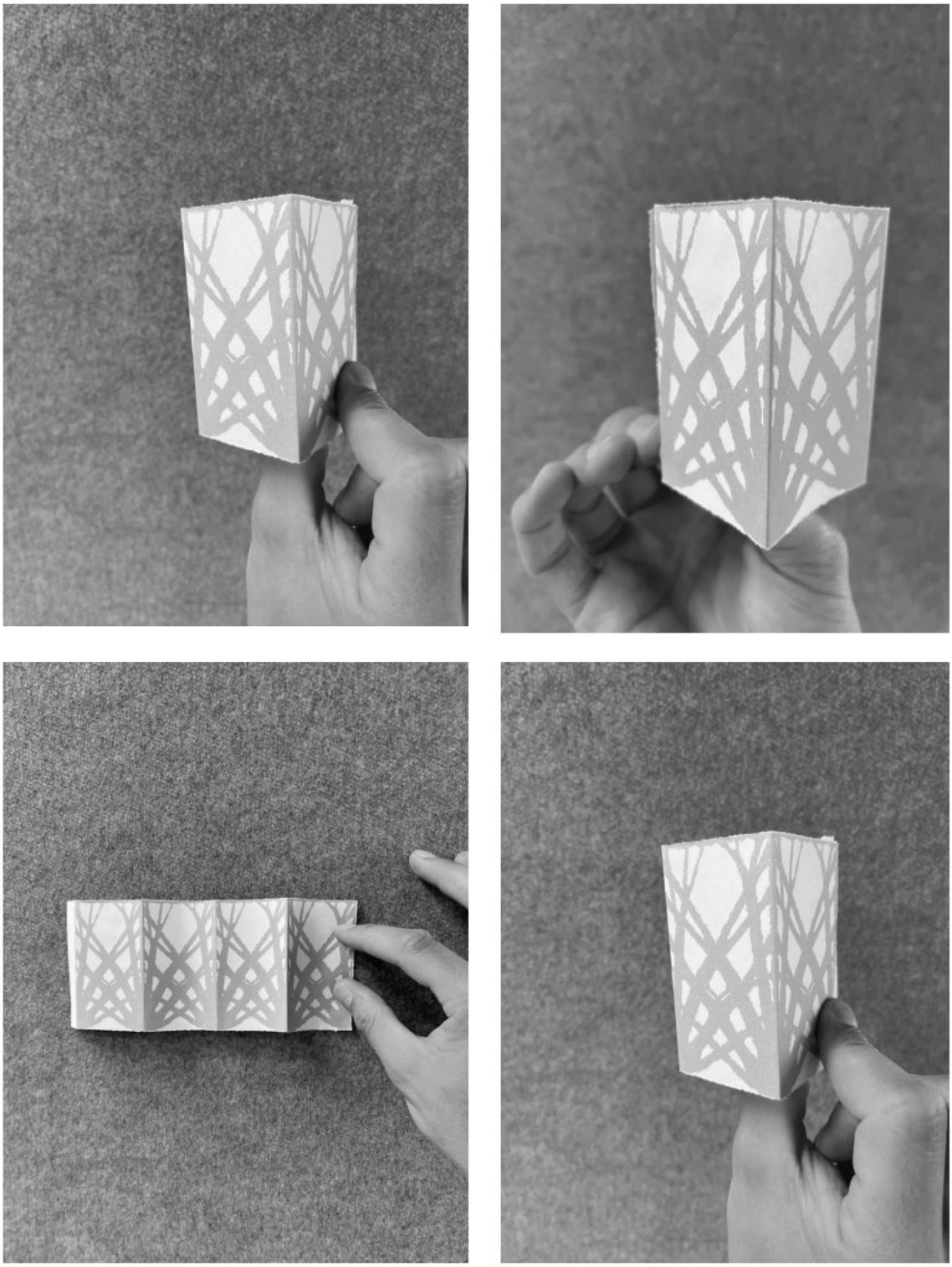
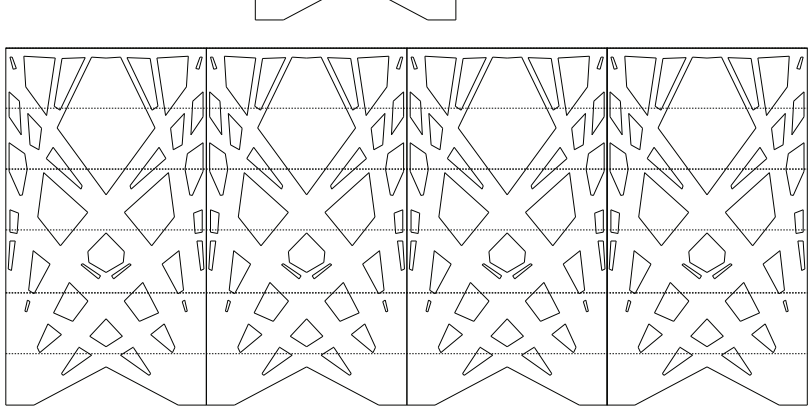
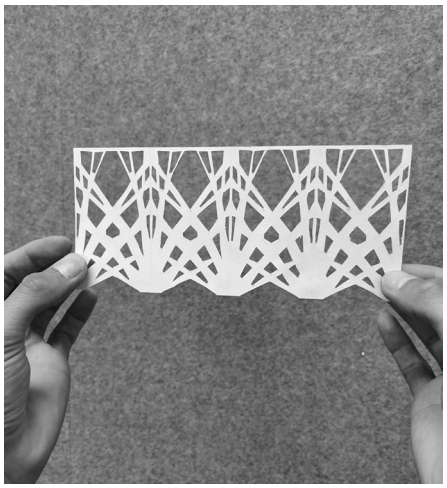
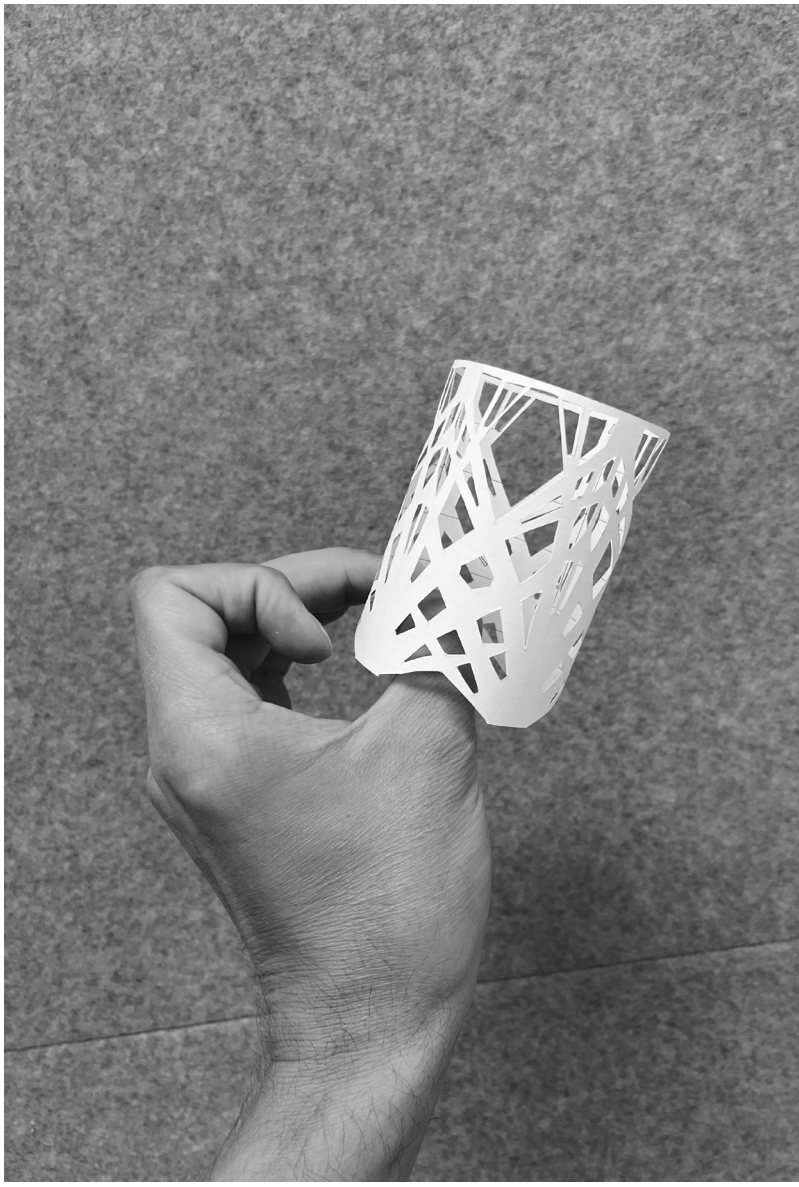


figure 2.3.2
wrapping, a structural draft for the engineer







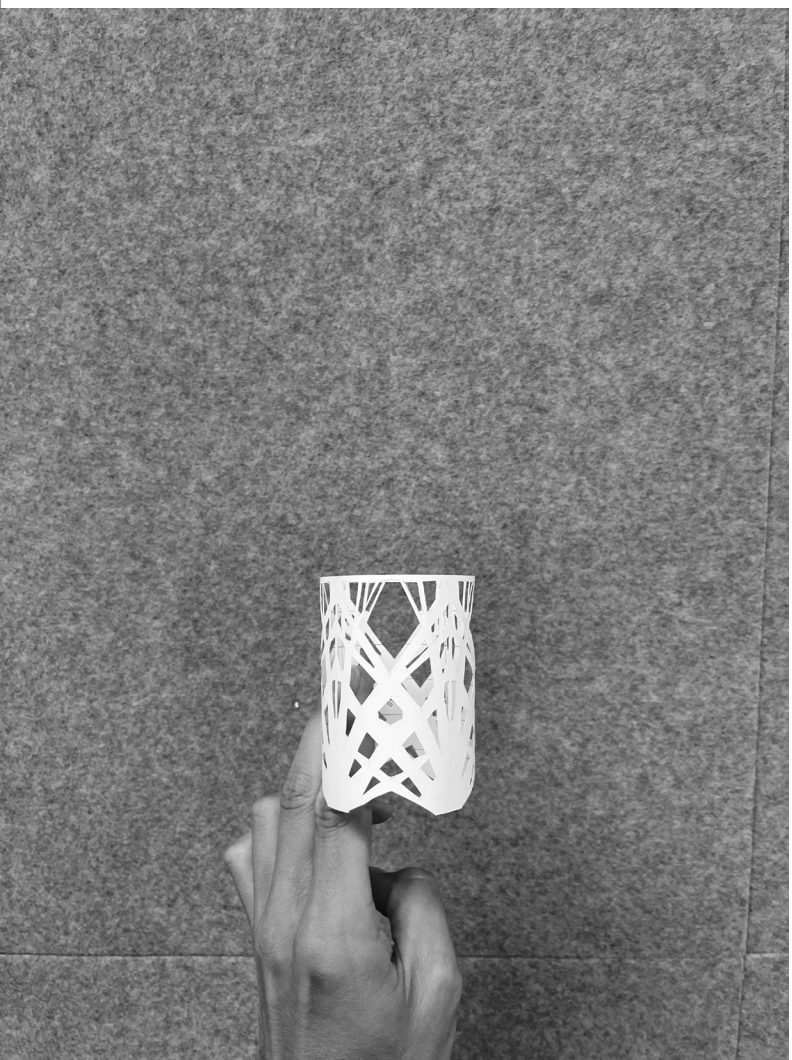


figure 2.4.3
wrapping

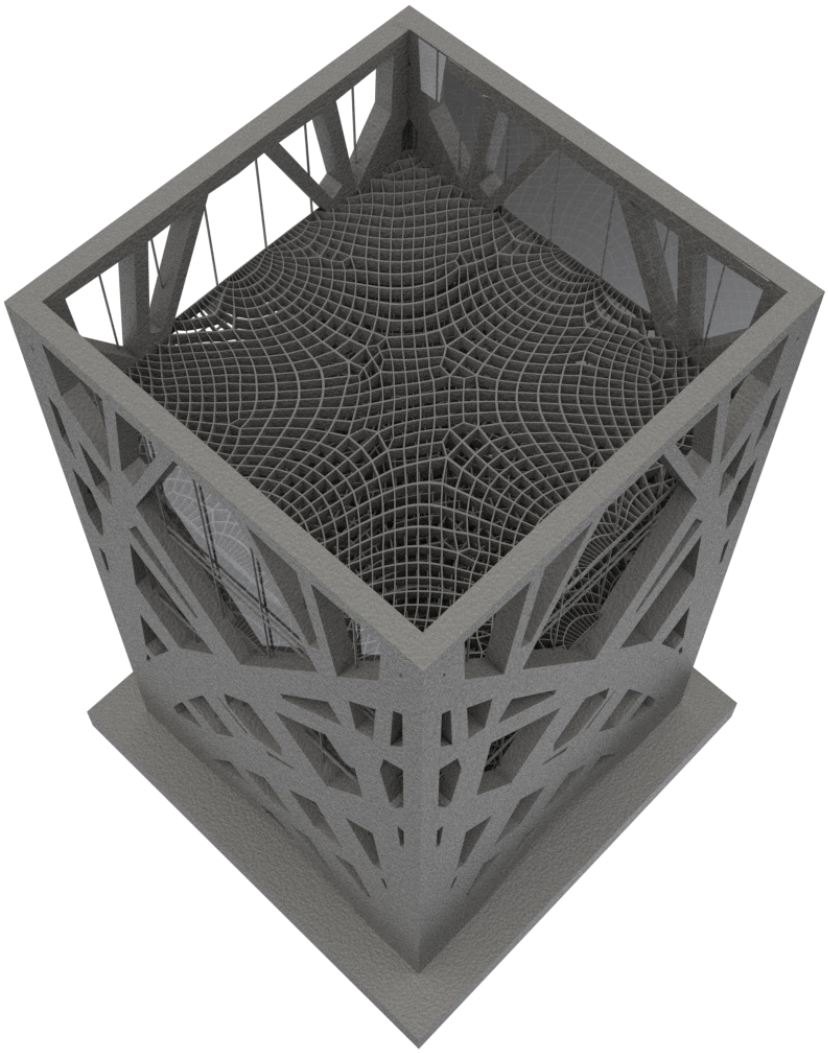


figure 2.4.4
a structural draft, a hypothesis of standing and spanning items:
treeing facade as strcuture and brise soliel;
isostatic floors are visable

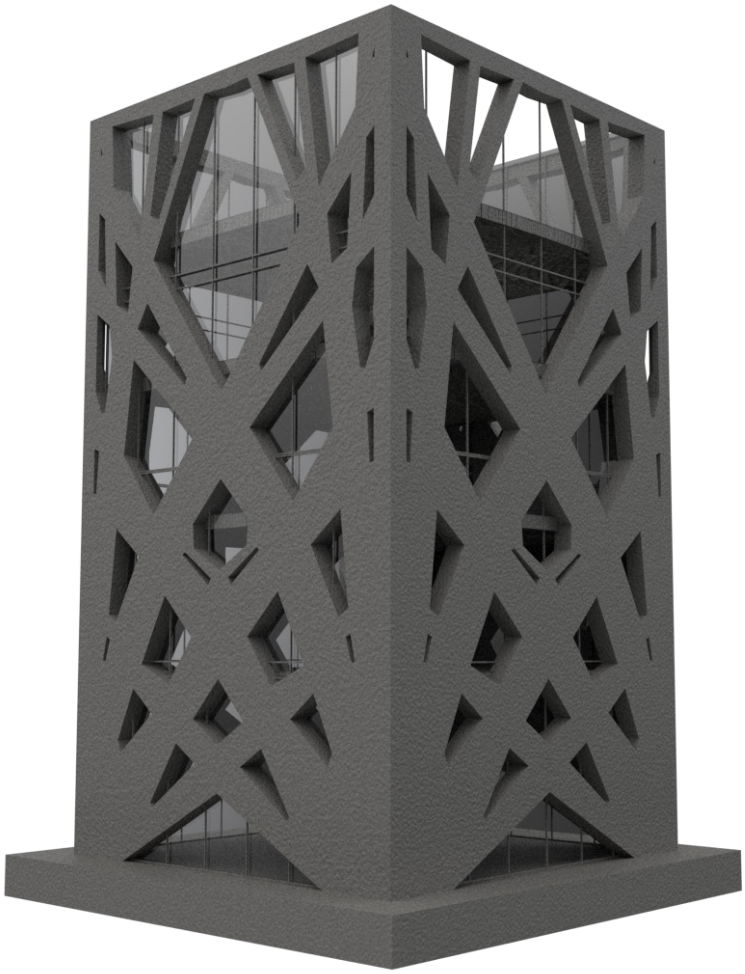
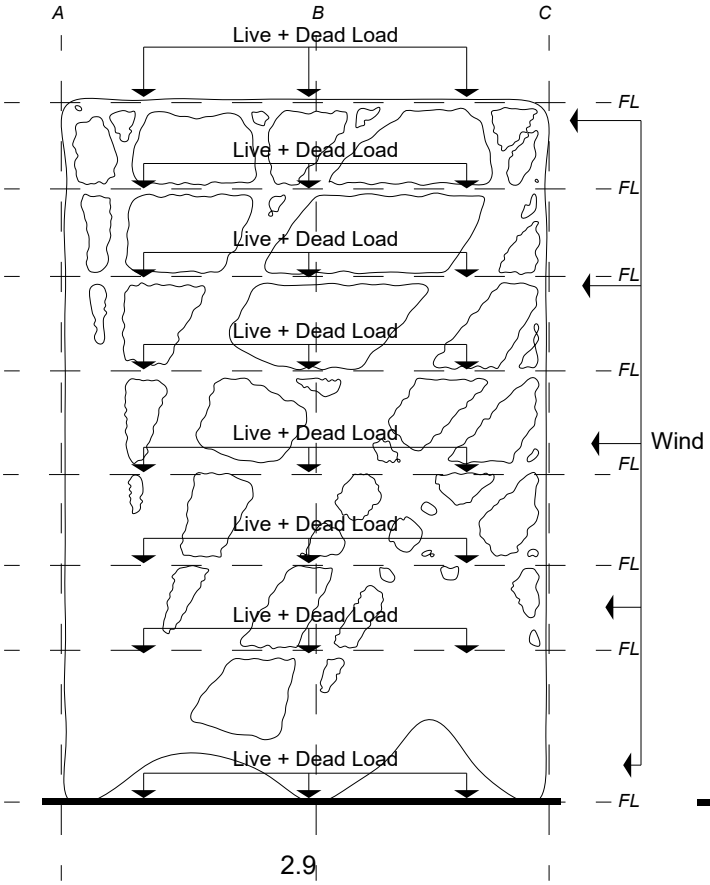
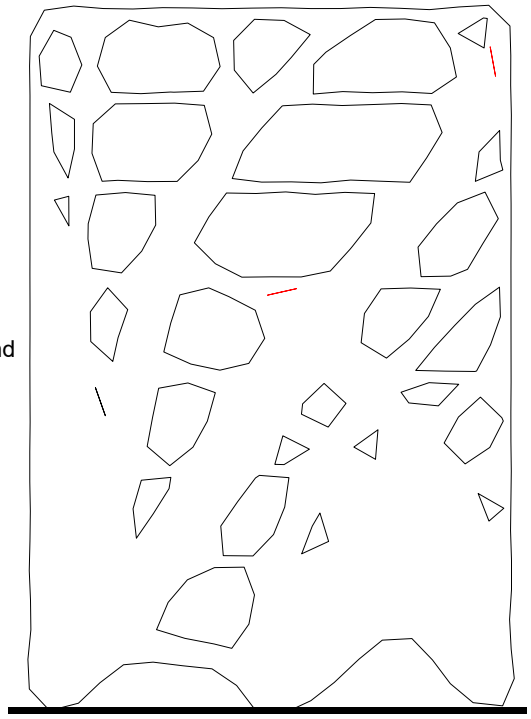


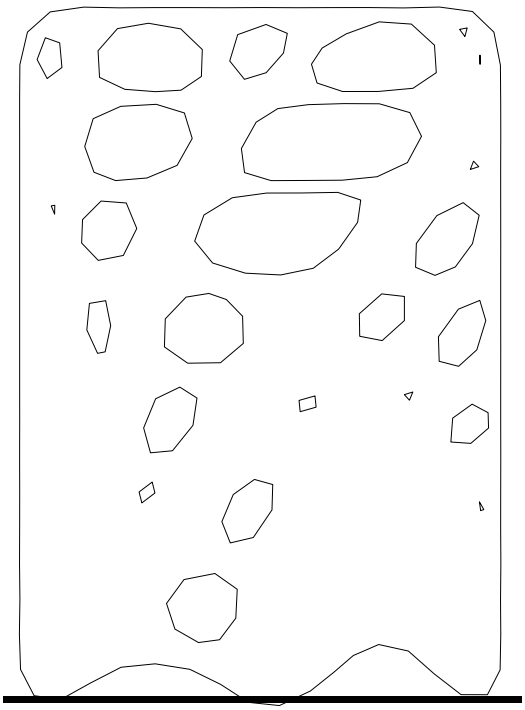
figure 2.4.5
a structural draft, treeing facade as brise soliel
a solution for a rectilinear plot



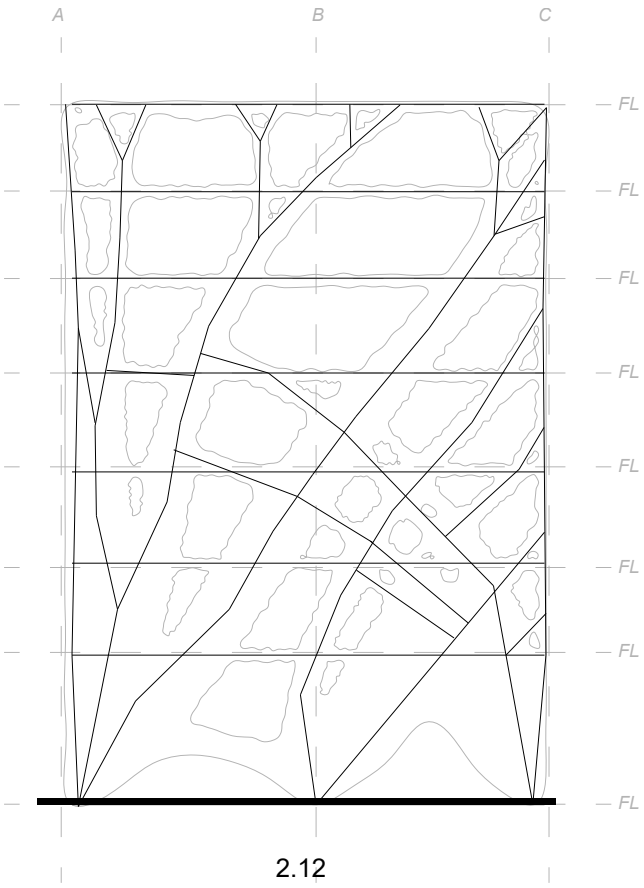
2.9
facade unprocessed: mesh edges



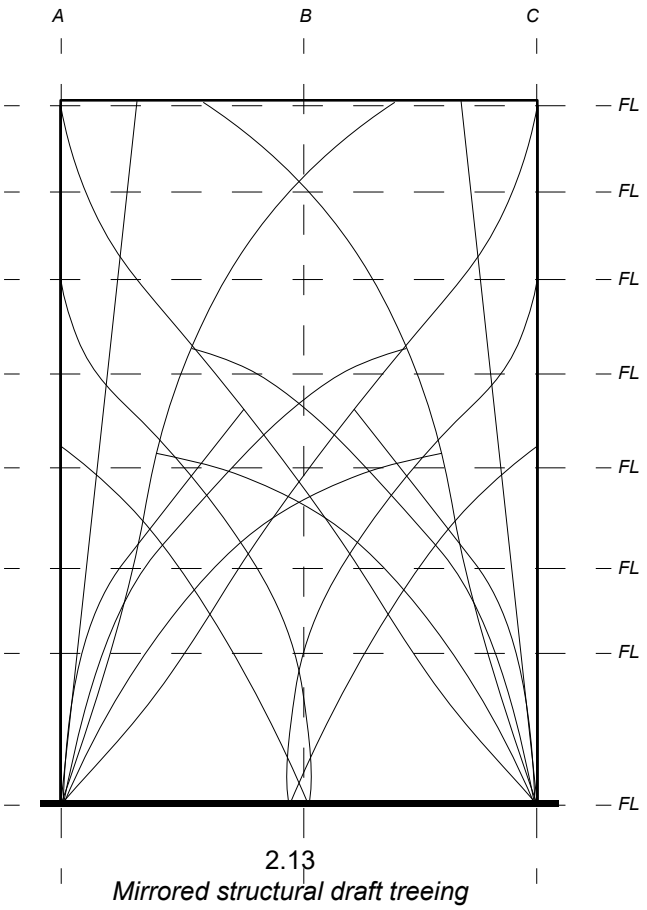
2.10
facade mesh edges 80% curve smooth



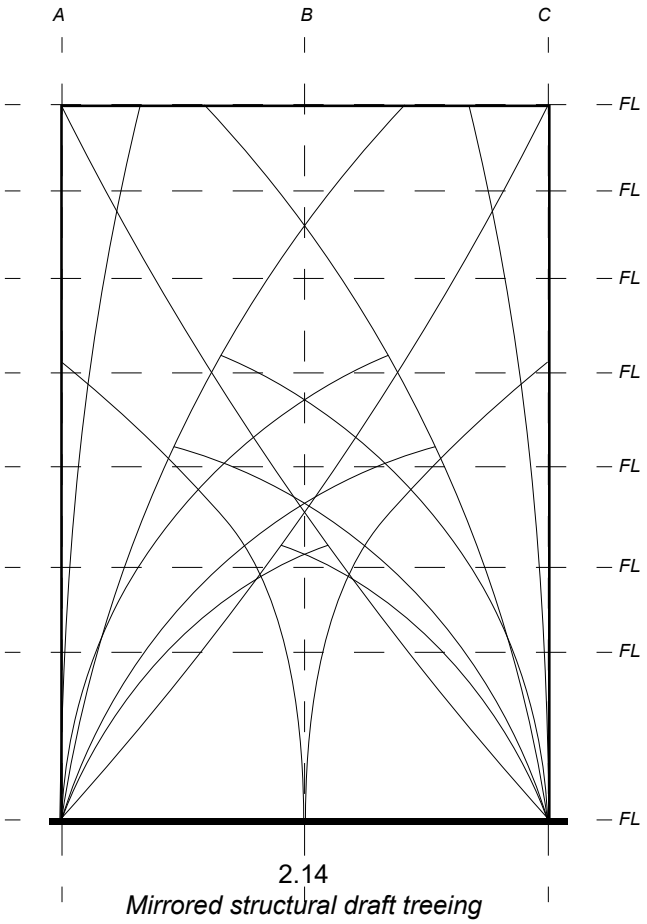
2.11
facade mesh edges 60% curve smooth



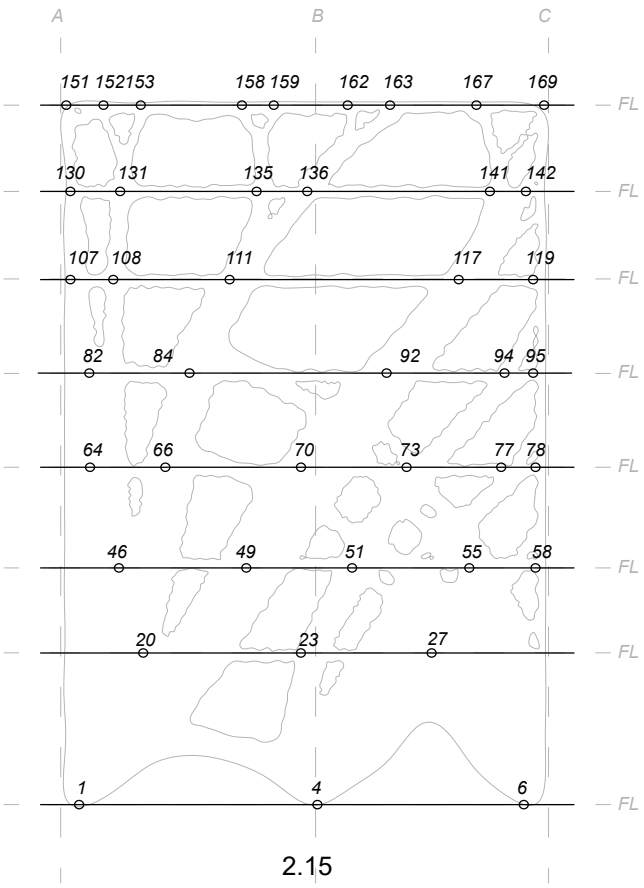
2.12
Tringulation mesh skeleton



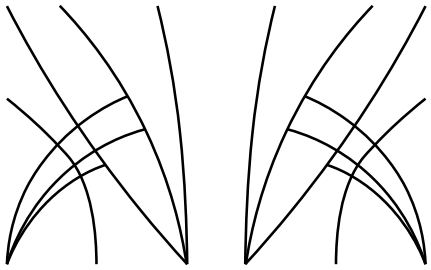
2.13
Mirrored structural draft treeing facade: point and curve



2.14
Mirrored structural draft treeing facade: point and curve



2.15
Node points taken from grasshopper contours at floor level



the base than at the top. We can see the difference between a simulation with SubD 2.18• and without 2.20•. The findings support a critique that columns and beams shouldn't exist when force paths are followed precisely; material wishes to perform load transfer whether it is a vertical or a horizontal member, the item wishes to participate, hence the efficacy of diagrid structures working both in compression and tension. We can also note the Mitchell truss similarity of 3.20 and 2.22• → where the geometry naturally follows the form of a cantilever, except the building is a vertical cantilever opposed to a horizontal cantilever expressed in Mitchell's findings.

2.17 and 2.25• → display a high-rise structure with a built ratio of 1/8. When considering floors, they become non-design-domains. The **NDD** lets us simulate floors as actively transferring load from the floor down through the structure. We can consider simulations of structure without the floors having alternate benefits. Buildings with tied super structures are more efficient (again, referencing diagrid structures which have diamond structures that span over floors, some floor ring beams connecting at nodes and others at mid span). The loading condition are wind loads which multiply in strength dependent on the height; live loading is applied to the floors. Gravity and self-weight are inherently integrated into the script.

2.27 and 2.28• → demonstrate a building with vertical presence and a significant horizontal cantilever: the resulting mesh is perhaps a failure, albeit the top chord of the cantilever produces geometry which resembles fingers point down from a hand and is structurally expressive. The architect could borrow from this failure and use the outcome, much to how a design studio will employ staff to make models of differing as design concepts. Here the BESO failed due to poor scripting but provides a novel solution proving the tool as an iterative aid.

The responsive super structures resist force with material being prioritized around the perimeter of the occupiable envelope (note Foster and Partners Der Commerzbank whose form is naturally resistant to force due to its triangular form in plan and the proximity of the structure to the building's edges; or, to use poorer example, someone who places their legs apart immediately becomes more resistant to say, a friend at a dinner party who wishes to push them over). Because buildings naturally cantilever, our periphery structural system offers best negotiation of that natural fact (a tree is another example of a cantilevering object whose roots resist lateral wind loading and subsequent uplift).

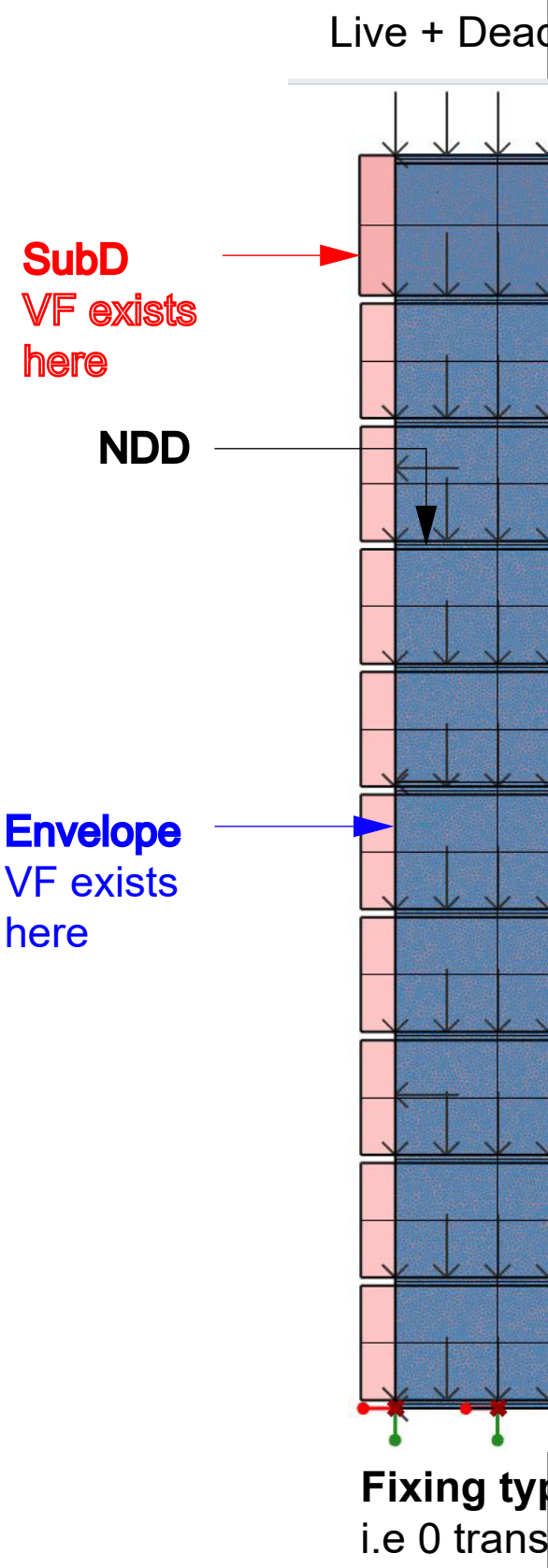


Figure: 2.17

note: base geometery

ER: 6%; RMIN: 0.05;

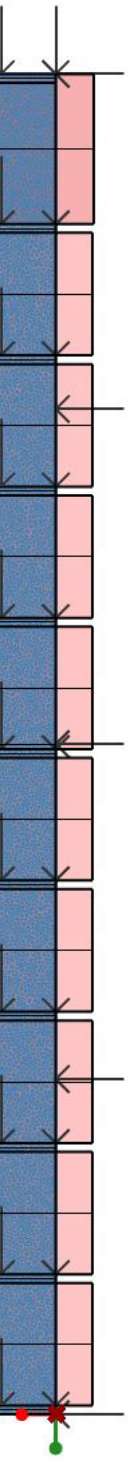
fixing type: fixed, 0 tra

magnitude loading: Y/

material: steel; built ra

SubD:yes; NDD: yes

d Load



Wind
proportional to
height

pe
lation, 0 rotation

w/ SubD+NDD
VF:10%; IT:0
nslation
-10kN
tio: 7h/1w

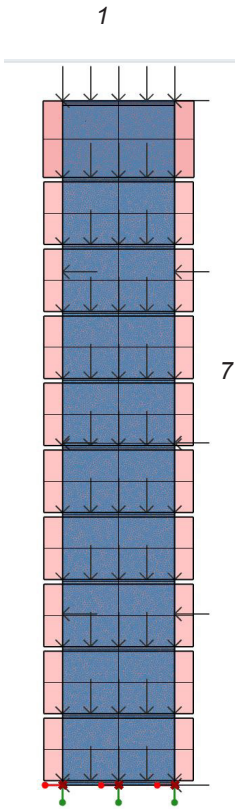


Figure: 2.17

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:10%; IT:0

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 7h/1w

SubD:yes; NDD: yes

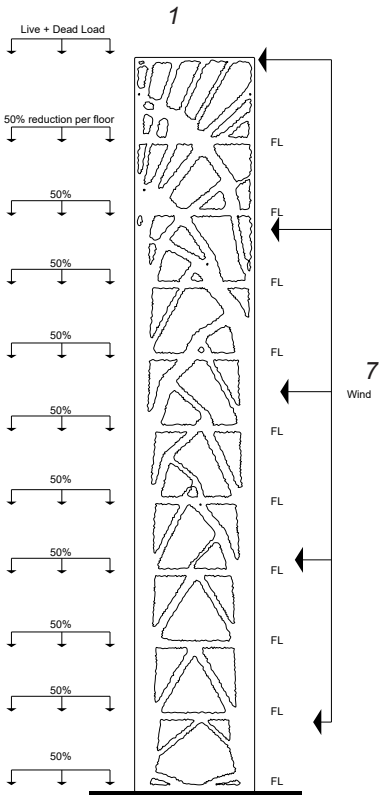


Figure: 2.18

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:50%; IT:86

fixing type: fixed, 0 translation

magnitude loading: Y,X/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

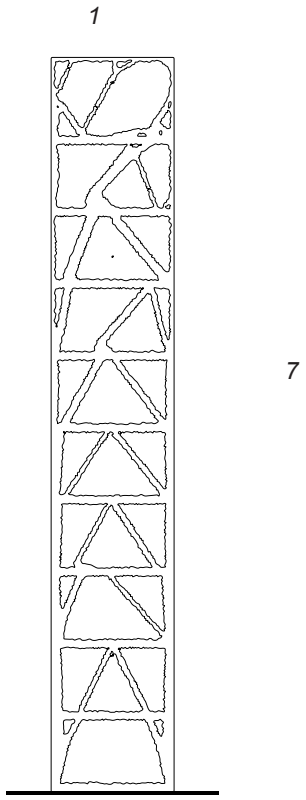


Figure: 2.19

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:50%; IT:75

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

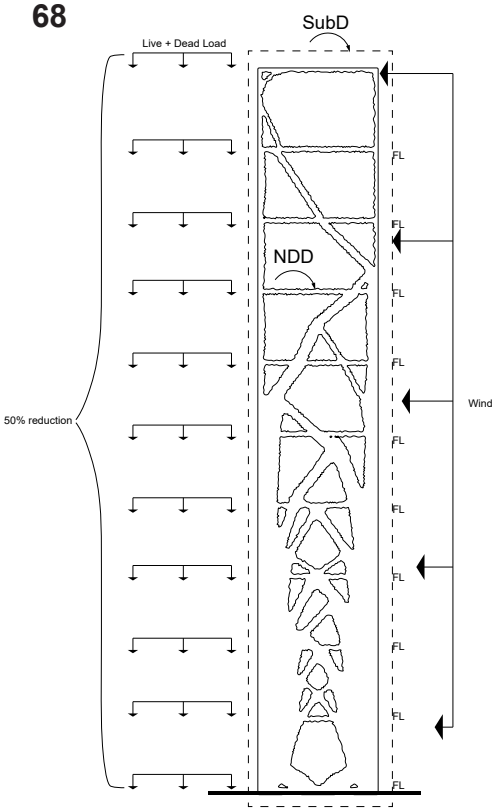


Figure: 2.20

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:10%; IT:102

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 7h/1w

SubD:yes; NDD: yes; Dimension: 2D

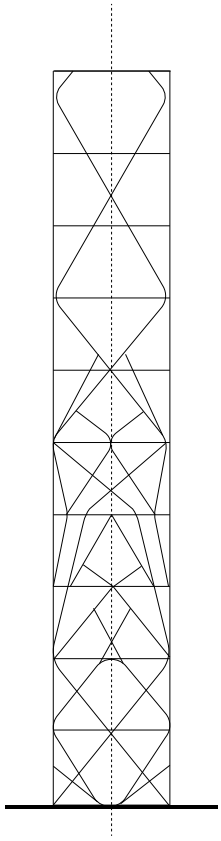


Figure: 2.21

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:50%; IT:56

fixing type: fixed, 0 translation

magnitude loading: Y,X/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

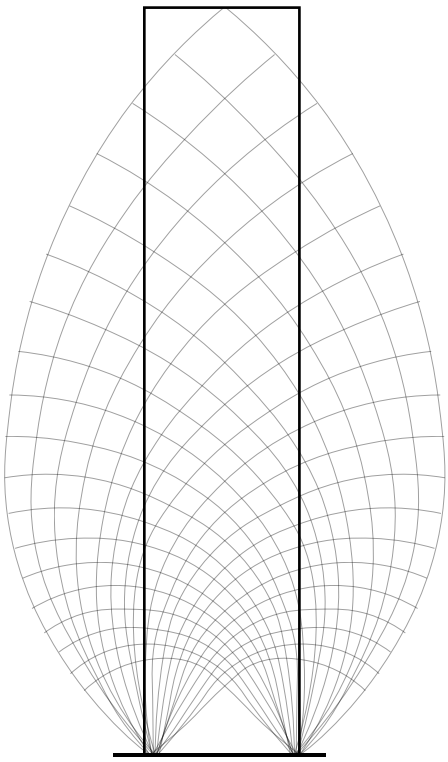


Figure: 2.22

note: Mitchell truss overlaid on plane

ER: 6%; RMIN: 0.05; VF:50%; IT:75

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

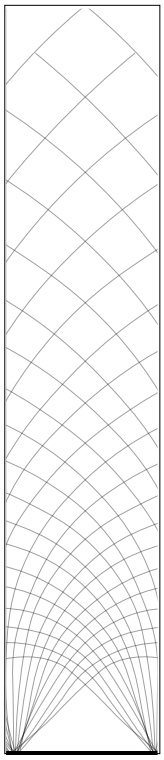


Figure: 2.23

note: Mitchell truss diagrid

ER: 6%; RMIN: 0.05; VF:50%; IT:

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

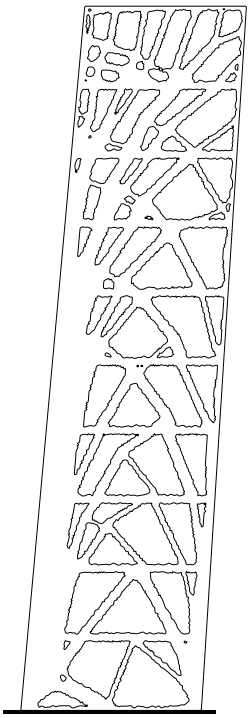


Figure: 2.24

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:50%; IT:67

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

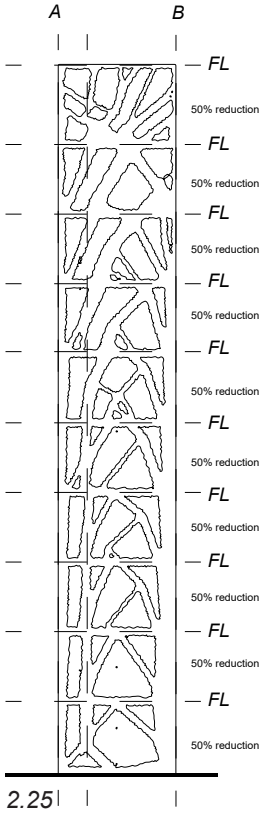


Figure: 2.25

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:50%; IT:67

fixing type: fixed, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

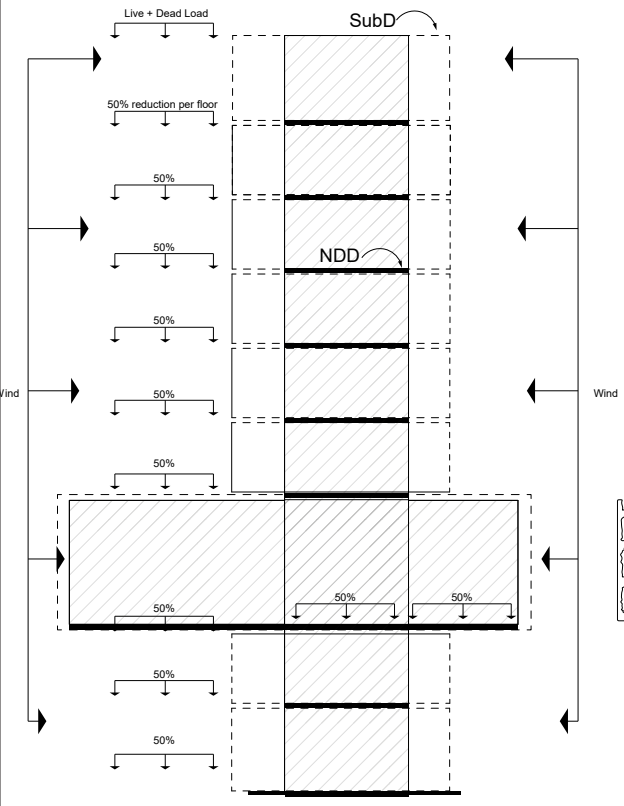


Figure: 2.26

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:50%; IT:-

fixing type: fixed, 0 translation

magnitude loading: Y,X/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

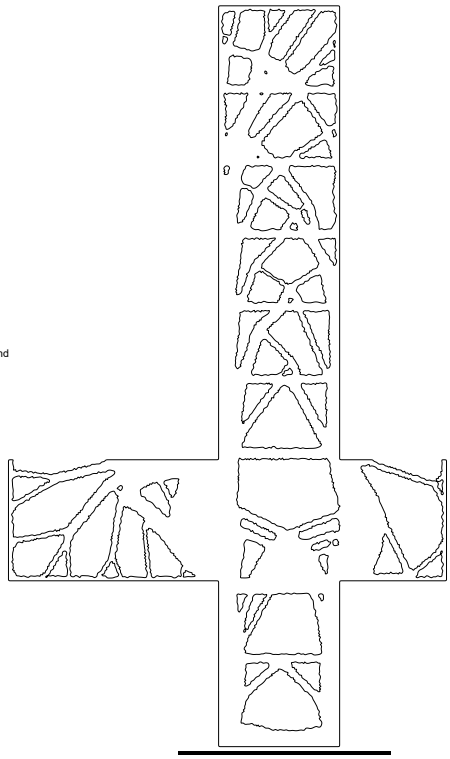


Figure: 2.27

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:50%; IT:75

fixing type: fixed, 0 translation

magnitude loading: Y,X/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 50%; NDD: yes

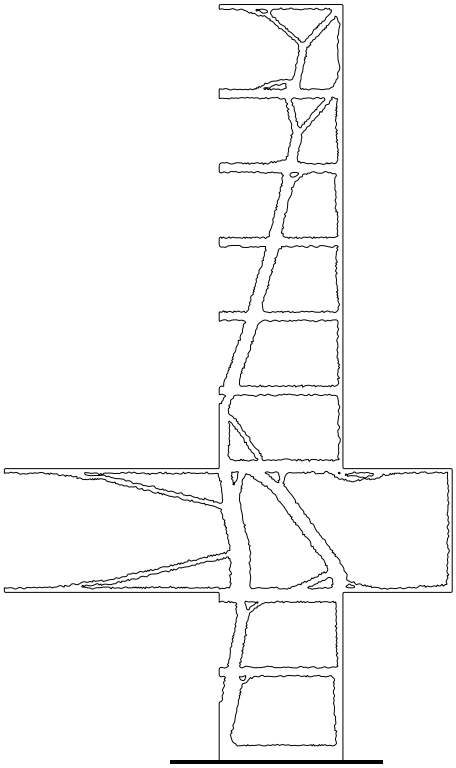


Figure: 2.28

note: base geometery w/ SubD+NDD

ER: 6%; RMIN: 0.05; VF:10%; IT:165

fixing type: fixed, 0 translation

magnitude loading: Y,X/-10kN

material: steel; built ratio: 7h/1w

SubD:yes at 10%; NDD: yes

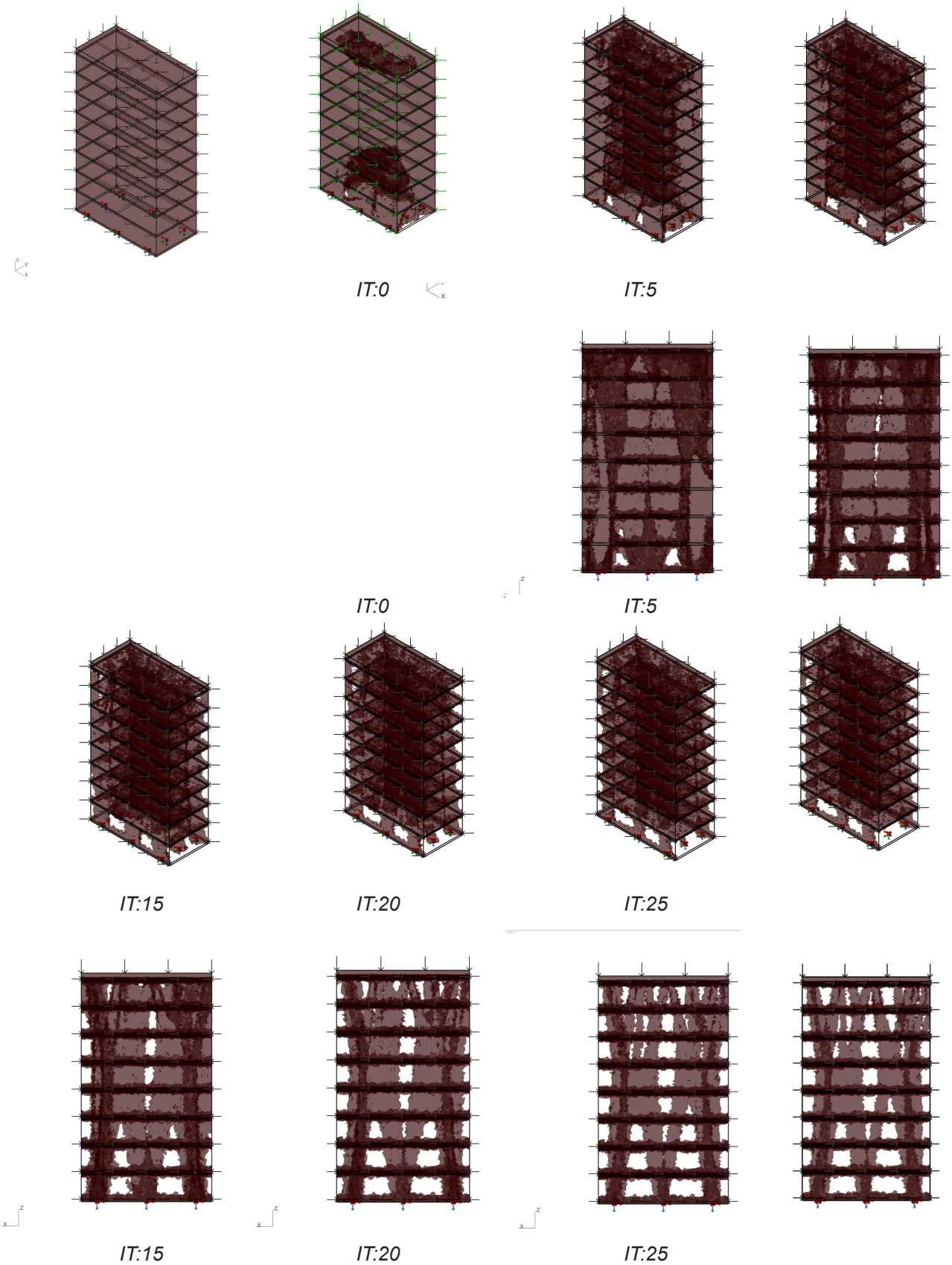


Figure: 2.29

note: BESO in 3D envelope

ER: 6%; RMIN: 0.05; VF:50%; IT:30

fixing type: fixed base, 0 translation

magnitude loading: Y/-10kN

material: steel; built ratio: 2h/5w

SubD:no; NDD: yes

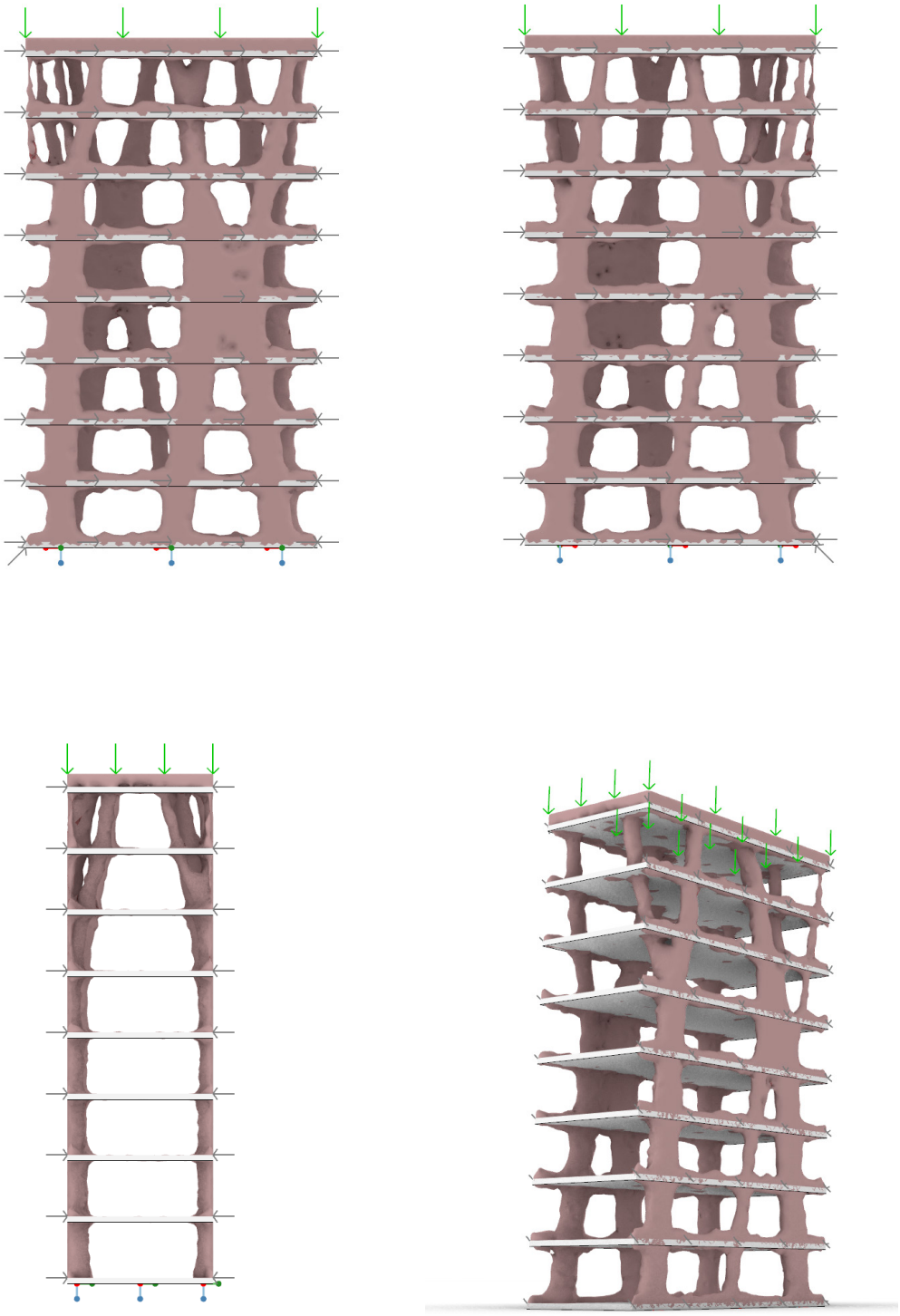


Figure: 2.29

note: BESO in 3D envelope

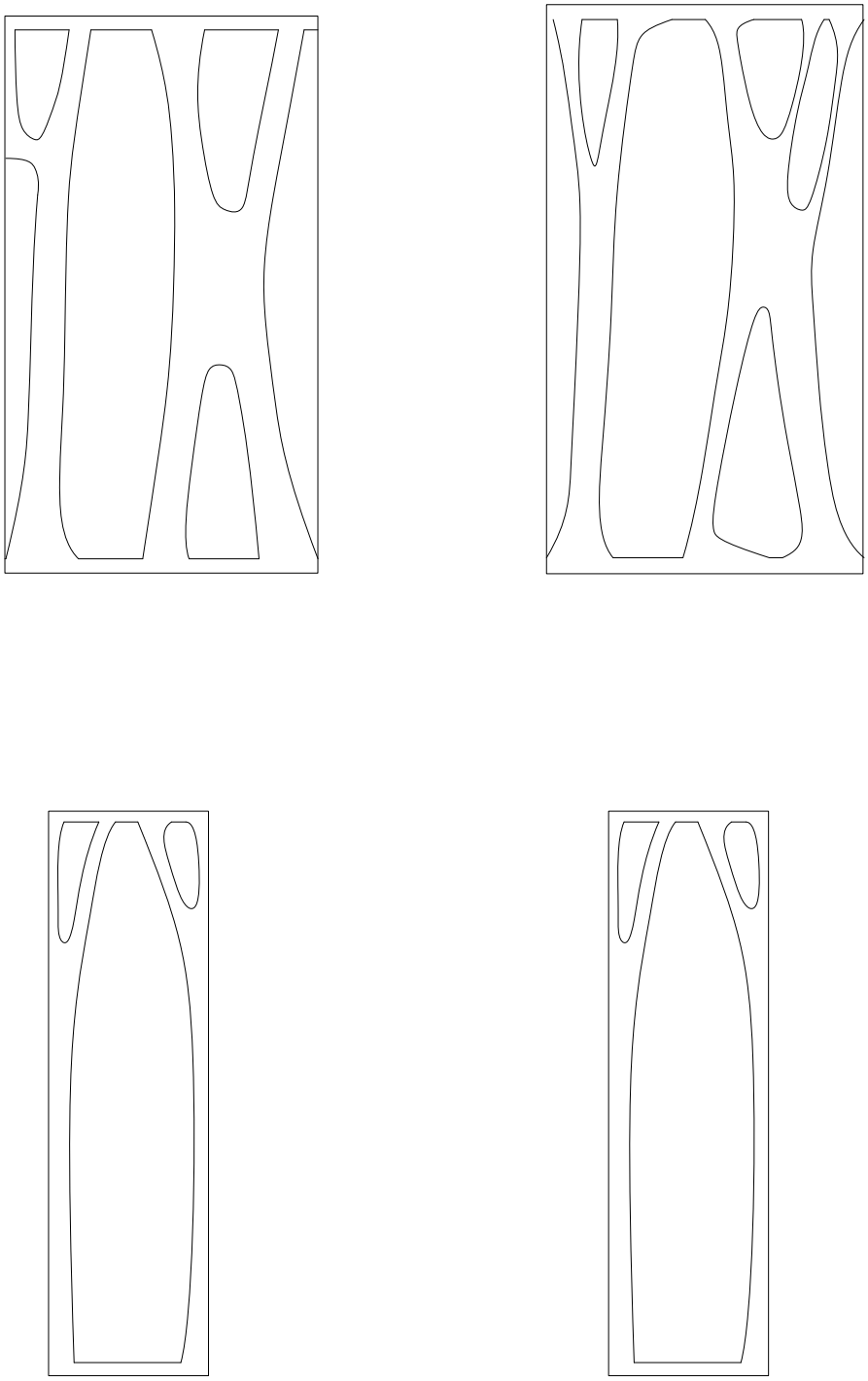
ER: 6%; RMIN: 0.05; VF:50%; IT:30

fixing type: fixed base, 0 translation

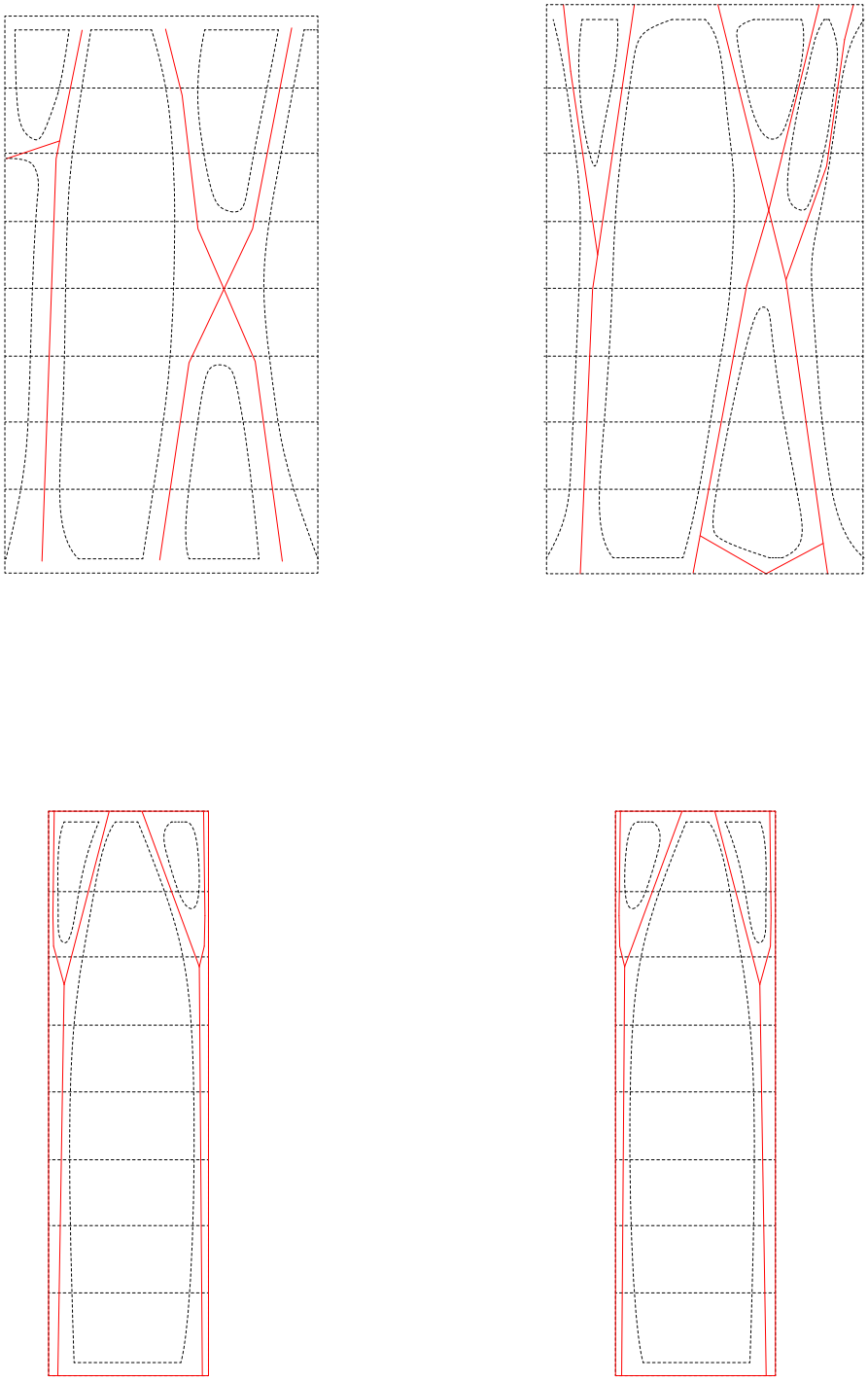
magnitude loading: Y/-10kN

material: steel; built ratio: 2h/5w

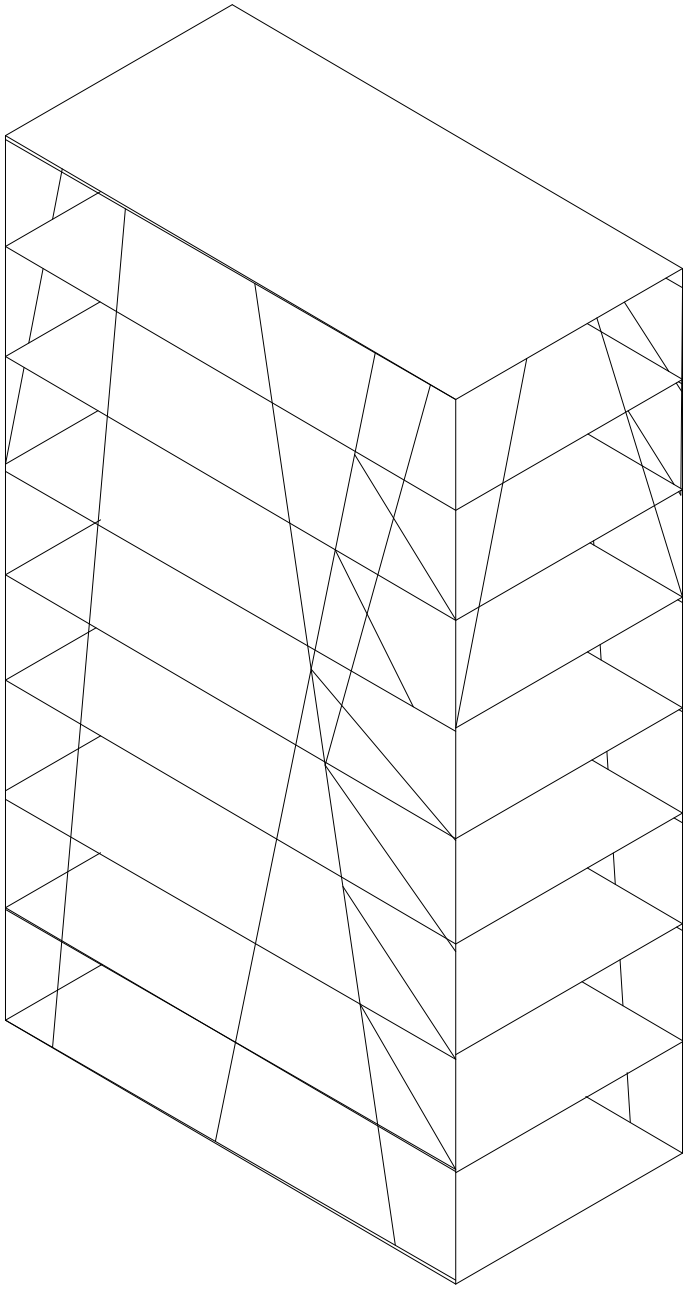
SubD:no; NDD: yes



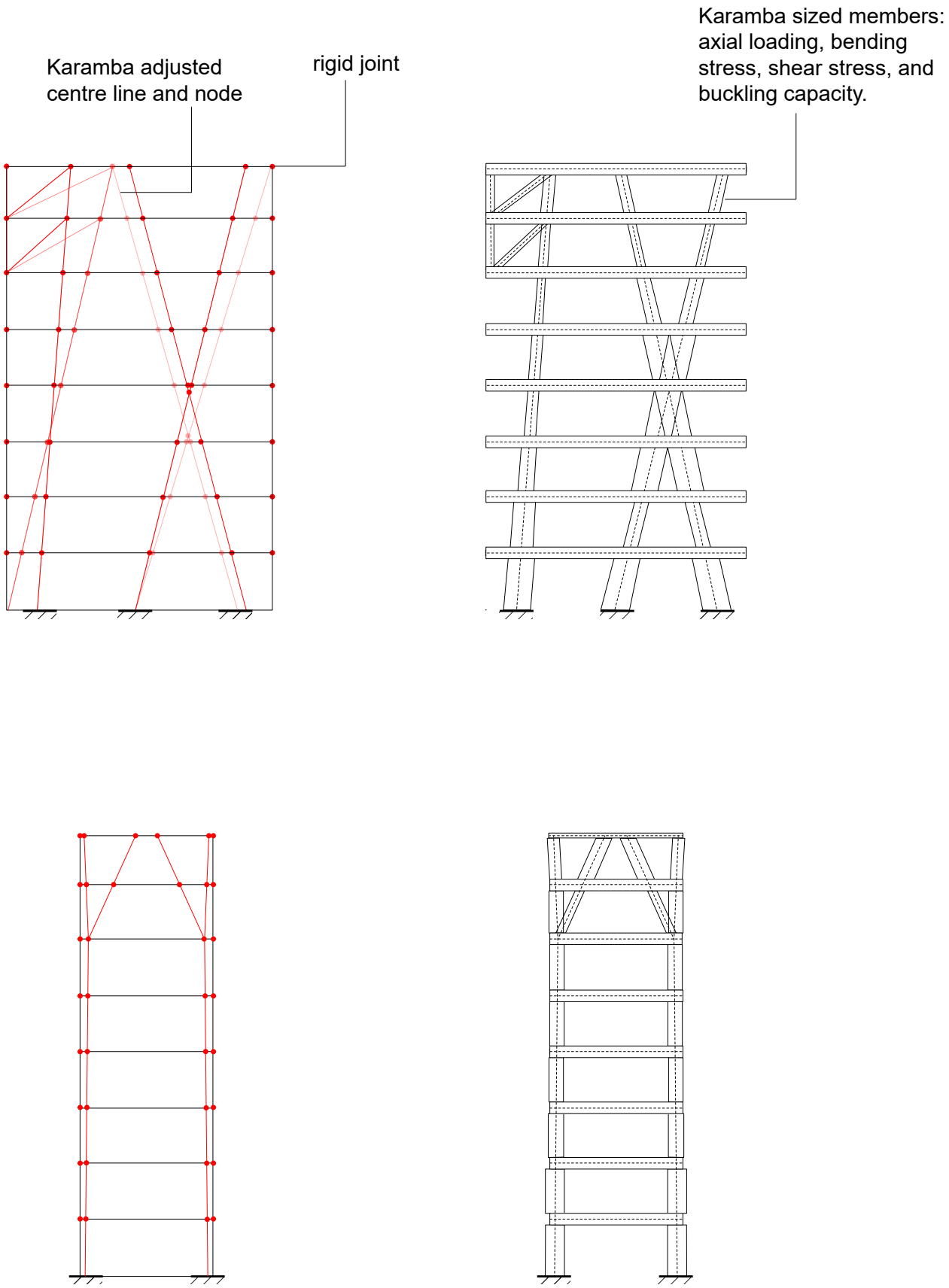
2.29.1
mesh edges extracted from Grasshopper



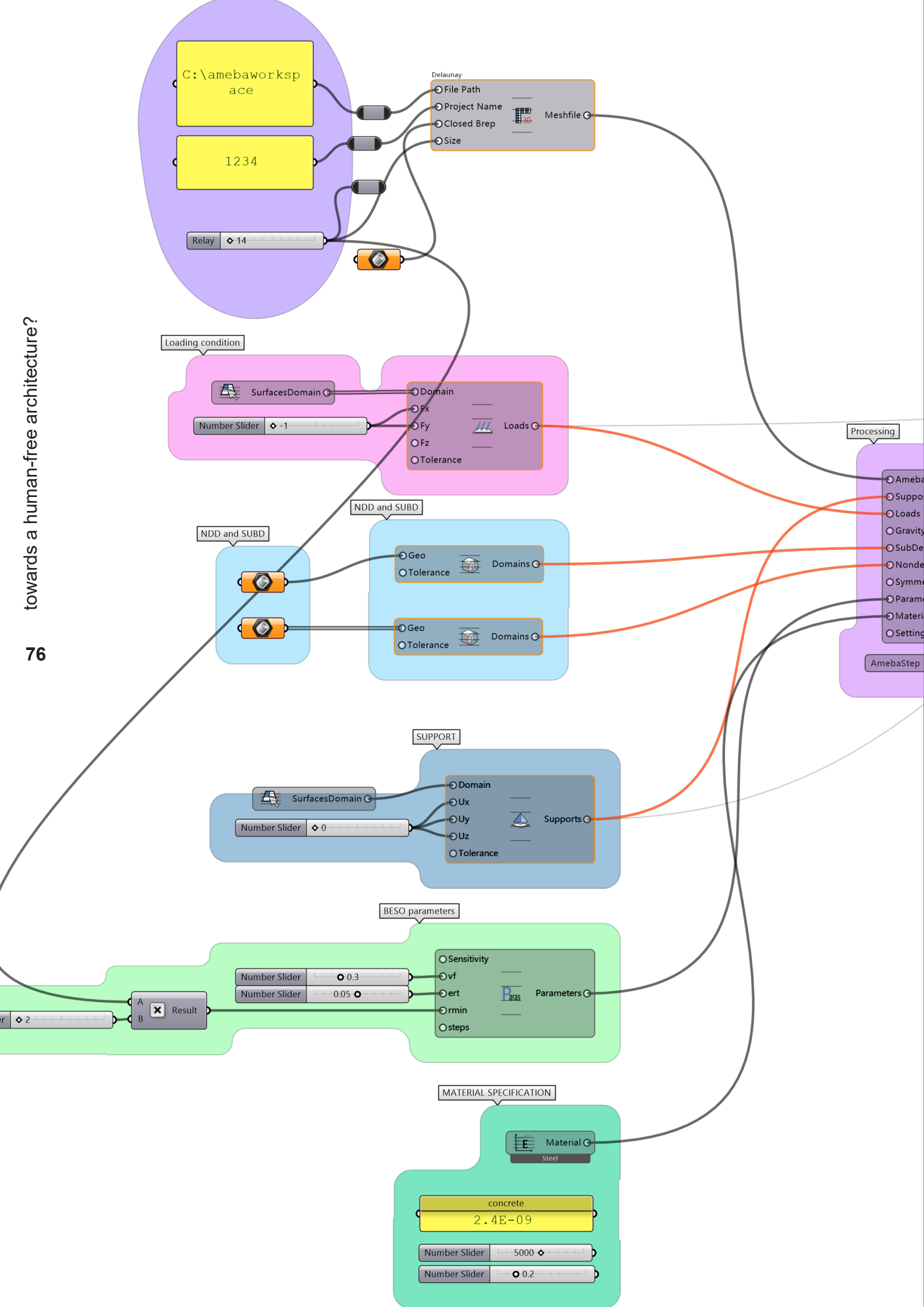
2.29.2
mesh centreline extracted from Grasshopper



2.29.3
centre-line structural scheme



2.29.4
structurally indeterminate system sized members in Karamaba moment frame in short section, braced standing items in the long section. All junctions rigid. Material steel.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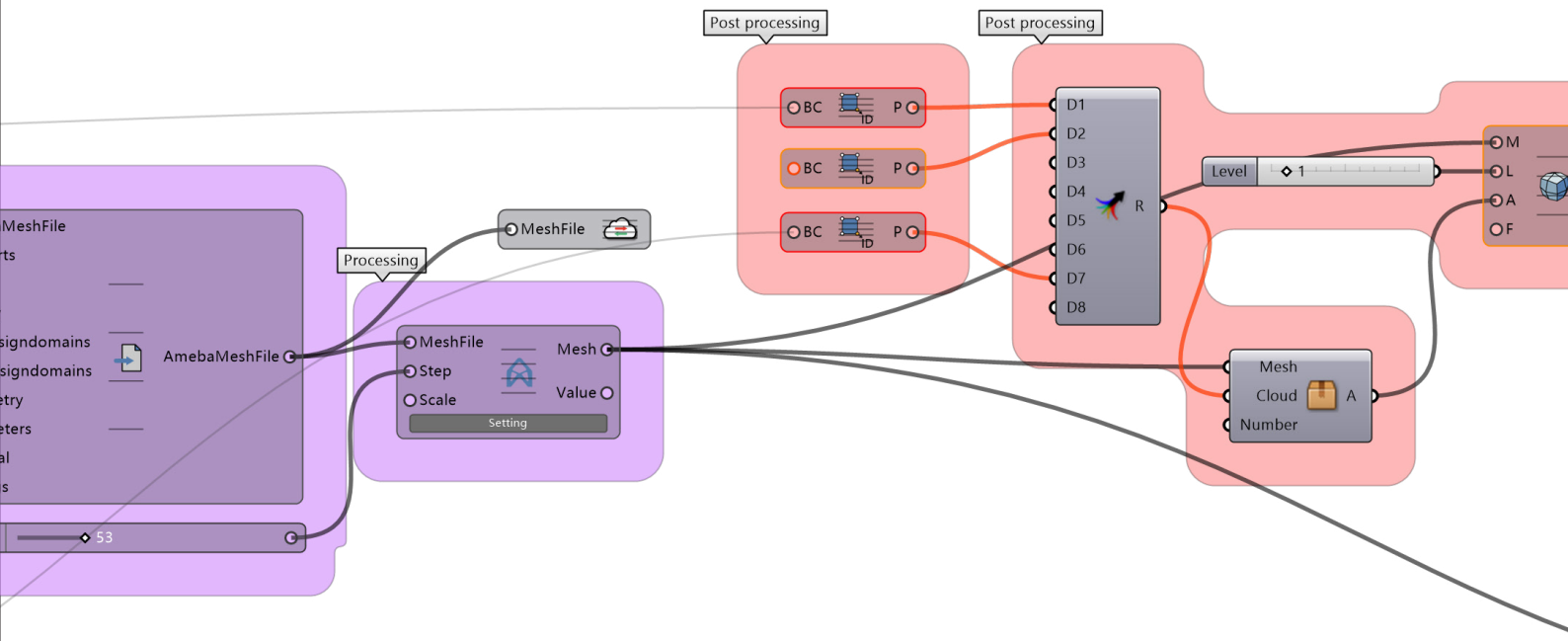
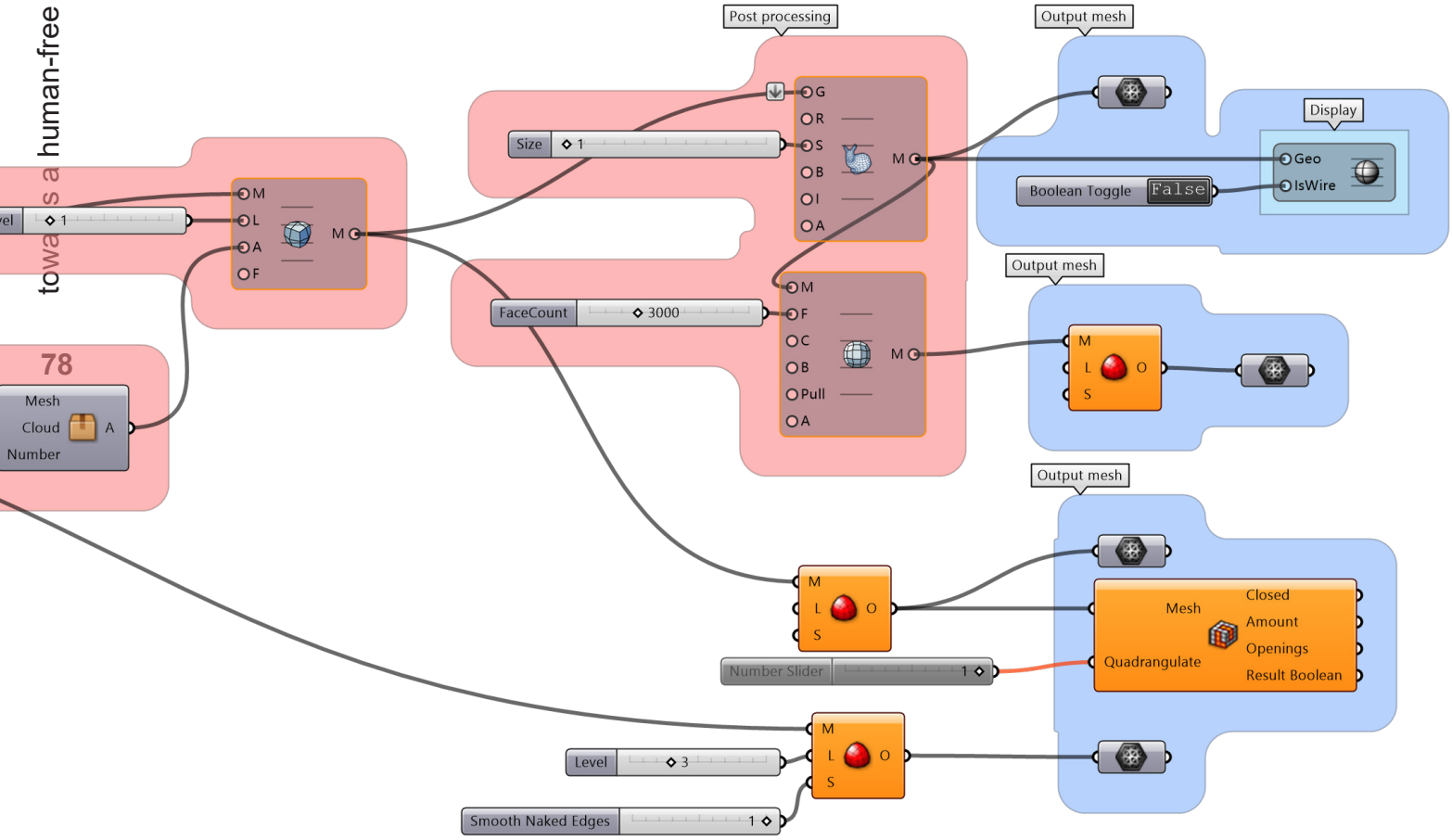
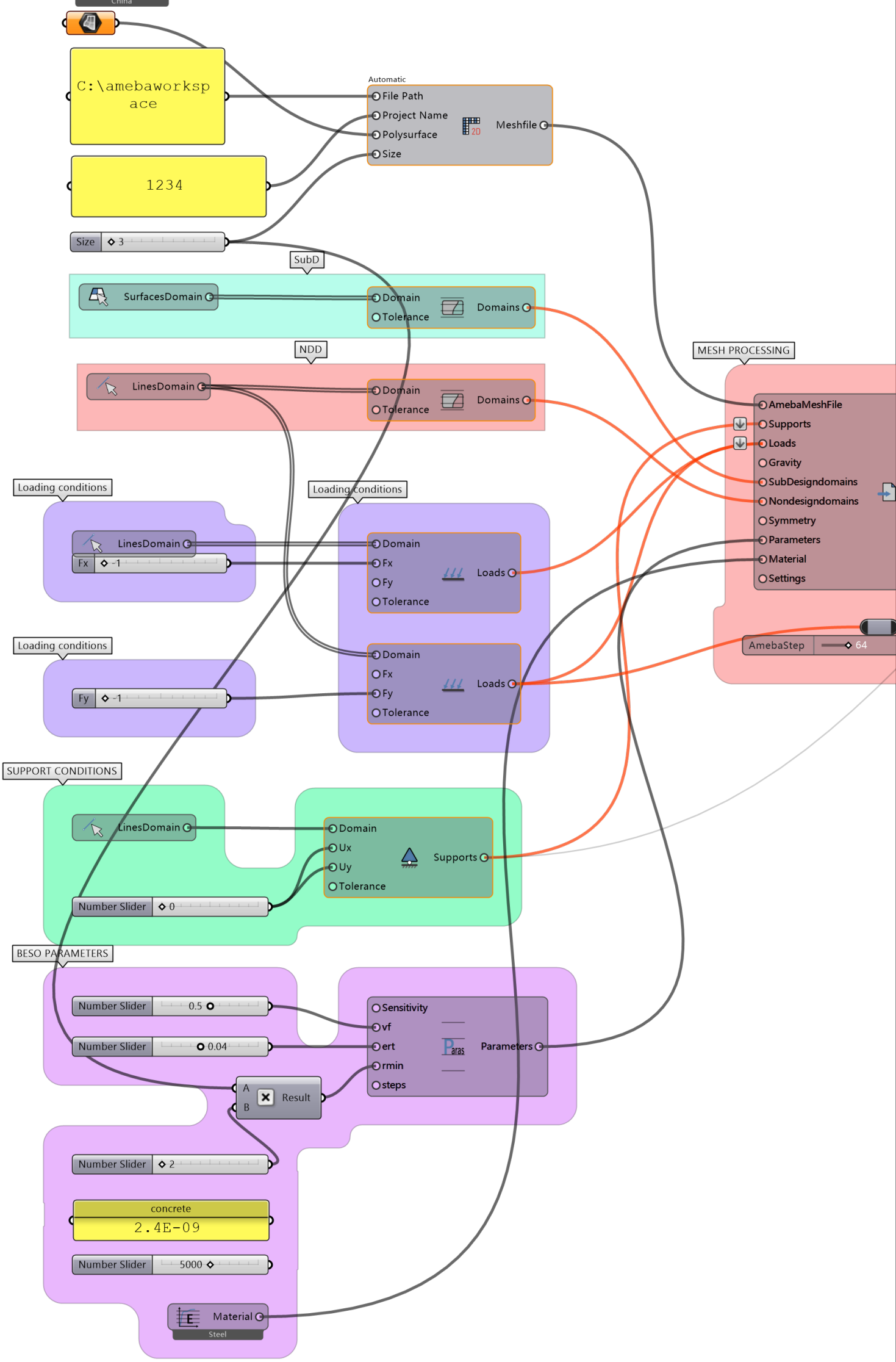


2.30
2D plane script of Ameba within Grasshopper

towards a human-free architecture?



2.30
2D plane script of Ameba within Grasshopper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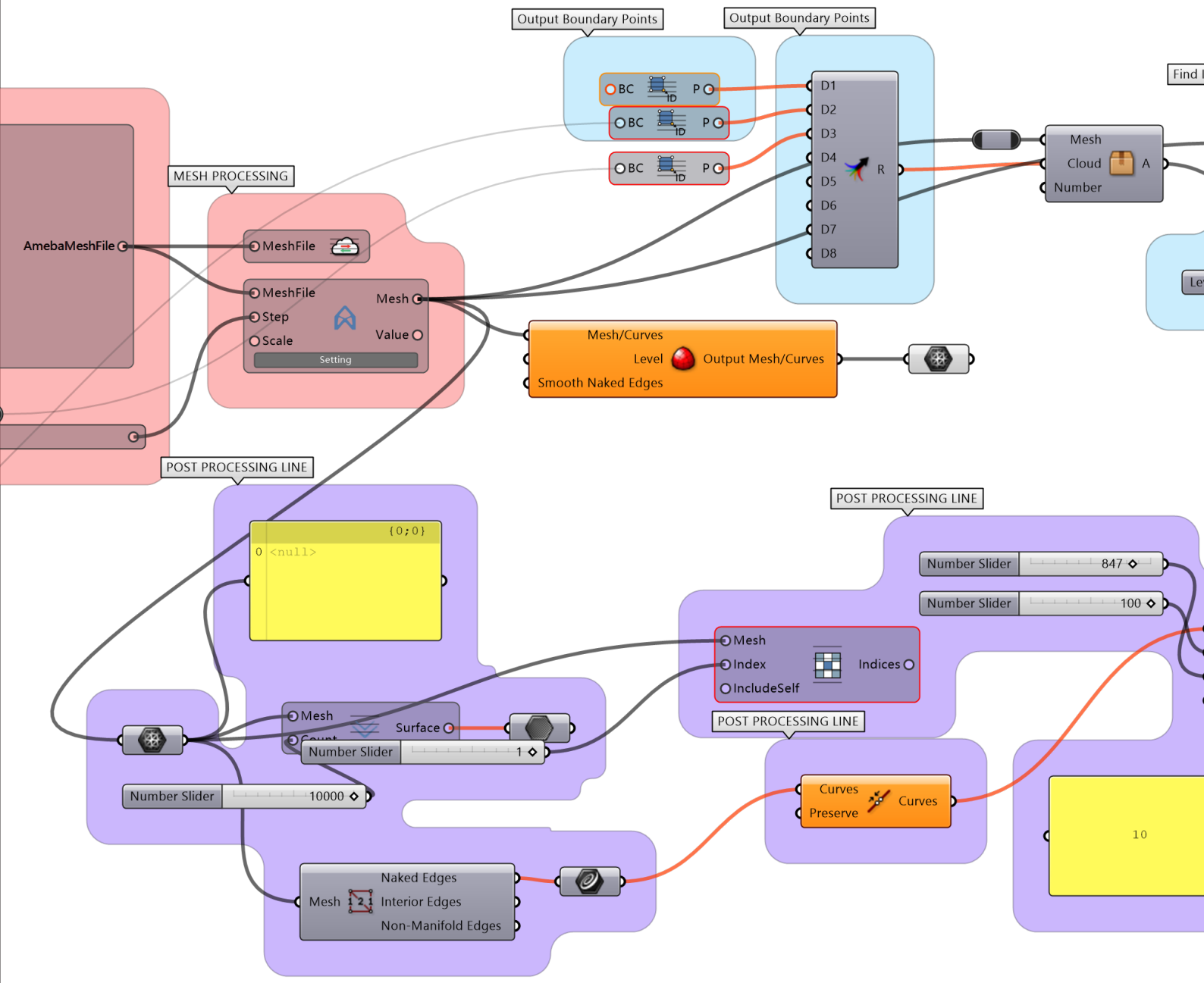
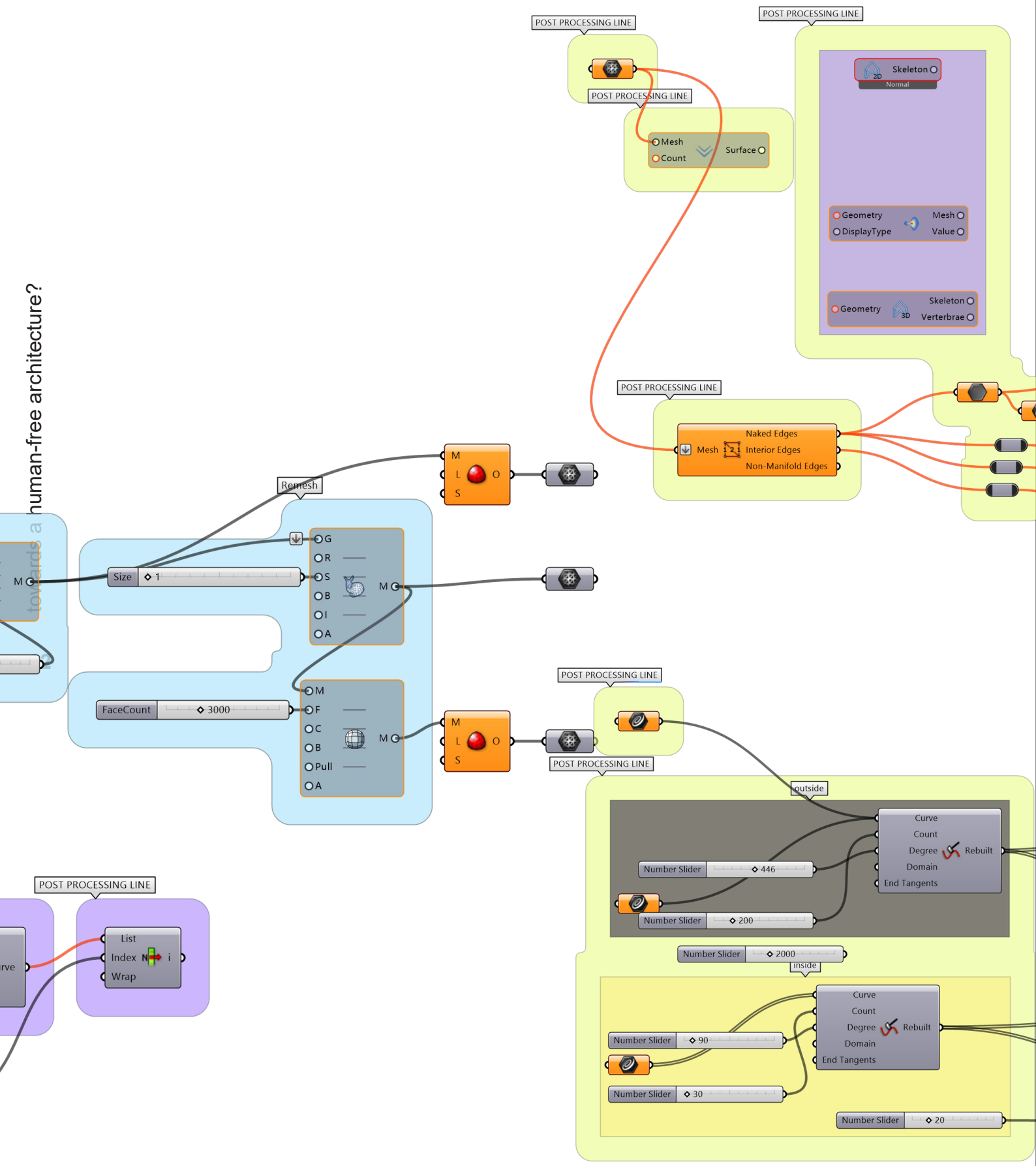


2.31
3D envelope script of Ameba within Grasshopper


towards a human-free architecture?
POST PROCESSING LINE
POST PROCESSING LINE
Mesh
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Surface
POST PROCESSING LINE
Skeleton
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DisplayType
Mesh
Value
Geometry
Skeleton
Verterbrae
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Mesh
Naked Edges
Interior Edges
Non-Manifold Edges
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200
Number Slider
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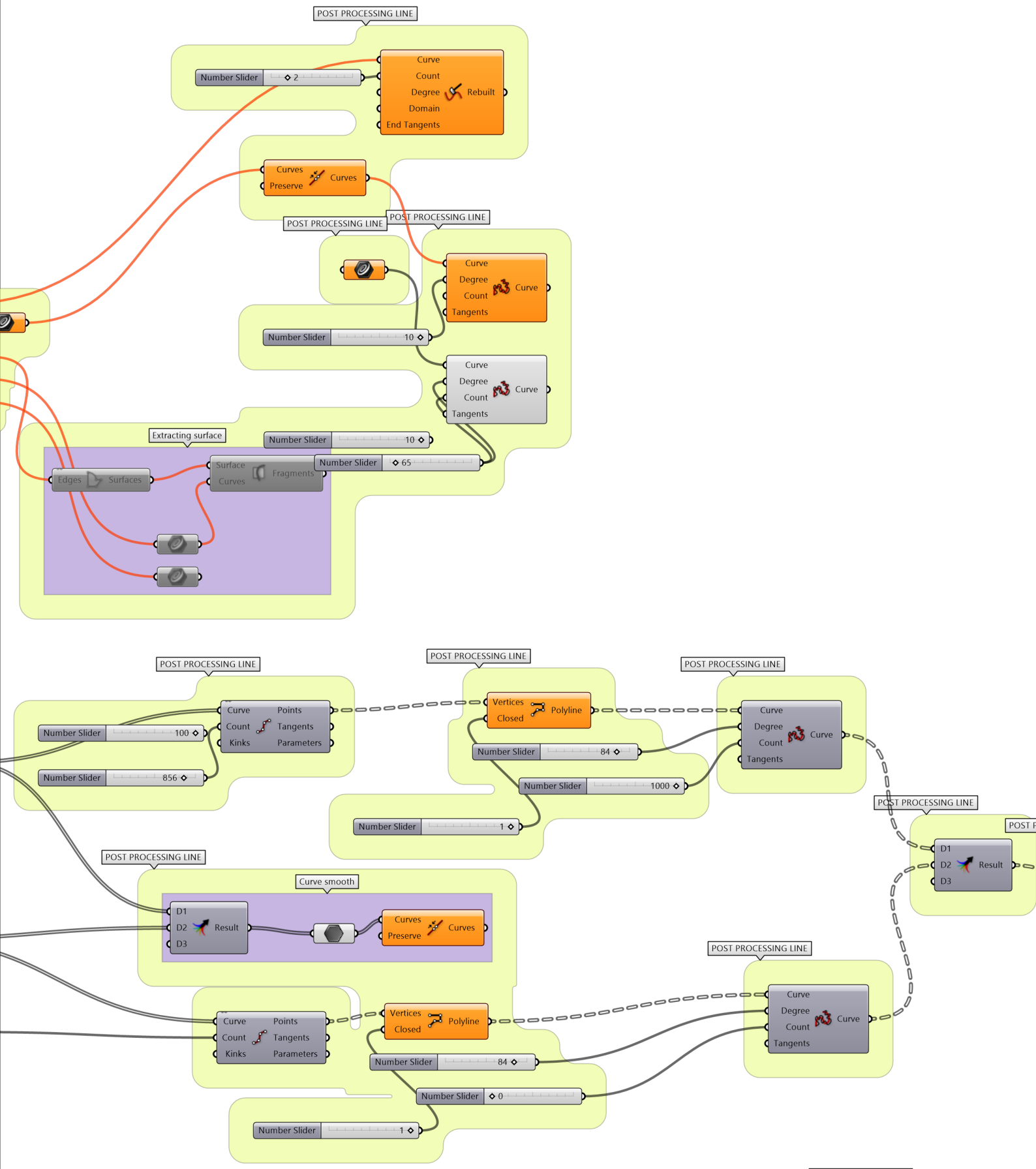


3.31
3D envelope script of Ameba within Grasshopper

2.32

2.33

In finishing **Chapter II** about standing items, a prosthetic retrofit exercise was explored with design constraints to see application of BESO to a pre-existing problem. 2.32 - 2.33• ← R House (132 Vivian St, Wellington) shows a 1960's concrete and glass modernist building, recently retrofitted building next to the Victoria University school of Architecture. The existing building without the K frames recently added shows an oblique similarity to Corbusier's Maison Domino, emblematic of the international style, something that is nonspecific to location; the building thus had inherent issues due to its European importation[40]. The R house was designed prior to the 1976 seismic requirements; no ductility, eccentric core, non-structural walls effecting seismic resistance, soft stories, short columns due to beams, weak columns, strong beams, and torsional symmetry, and, if a detailed seismic report (DSA) would result in the building been classified as seismically prone. The CCTV building which collapsed following the 2011 Christchurch earthquake had asymmetrical bracing due to an eccentric core (and other similarities)[41]. The retrofitted K frames on the R House are effective: massive grotesque concrete base frames, a meter thick profile to mitigate the soft story, and significant horizontal I beams at each floor level to support transfer, ductility in the eccentric braces that do not meet to allow a structural fuse; albeit the tectonics do not evoke architectural quality. A question was posed: how could BESO be used to find a solution to enrich the architecture if BESO was applied to the building's original geometry? Design considerations where car parking room for the base and the windows, and fixing to the floor plates. Ductility for structural elements could not have been integrated with the BESO mesh thus the initial topology would instruct the result to work in tension rather than compression. The non-design domains became:

1. not blocking view (thin members, ideally working in ten-

sion).

2. carparking access.

The resulting prothesis jacket retrofit is another **point and line** system. Here as BESO was an aid: proposal discovers a lateral resisting mesh, which in turn can be converted into centre skeletal line through triangulation mesh skeleton; the result is the inverse of a compression mesh, a tensile alternative (*'a slack line stands rigid when inverted'*). Using a thick member that resists buckling was impossible here to enrich the architecture due to the ribbon windows. Two proposals were then formed, both including a strung prolateral tensile cable system around the existing building, fixed at the corner foundation and with corner columns used to spread loading; I beams fixed to each floor plane at each corner and to concrete columns – the architecture is arguably enriched. The proposal is adapted from Charleson et al (2000) and provides a more enriched methodology for providing lateral and seismic bracing to the building with a visible soft story and eccentric core. The K frames which are now present are interesting in a grotesque fashion, but arguably do not enhance the architecture; it becomes a tectonic symbol of the building's lateral vulnerability and its inherent seismic inadequacy of a settler colonial building. Engineers may be *literal* with problem solving, opting for the immediate solution instead of *discovering* a solution; ***BESO provides a discovery process, important to all novel design, which provides a preliminary insight into how a problem may be solved with its structural draft***. It should also be stated that how the BESO resultant is interpreted and converted can vary, as demonstrated by the R House retrofit. No structural analysis as commenced on Charleson et al (2000) or this proposal.

2.29
north and south elevations

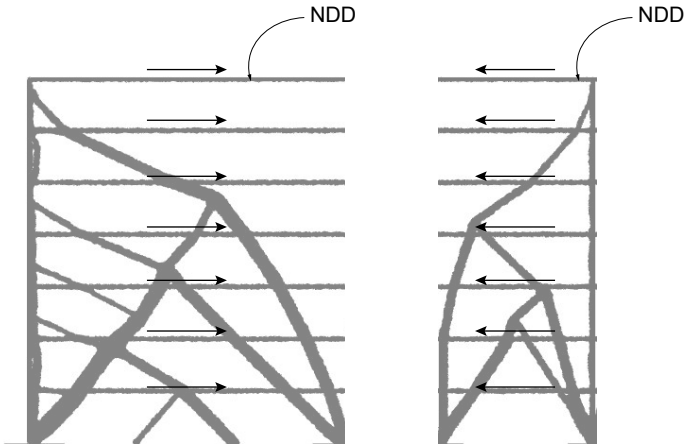


Figure: 2.30
note: compressive mesh resultant
ER: 6%; RMIN: 0.05; VF:50%; IT:37
fixing type: fixed base, 0 translation
magnitude loading: X/-10kN
material: steel; built ratio: 2h/5w
SubD:no; NDD: yes

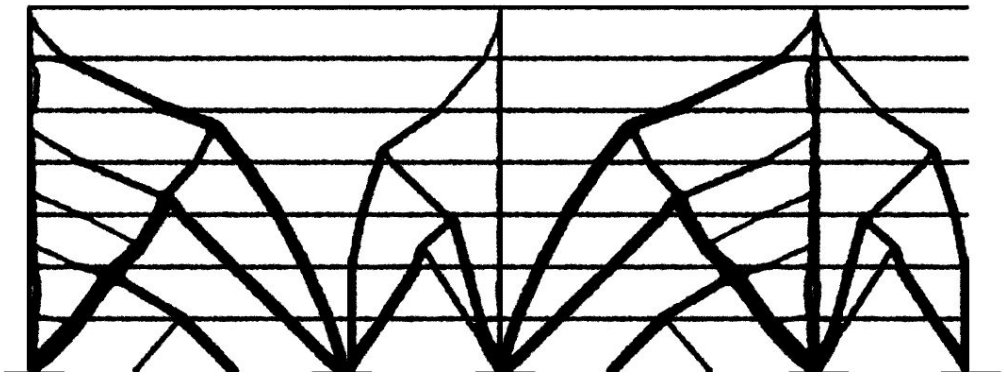
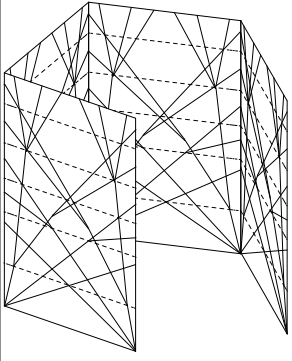


Figure: 2.31
note: compressive mesh resultant
ER: 6%; RMIN: 0.05; VF:50%; IT:-
fixing type: fixed base, 0 translation
magnitude loading: X/-10kN
material: steel; built ratio: 2h/5w
SubD:no; NDD: yes



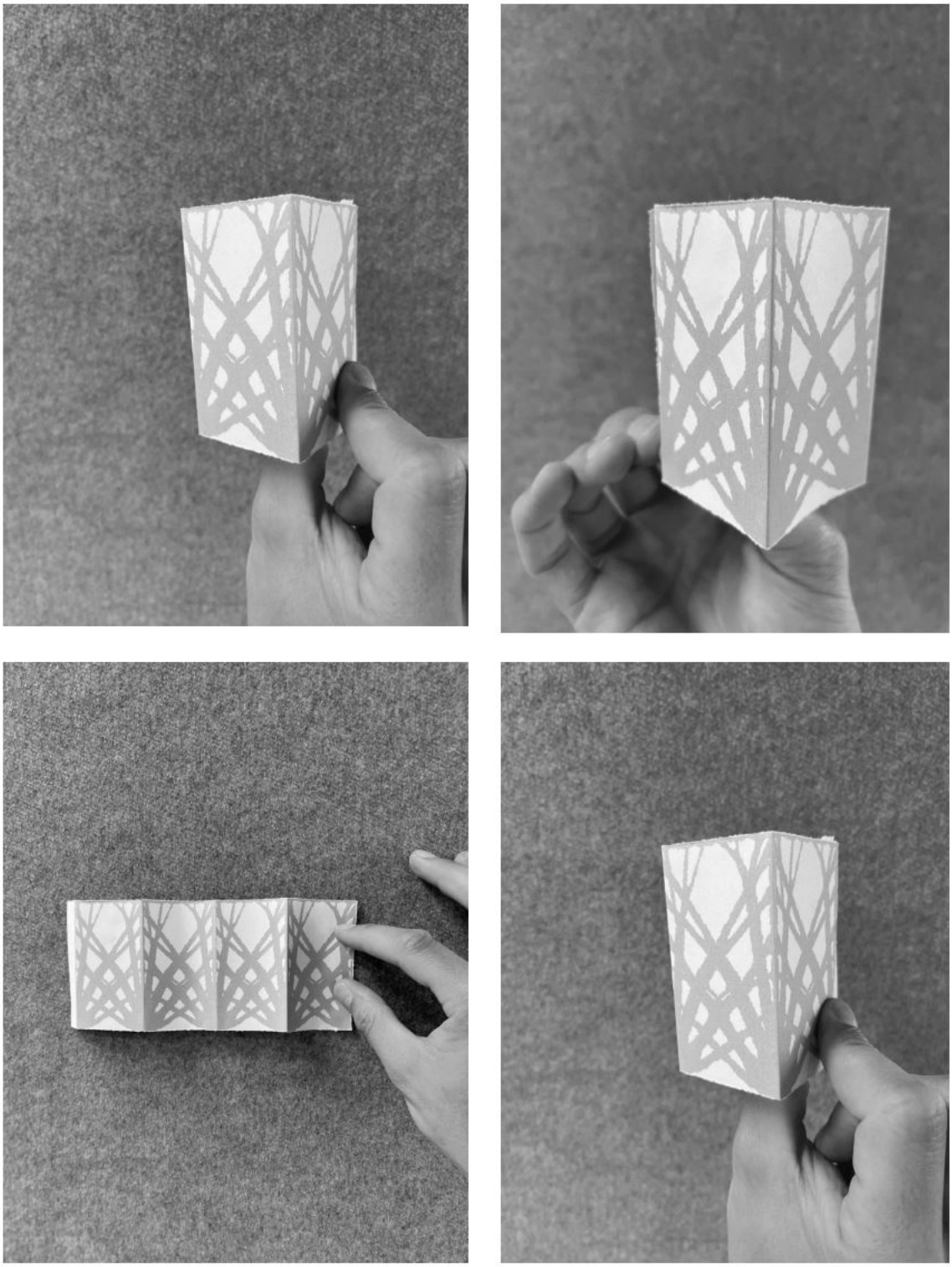
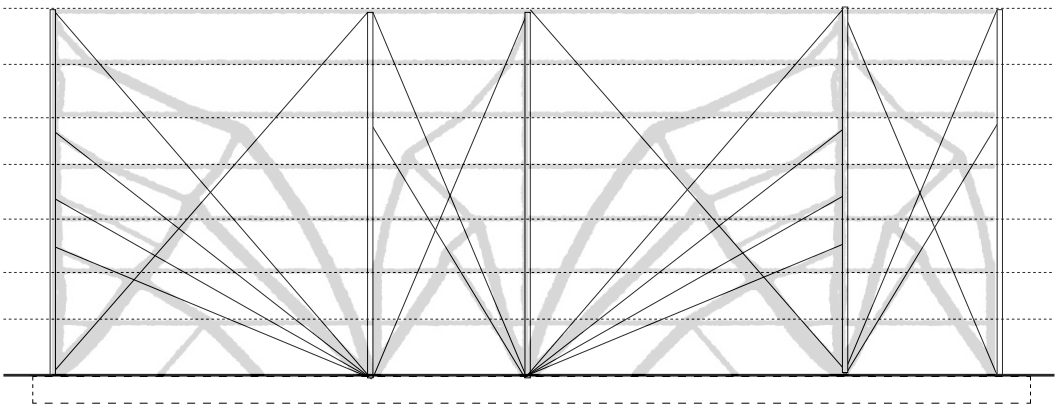
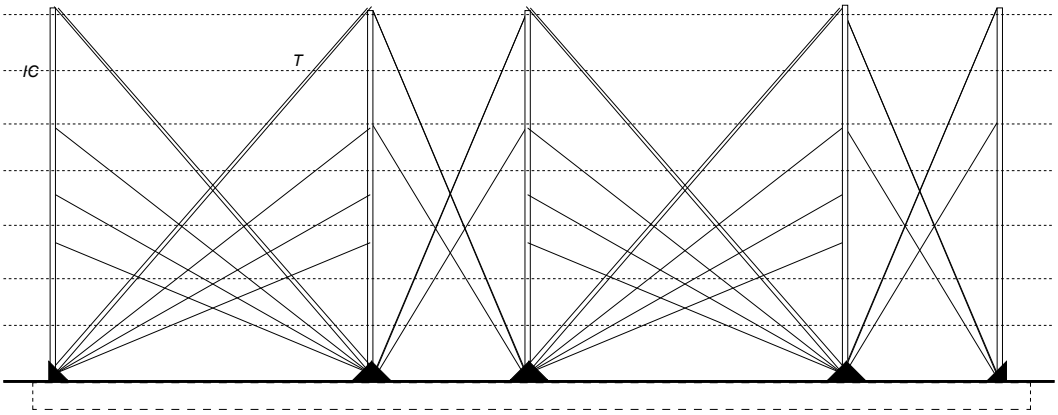


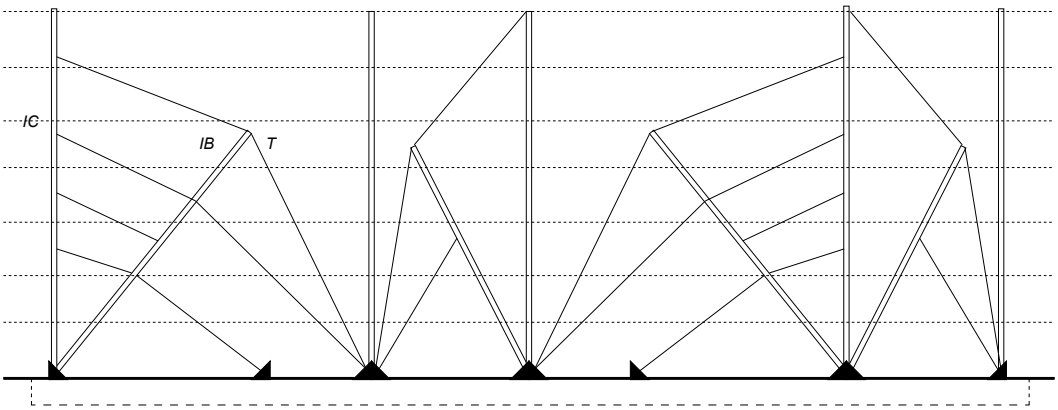
figure 2.3.2
wrapping, a structural draft for the engineer



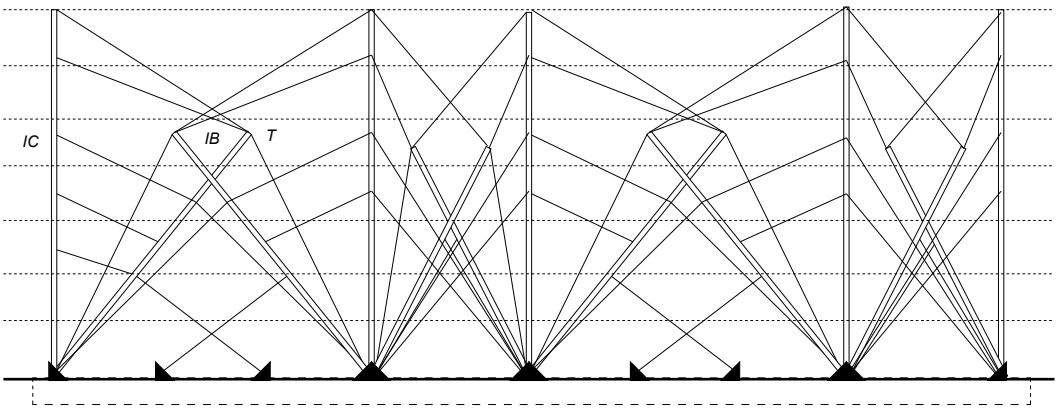
2.33
mono-lateral tensile structural draft
from compressive mesh iteration 1



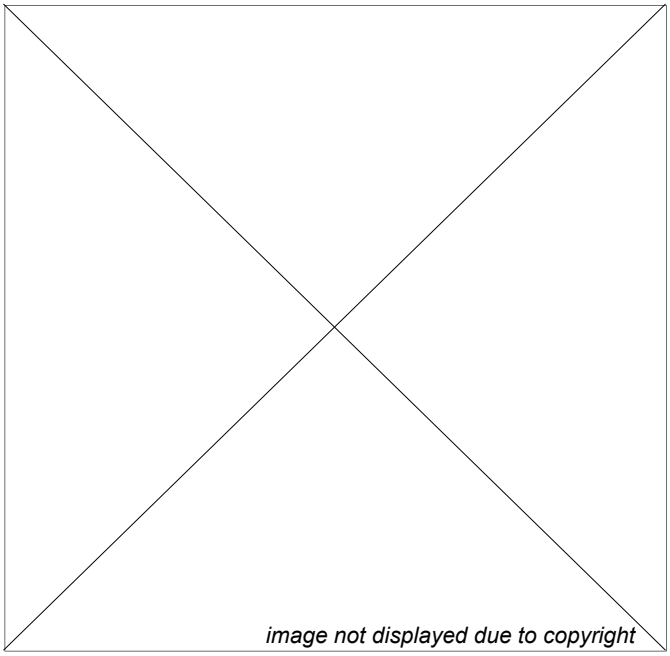
2.34
pro-lateral tensile structural draft
iteration 2



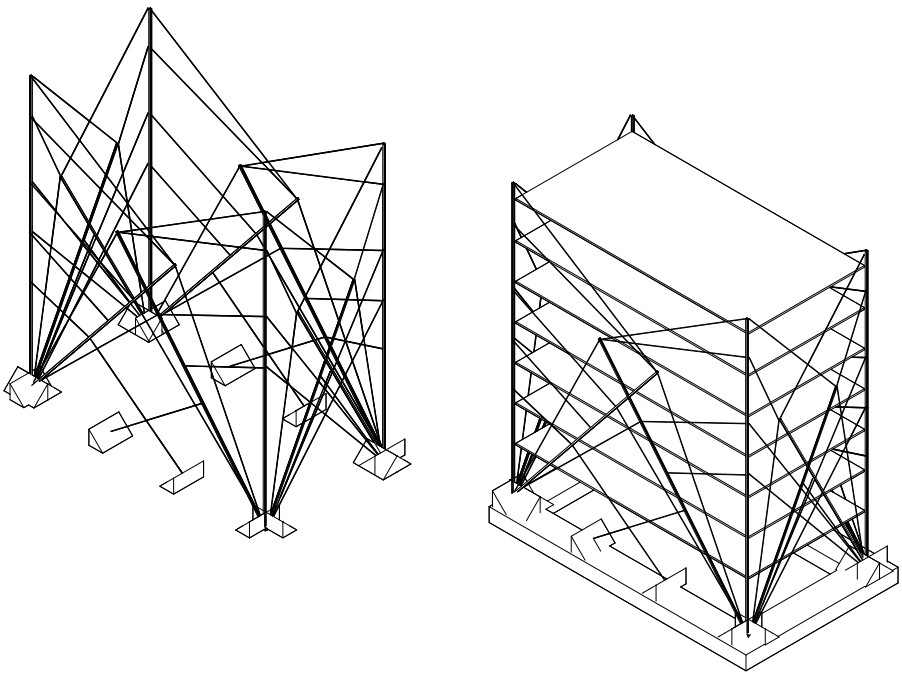
2.35
mono-lateral tensile structural draft
iteration 3



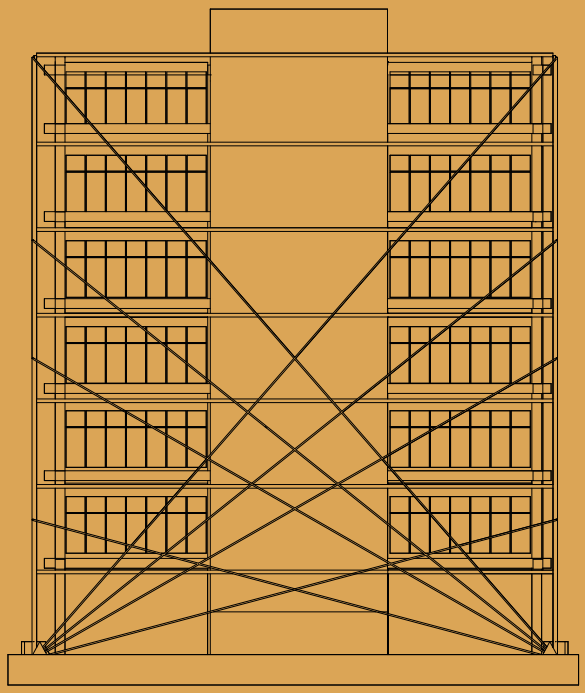
2.36
pro-lateral tensile structural draft
iteration 4
note: connection to NDD at each floor

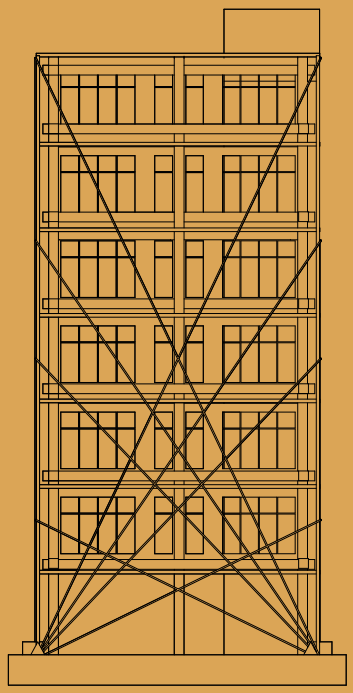


2.37
Charlson et al (2000) footing detail for R House retrofit.

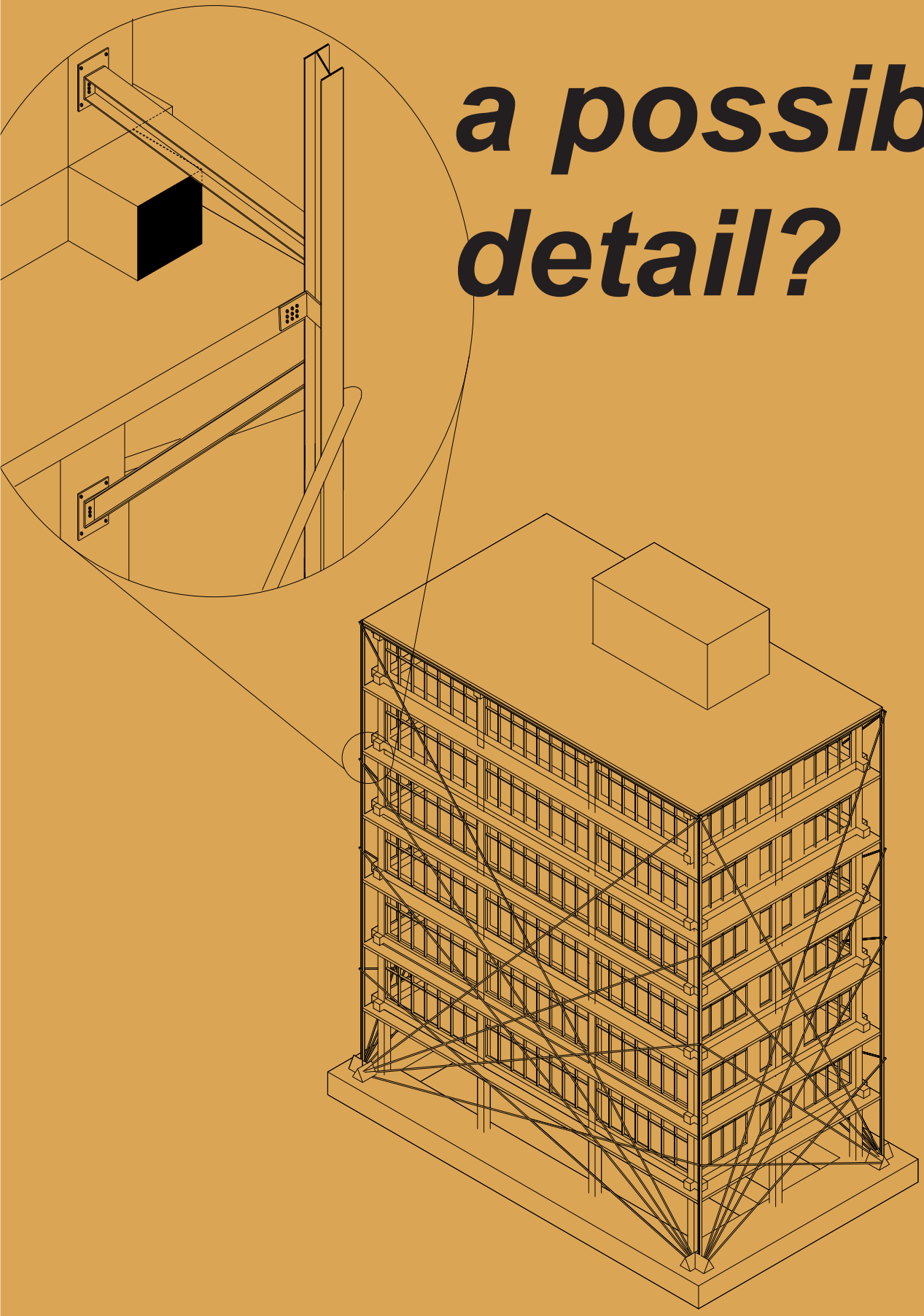


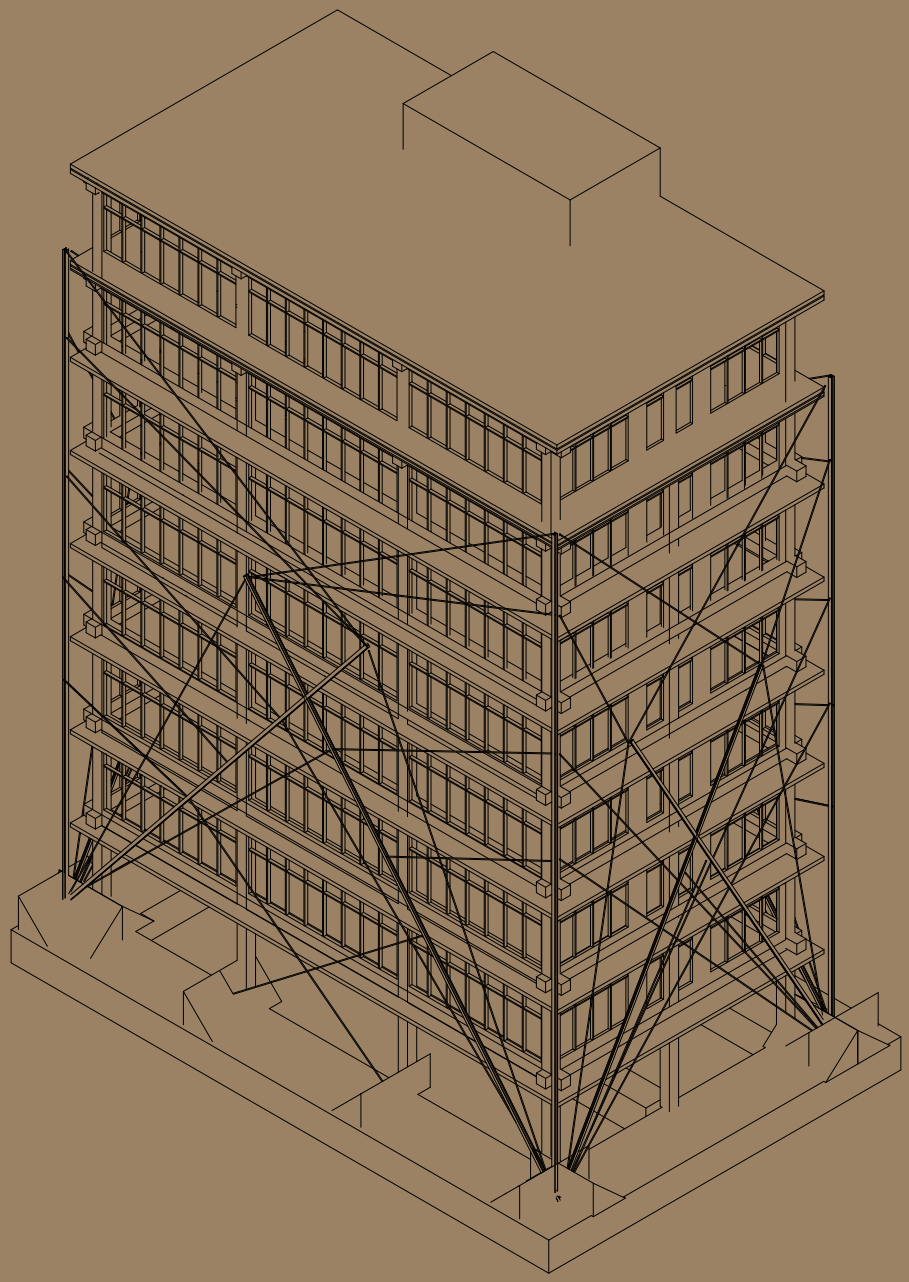
2.38
3d Isometric of wrapped pro-lateral tensile structural draft
iteration 4





a possible detail?





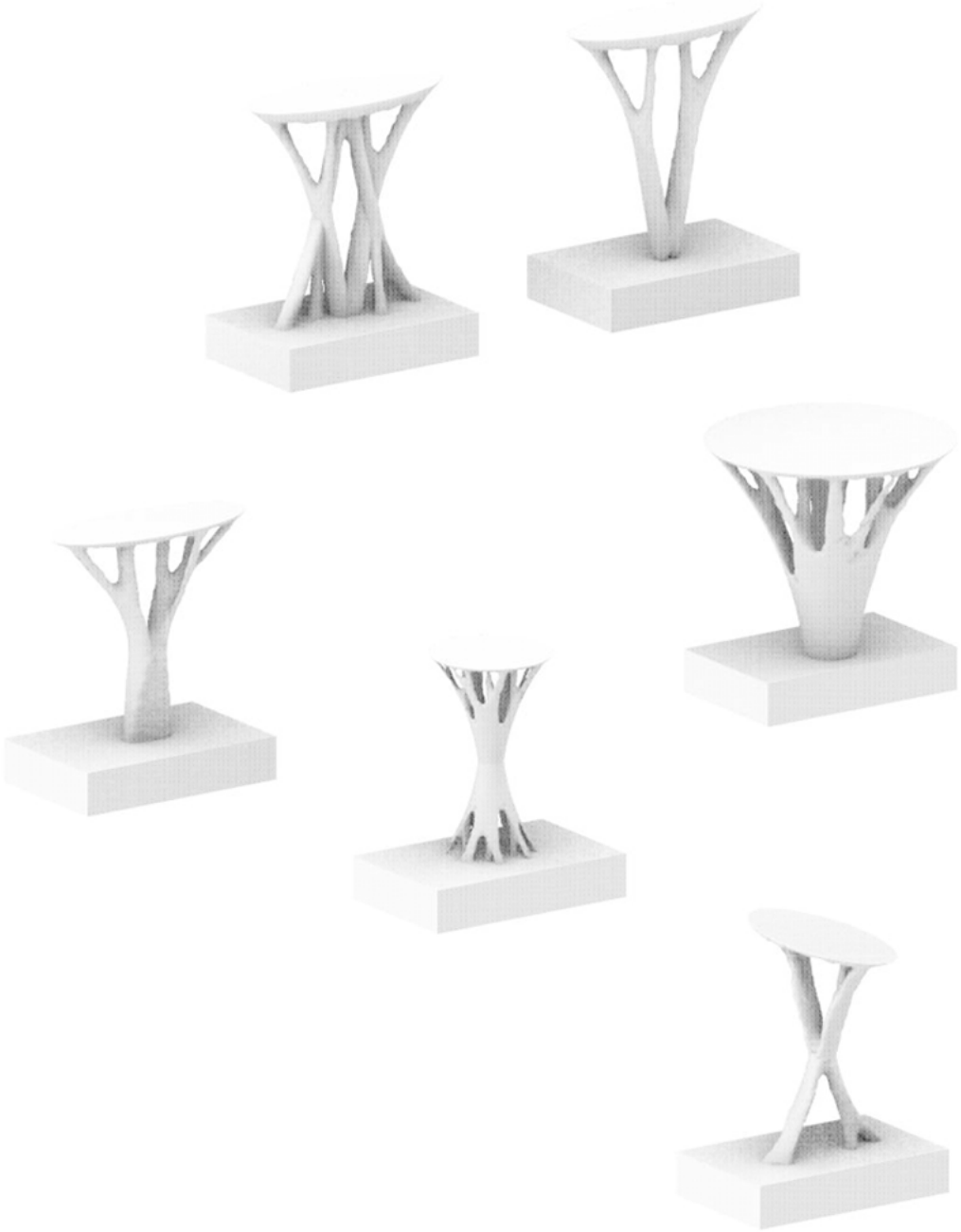
2.42
isometric pro-lateral tensile structural draft iteration 4

CHAPTER III

generation of mirco items

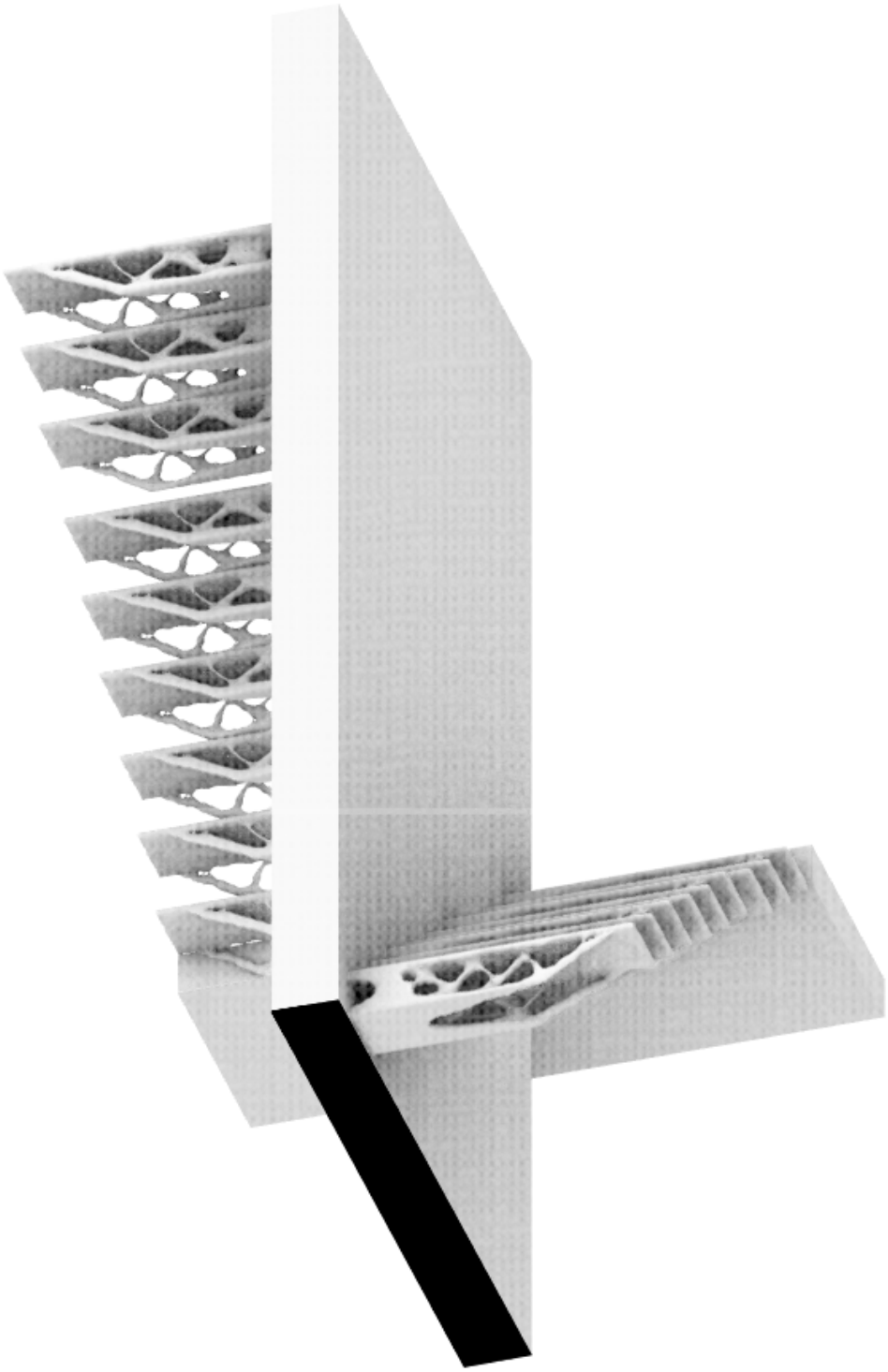
Chapter III is a study of micro elements: generation of micro items: columns, stairs, stair treads, stair landings, spiral stair. Considering each fundamental architectural item as a separate entity, then optimizing, provides visibly interesting outcomes. The resultants in this chapter are meshes, of low resolution. **Columns** 3.1•→ when optimized have tendencies to *tree-out*, settling with mass concentrated at the base. The reverse can be made, *rooting*, to resist uplift[42] and add character. **Stair landings and treads** 3.4•→ can be created showing cantilevers. **Beams** can be optimized as a separate entity, despite the push in this dissertation towards homogeneity (the floor and beam are one item constituting a spanning item; and with a column, it is a standing item as it works as a brace). The following chapter will display an array of topologies specific to a function.

3.1
column pavillion

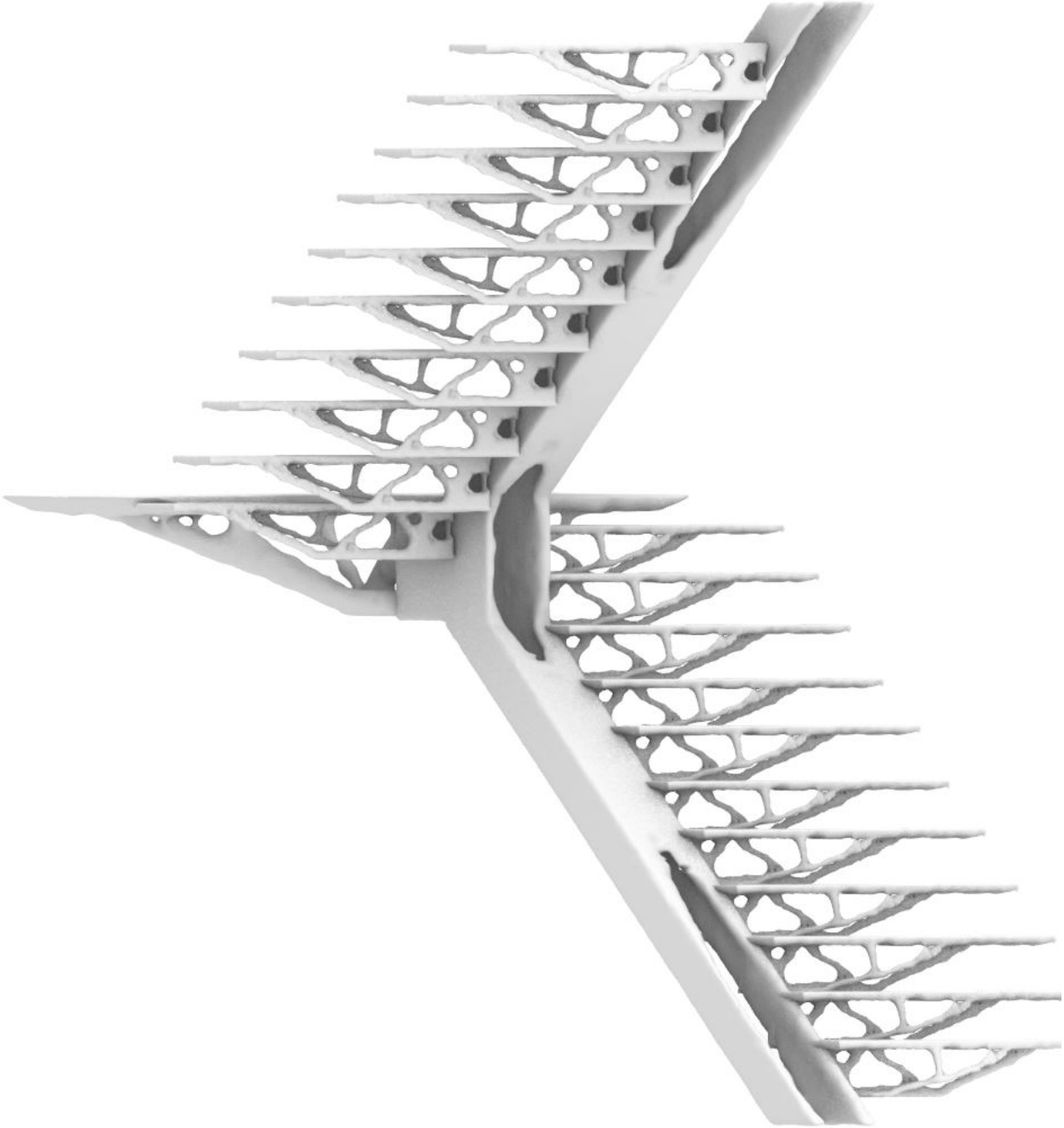


3.2
taxonomy of treeing columns; where meshes exist, resolution becomes problematic

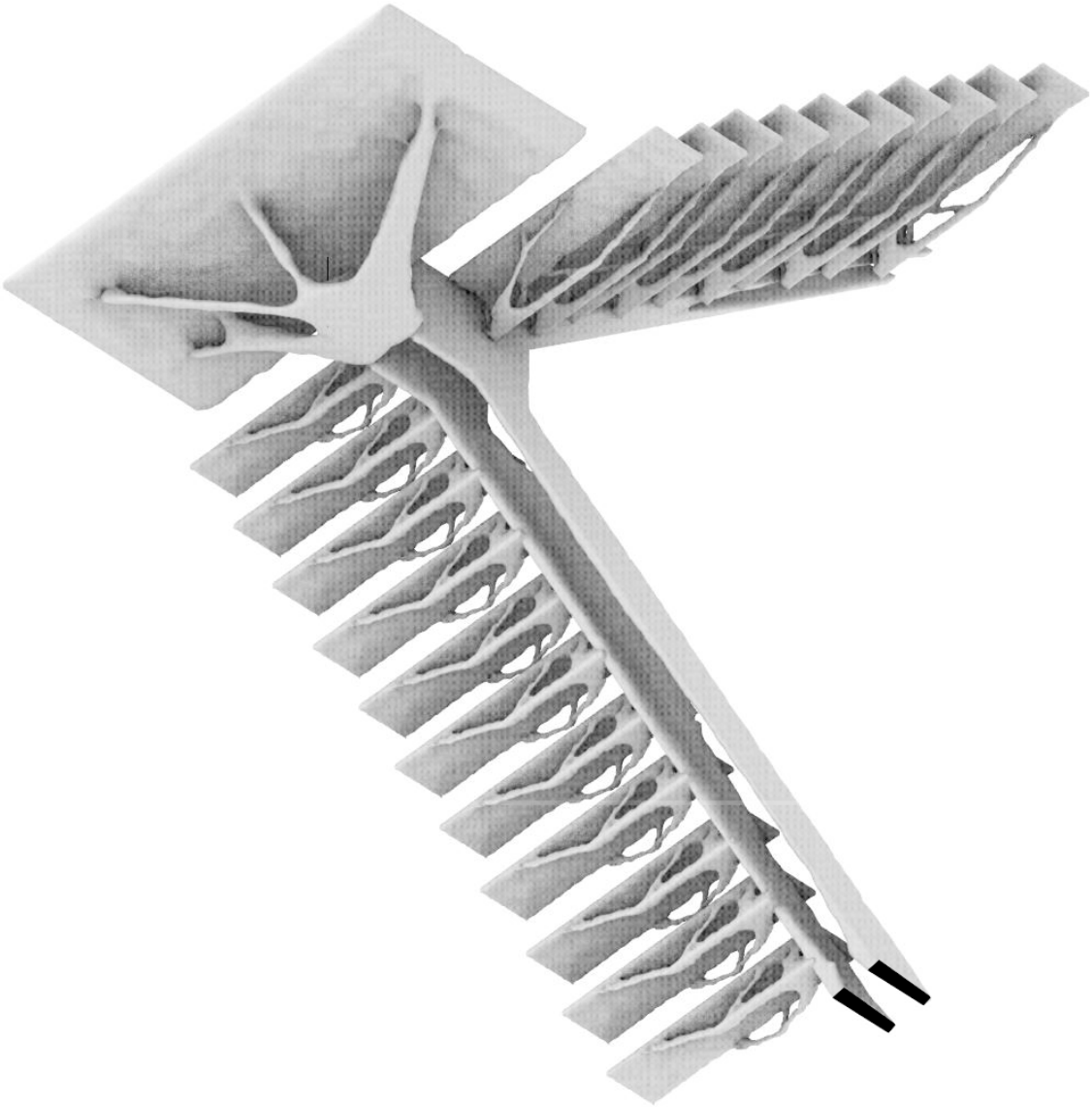
3.3
stair



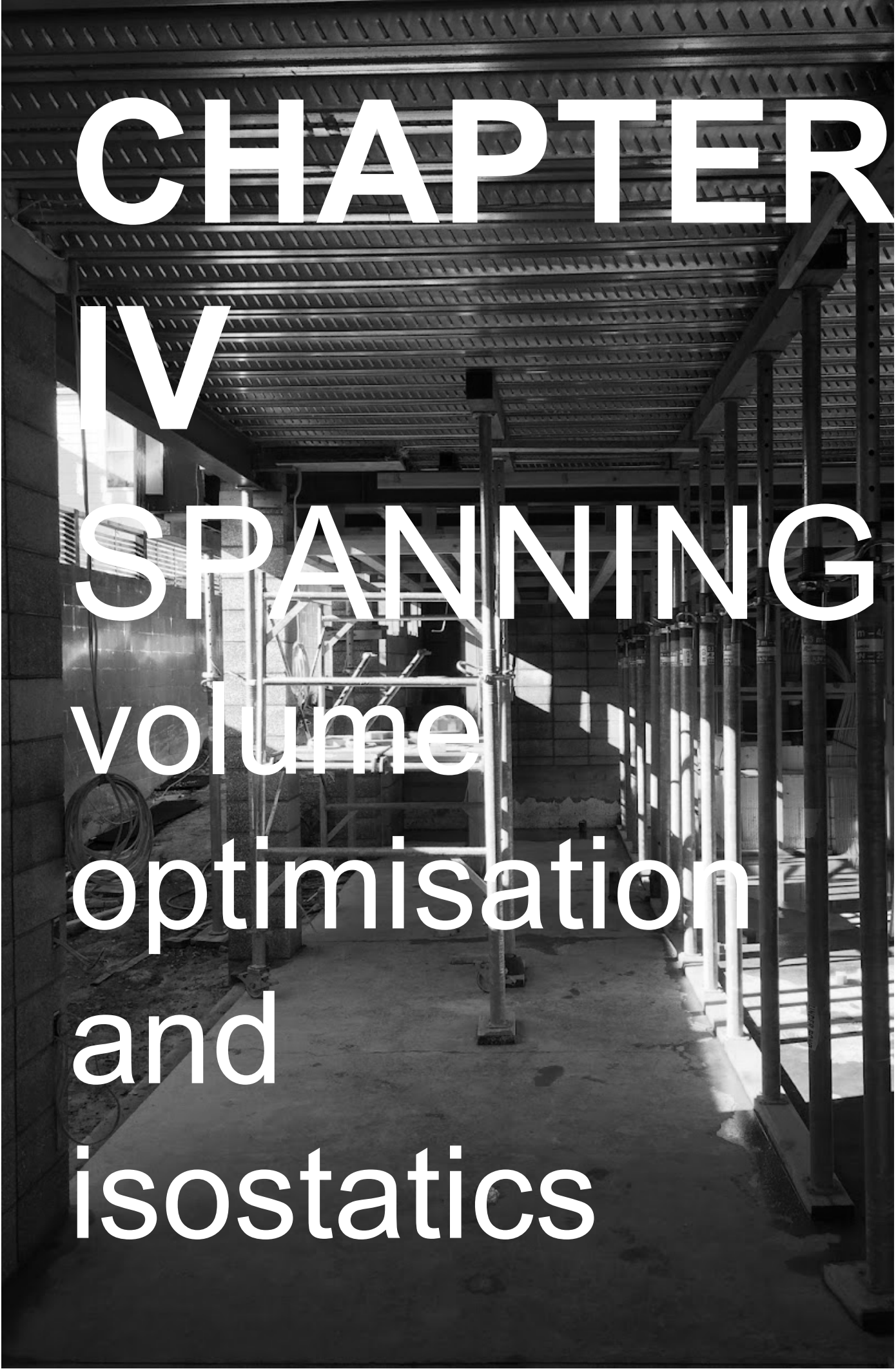
3.4
worms eye isometric cantilevered treads on wall



3.5
stair treads, landing and frame



3.6
stair treads, landing and frame

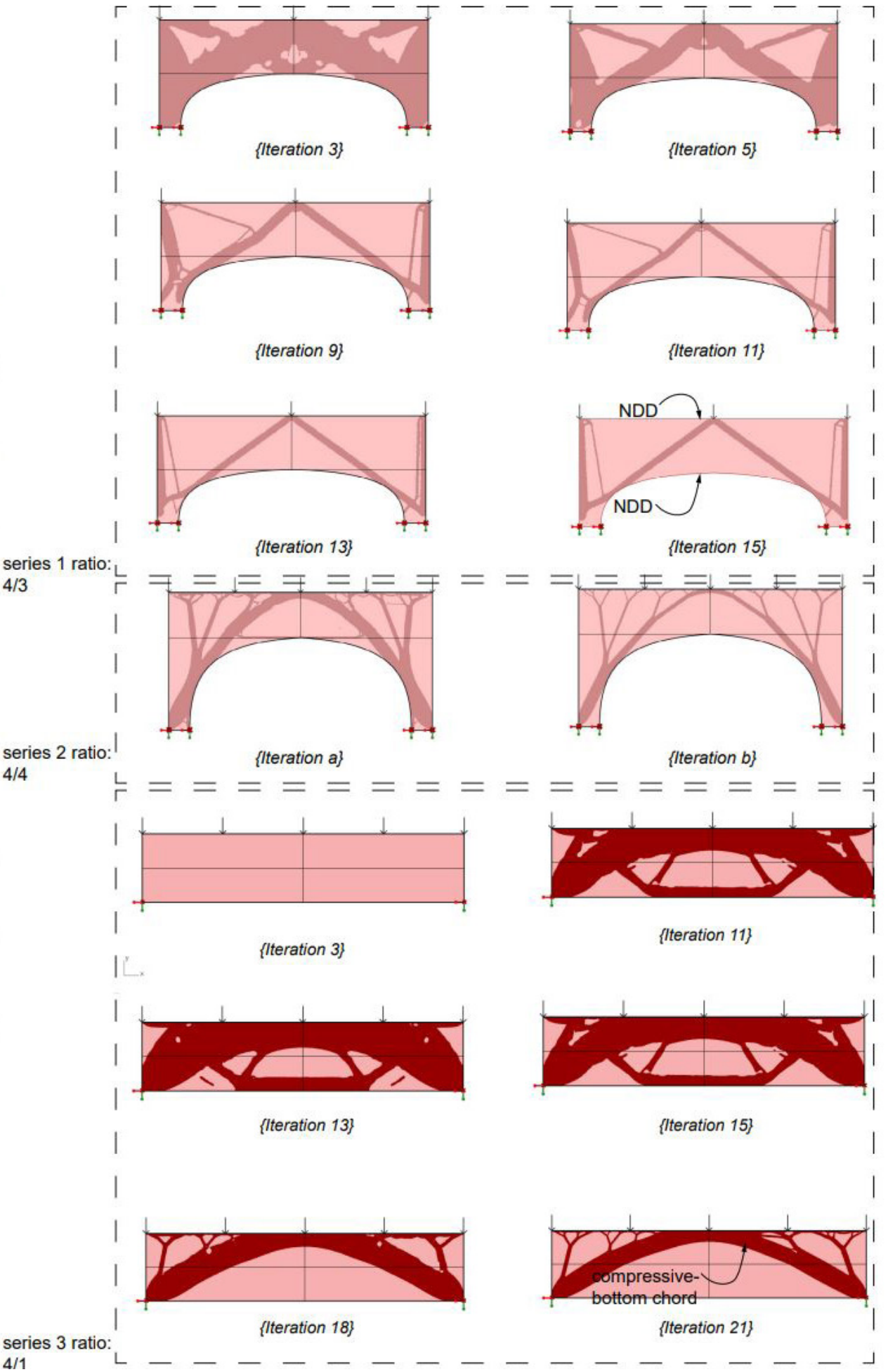


CHAPTER IV

SPANNING

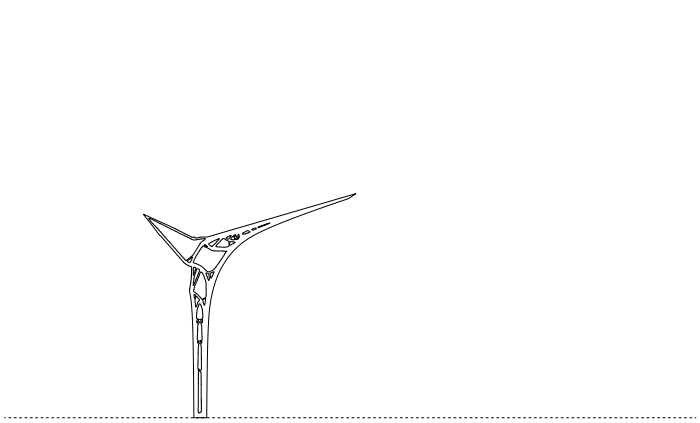
volume optimisation and isostatics

4.2
the craft age


{Iteration 3}
{Iteration 5}
{Iteration 9}
{Iteration 11}
NDD
NDD
{Iteration 13}
{Iteration 15}
series 1 ratio: 4/3
{Iteration a}
{Iteration b}
series 2 ratio: 4/4
{Iteration 3}
{Iteration 11}
{Iteration 13}
{Iteration 15}
compressive-bottom chord
{Iteration 18}
{Iteration 21}
series 3 ratio: 4/1

CHAPTER IV is concerned with spanning items: **sectional optimization** and I**sostatics**, and then a combination of the two. The chapter can be summarized: when force is followed in spanning items, BESO suggests all items should arch; the bottom chord which acts in compression (like a shell) can be further optimized through stress line ribbing, known as Isostatics, where the line of principle stress is indicated computationally, and the thickened in the floor slab[43]. Developing spanning items involves the acknowledgment to the Italian school (Nervi, Danuosso), Adriaessens et al (2019) for structural analysis on Isostatics, Jiang (2019) and Jipa (2016) to produce optimized precedents. Kirdeikis (2020) provided important scripting for the conversion of stress line to mesh (quadmeshing).

Having discussed principal stress lines, this section considers **spanning volume optimization**, focusing firstly in 2- dimensional short section using the repeated loading with different depth dimensions to understand characteristic changes. There are distinct differences in the characteristics of spanning items with BESO, premised on fixing type and location (is it side fixed or ground fixed?), height to width ratio in short section, and loading condition (gravity, lateral loading left to right, uplift), material properties and BESO parameters, as described by the iterations 4.3• ←. 4.4 • → is fixed at 4 points, with a shallow depth, and a height to span ratio of 0.5/15, 2500mm clearance above head height requiring no non-design-domain constraint except for the flat floor it is needed to support, and a 50% volume reduction, develops a highway or bridge box girder section. The void created is a means of a truss, bottom in tension, and an compression arch as illustrated. We can fit the horizontal distribution of services in this void, meaning fire rating is inherently achieved as well as



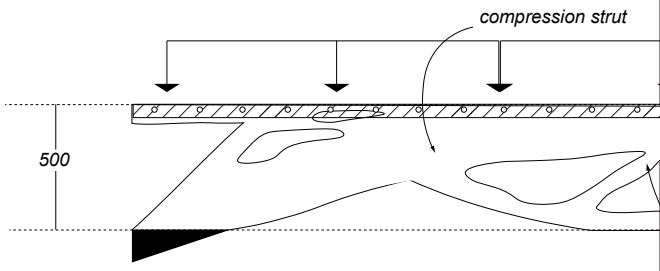


Figure: 4.4
note: BESO spanning short section
ER: 6%; RMIN: 0.05; VF:50%; IT:20
fixing type: 4p fixed base, 0 transla-
magnitude loading: refer to arrows
material: concrete; built ratio: 1/8
SubD:no; NDD: yes, only flat floor

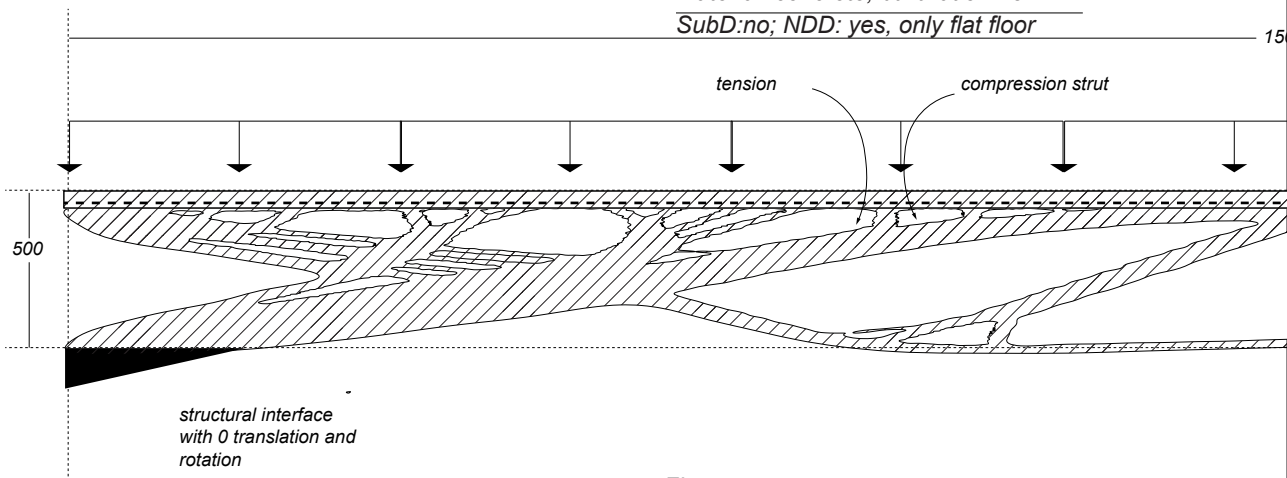


Figure: 4.5
note: BESO spanning short section
ER: 6%; RMIN: 0.05; VF:30%; IT:80
fixing type: 4p fixed base, 0 transla-
magnitude loading: refer to arrows
material: concrete; built ratio: 1/15
SubD:no; NDD: yes, only flat floor

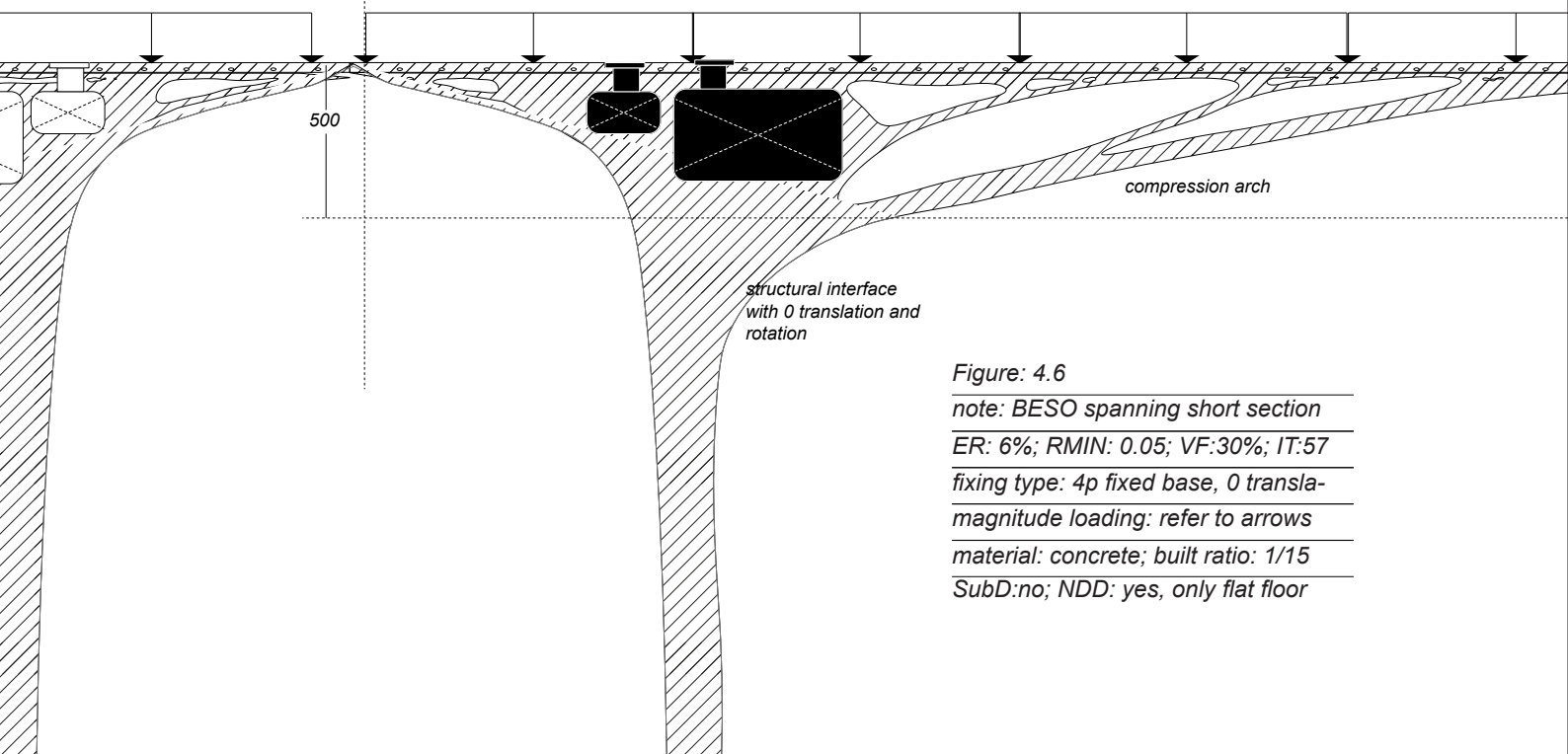
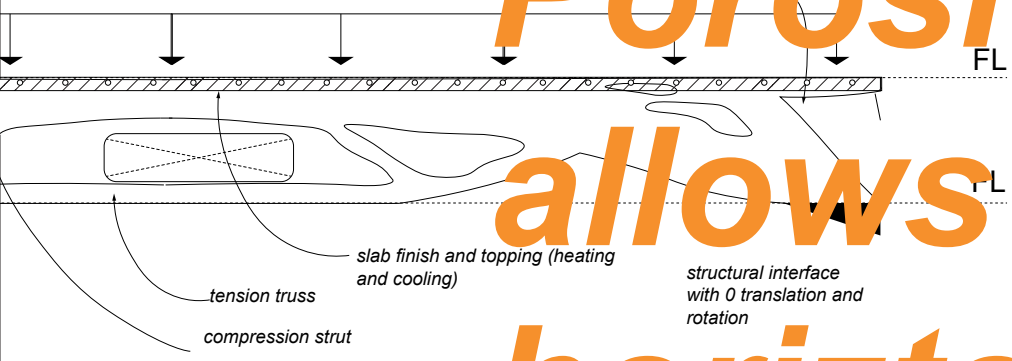
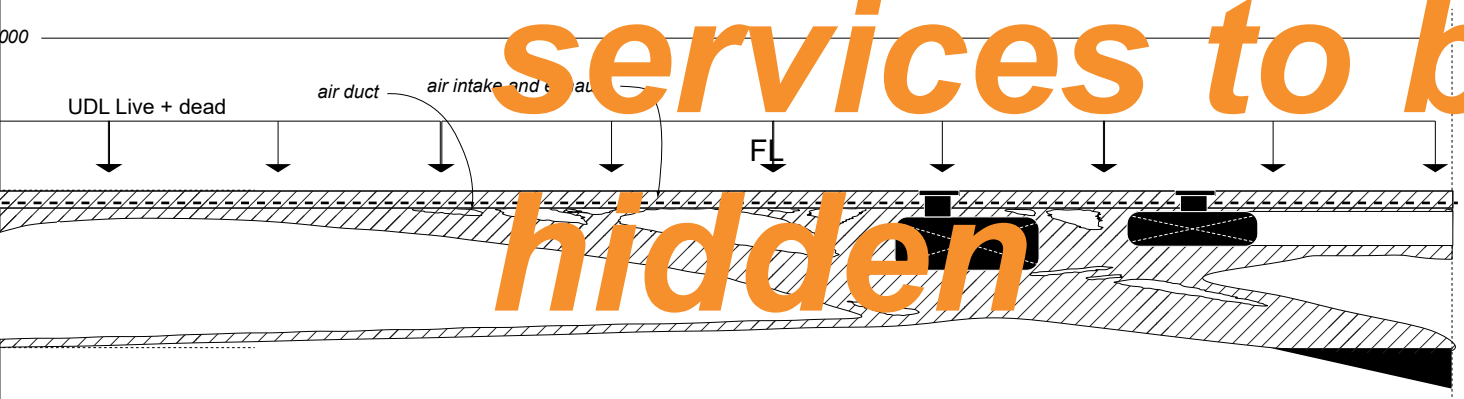
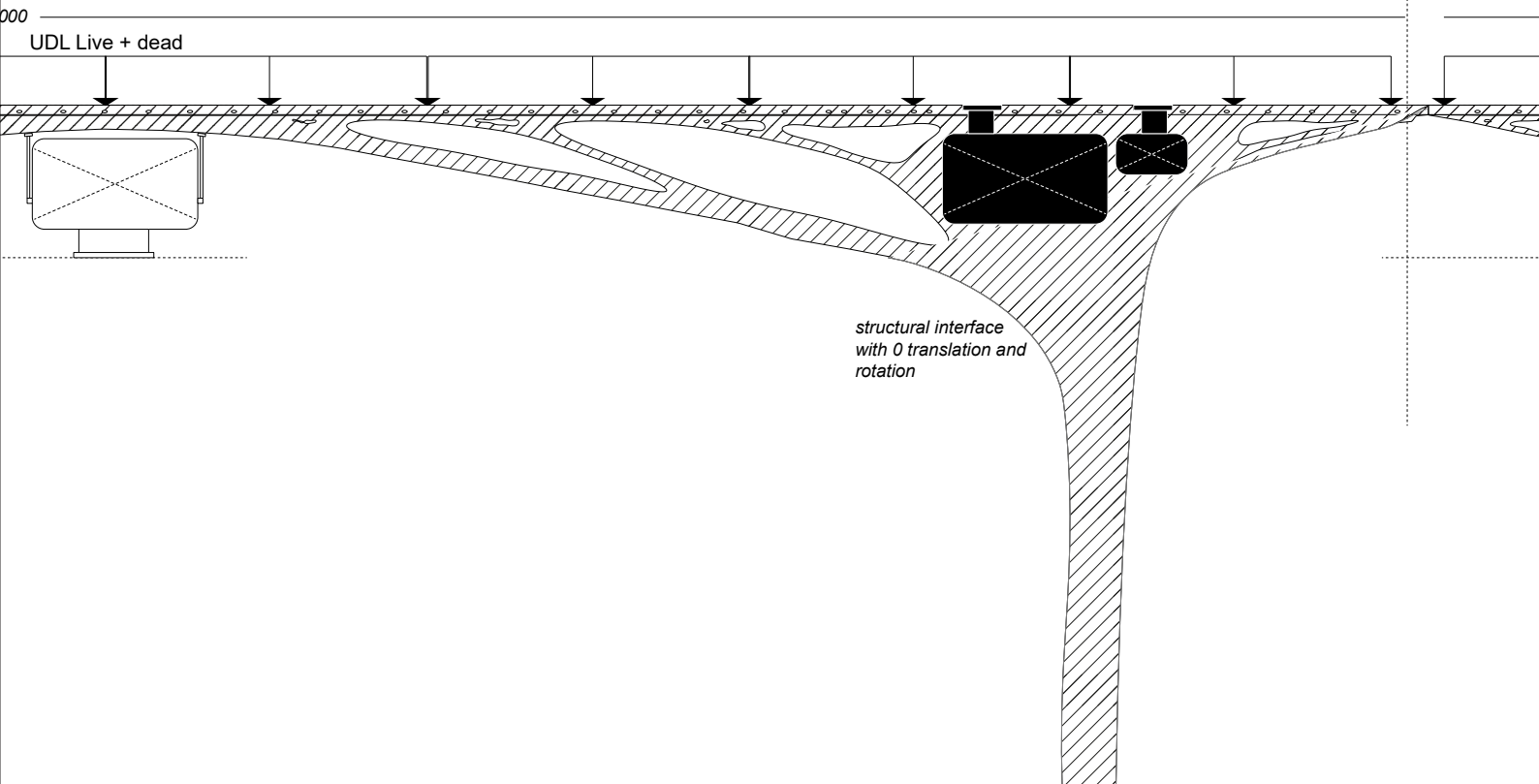


Figure: 4.6
note: BESO spanning short section
ER: 6%; RMIN: 0.05; VF:30%; IT:57
fixing type: 4p fixed base, 0 transla-
magnitude loading: refer to arrows
material: concrete; built ratio: 1/15
SubD:no; NDD: yes, only flat floor

Porosity allows certain horiztonal services to be hidden







the purity of form (because the services are concealed, the ceiling is homogeneous to the floor: all is one material). We see the depth required in commercial floor construction for beams, MEP, services, liquid services, heating pipes colling pipes; plumbing and drainage, general air handling et cetera. The inherent properties of the floor does not integrate services nor follow the basic principle of the optimal passage of force. Spanning items (floors + beams), when force is followed, should theoretically not be flat, but arched. The geometry should be thicker around the periphery and thinner in the middle like a bridge. When depth is not possible and a spanning item must be flat underneath, Isostatics provide a novel methodology for optimizing a flattened slab.

4.5• ← maintains 4-point support system fixing in section, however, has a lateral loading system applied in the x direction, and is left to resolve 80% material, creates a asymmetrical truss type snape maltings, and a compression arch. We can quickly draw conclusions that the tension element works like reinforcing in a simply supported beam, and the arch, mimicks concrete [22]. The floor is considerably thinner in the middle section, reduced to 75mm. A treeing effect of structure is used to support the 50mm floor. *Figure 4.8•* → is ground fixed at 2 points, with a 3500mm depth, and a height to span ratio of 1/1, a 2500mm radial clearance non design domain and a 80% volume reduction, results in a 'treeing' effect and a 75mm thinning centre thickness of the floor. The result mirror's Frei Otto's short path tests. There is a important difference between allowing depth and a 2 point fixing, primarily being the column merging into the floor. *Figure 4.8•* maintains the same loading as *Figure 4.7•* however, it does not use a radial non design domain to allow for more lettable space. An alternative solution is to define an initial geometry that predetermines voids for services in its boundary condi-

tion. The resulting spanning topologies put material in necessary areas to transfer force in similar capacities to Arup's 49 x 1.3 metre spanning concourse moment beams in the Sydney Opera house. The beams change section profile over the span from a T mid span to a U on the end points, putting the concrete and steel reinforcing in the most effective location; a response to wasted un-working material. The results can be described as structural honesty. 4.7• represent an iterative series of a spanning element. The steps taken are:

1. Optimize a base boundary condition of 500mm X 15000mm available depth (too allow for arching and porosity for services) at 90% material reduction to allow for the most critical paths to be established. High VF of 10%: structure must prioritise,
2. Once the boundary is defined, VF is relaxed to 40% measures by optimising at a slower rate inside the initial optimized boundary condition with a non-design domain of 100mm topping slab.

4.9, 4.10, 4.11 • compare the internal forces of a BESO derived solution, to a typical concrete beam with bent barred reinforcing, and a Howe truss. The tension elements between all three figures show similarities: tension in *4.10*• resembles bent bars in reinforcing of a typical concrete beam. The horizontal reinforcing bars resist the bending moment (highlighted red), while the bent bars which are diagonal (highlighted blue) resist the extreme shear force that is at its greatest at the ends of the beam. The bent bar is inherently shear resisting and performs more effectively than regular stirrups which are perpendicular to the length of the beam but are used due to the ease of construction. The bent bars make the steel 'work harder'. We see parallels to Rice's Gerberette's and Utzorn's concourse beams in which the customised profiles change relative the extent of bending moment or shear calculated to

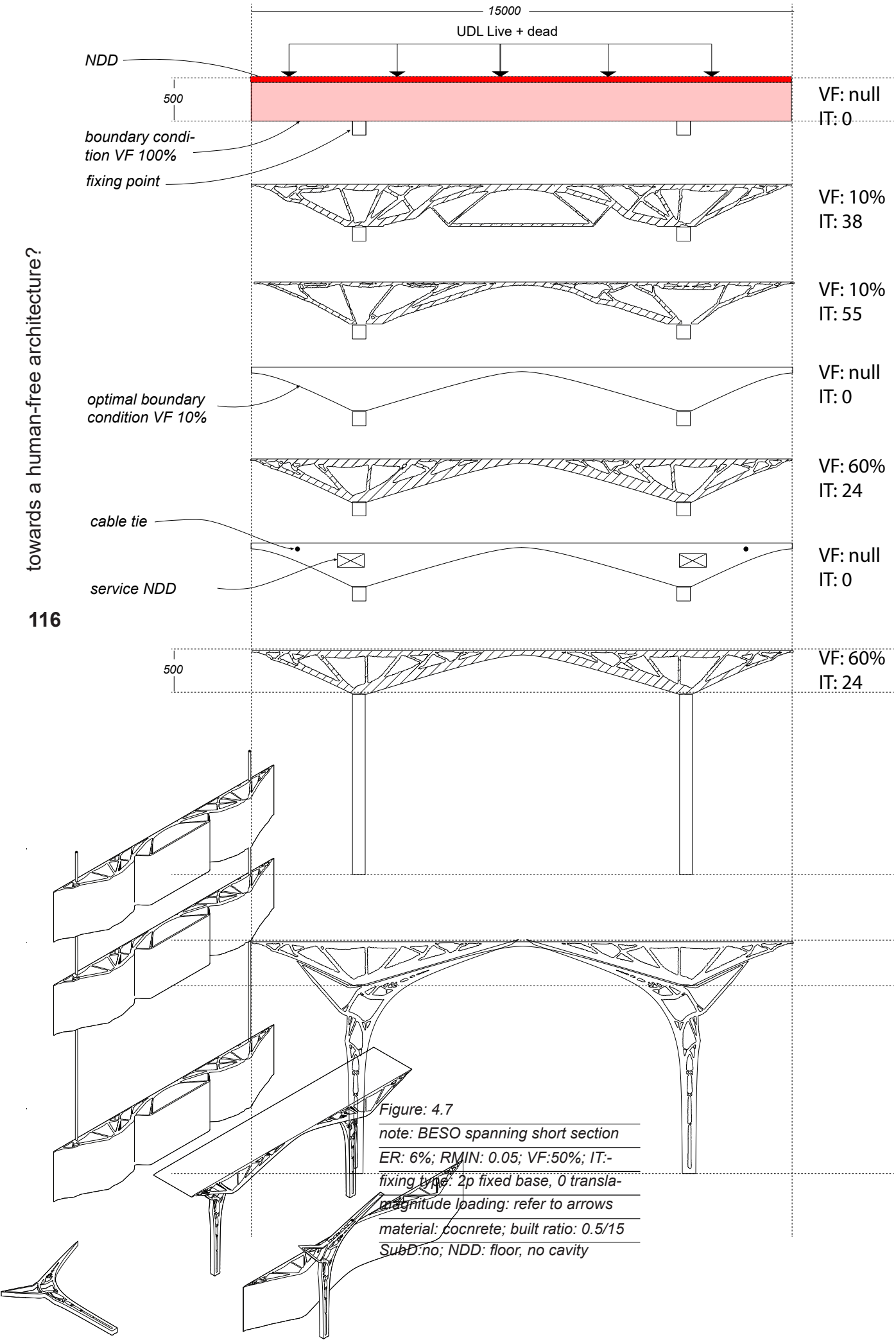


Figure: 4.7

note: BESO spanning short section

ER: 6%; RMIN: 0.05; VF:50%; IT:-

fixing type: 2p fixed base, 0 transla-

magnitude loading: refer to arrows

material: cocnrete; built ratio: 0.5/15

SubD:no; NDD: floor, no cavity

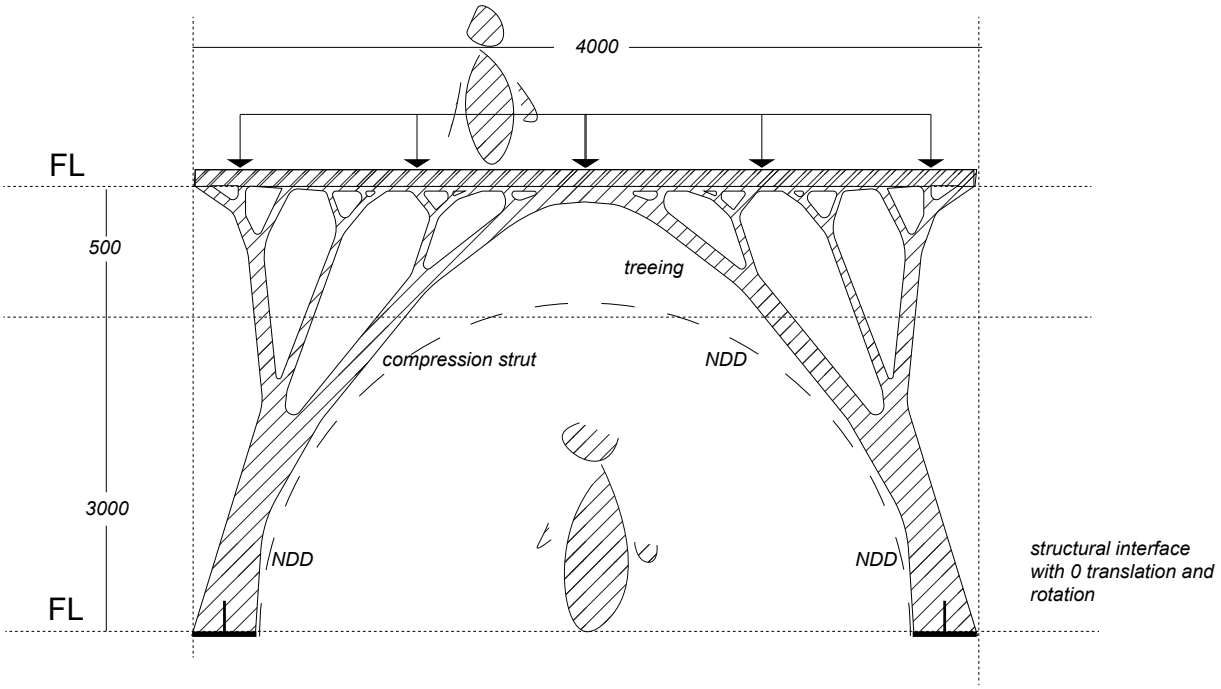


Figure: 4.8

note: BESO spanning short section

ER: 6%; RMIN: 0.05; VF:50%; IT:60

fixing type: 2p fixed base, 0 transla-

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: floor, cavity constraint

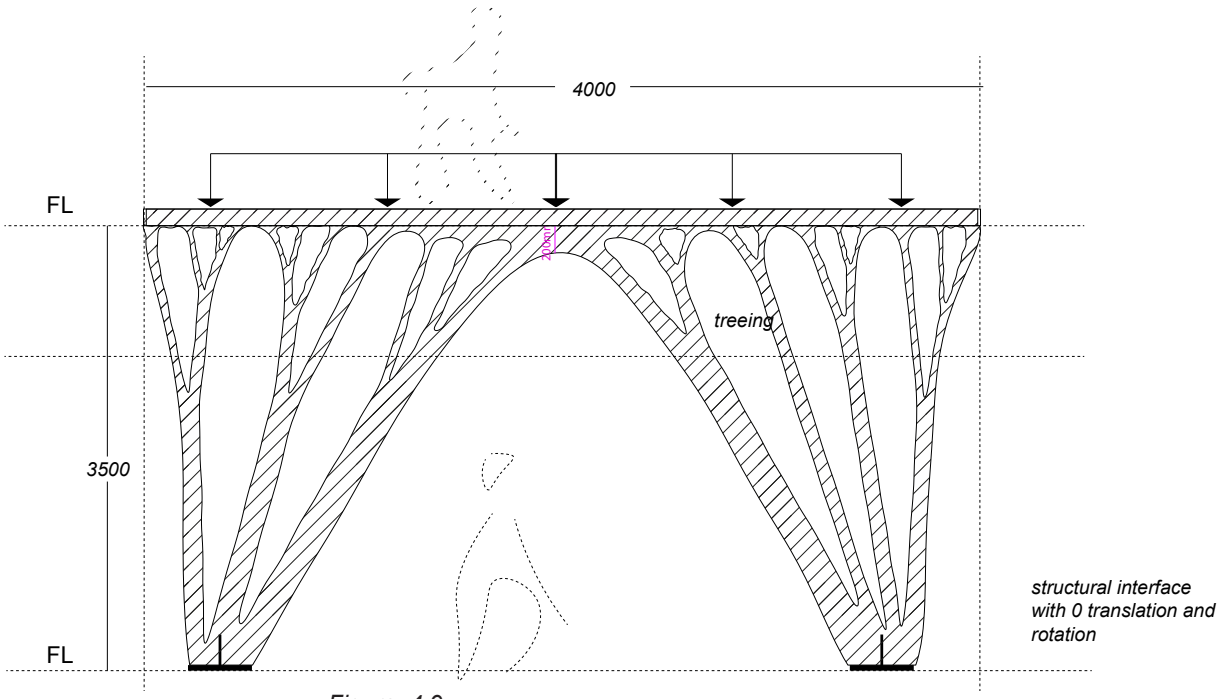


Figure: 4.9

note: BESO spanning short section

ER: 6%; RMIN: 0.05; VF:50%; IT:26

fixing type: 2p fixed base, 0 transla-

magnitude loading: refer to arrows

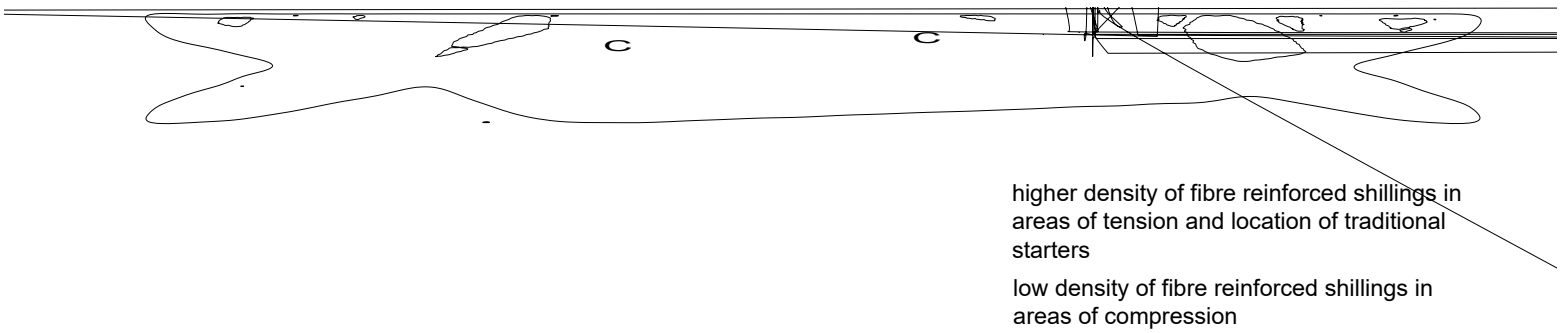
material: concrete; built ratio: 1/1

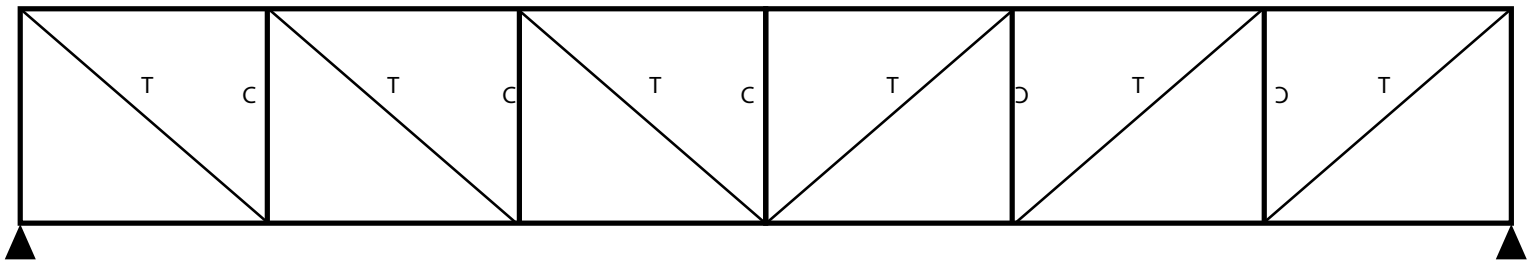
SubD:no; NDD: floor, no cavity

existing under loading; this is done by changing the extents of webbing to take shear force or flange to take bending moment[44]. 4.11• displays a tensioned truss struts are thin and provide structural efficacy with minimal material[22].

4.13• describes a typical solution where BESO works to negotiate a loading condition. *Figure 4.14* demonstrates when an initial geometry is defined with voids for services, the BESO works around the voids to negate and form a responsive structure. Koolhaas' chapter in Elements of architecture titled, *Bimness, or , the problem of integration,* negotiates the issue of allowing space for horizontal service distribution through utilising the natural porosity achieved through optimisation. Nnaturally, servicing a large space requires significant servicing and more foresight than proposed here: how could services be replaced, maintained?. By creating porosity through volume reduction, we achieve: a) a more elegant structural solution, an arch; b) the homogeneous solution; c) no ceiling, only floor; for rating and visual removal of services: piped liquids, plumbing and drainage, general air handling and all general items needed in horizontal distribution (in a residential scale, these will be significantly less); and material reduction/structural performance. Perhaps most importantly, in large scale buildings where drop ceilings would be a go-to, by using porosity or programming voids as non-design-domains, we escape the reminiscent view one gets during a dentist trip. The figures combine loadbearing, thermal massing, durability, fire rating, low operating costs, climatically inert materiality – only allowing the reduction to necessary items [45].

The short sections demonstrate structural resisting material, inclusive of tension and compression. Simulated with steel in mind, the form works both in compression and tension. In the case of concrete construction, we can theorise a reduction in


C
C
higher density of fibre reinforced shillings in areas of tension and location of traditional starters
low density of fibre reinforced shillings in areas of compression


T
C
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T

reinforcing, as proven by West in his bending moment beams under full scale stress testing. The use of fibre reinforced concrete would allow potential removal of reinforcing bars, with the implementation of different amounts of steel shillings in areas of tension loading opposed to compression based. We can see in 4.10• the differing levels of shilling density measured across the areas of tension and compression, showing efficacy. Where typical areas of starter bars would exist, the shilling technique applies a similar logic. The use of BESO is considered with the fabrication process by simulating formwork themselves and able to be reused and melted for more use, effectively removing the waste. Given the construction industry is a large contributor to waste in New Zealand, contribution 50% of all waste generated[46].

Using Millipede plug in for grasshopper, **Isostatics** (rib thickening in slab) are created FEA is applied and recorded with stress measured. The principle stress lines are rationalized into simplier contoure lines through a process of quad meshing[47]. As a micro study of an element within the building, we can see how stress lines correlate to the connection or homogenization junction with the column. The following Isostatic investigation continues on the following pages.

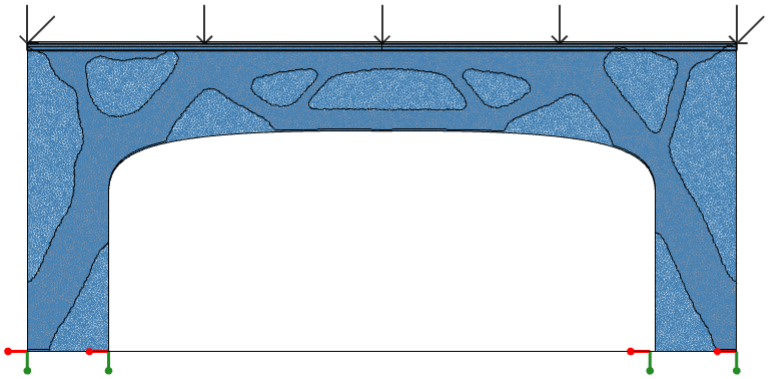


Figure: 4.13

note: BESO from boundary, no voids

ER: 6%; RMIN: 0.05; VF:40%; IT:35

fixing type: 2p fixed base, 0 transla-

magnitude loading: refer to arrows

material: steel; built ratio: 1/8

SubD:no; NDD: floor, and cavity

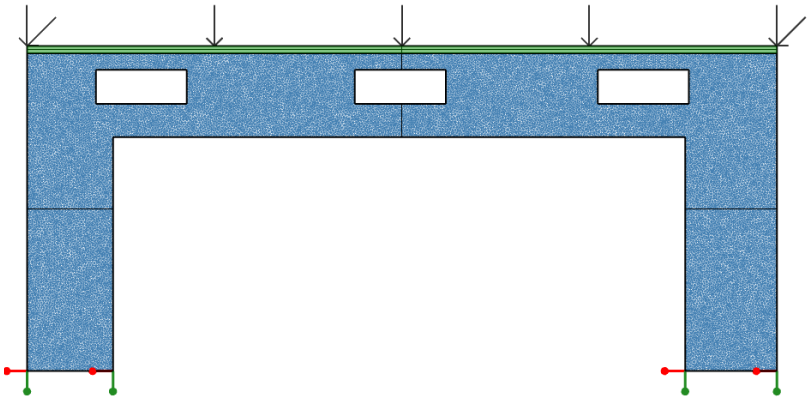


Figure: 4.14

note: boundary condition

ER: 6%; RMIN: 0.05; VF:40%; IT:35

fixing type: 2p fixed base, 0 transla-

magnitude loading: refer to arrows

material: steel; built ratio: 1/8

SubD:no; NDD: floor, and cavity

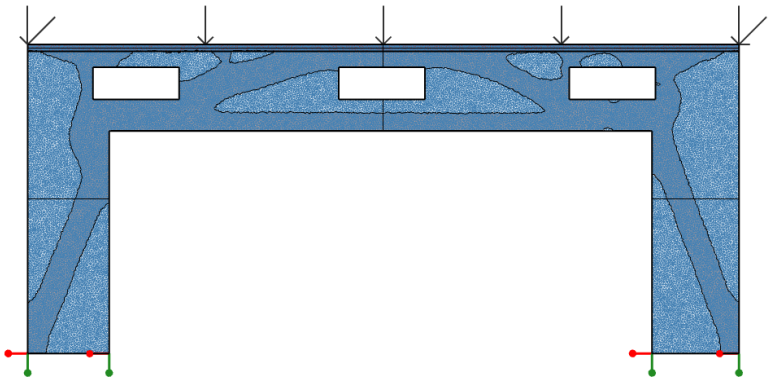


Figure: 4.15

note: frame section with service voids

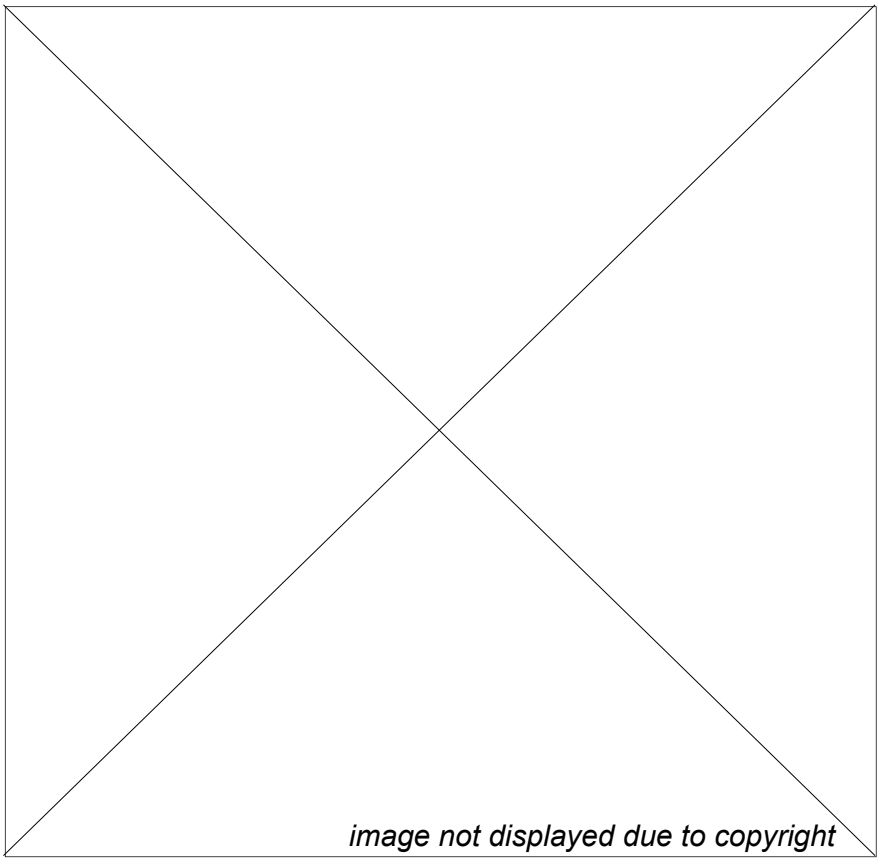
ER: 6%; RMIN: 0.05; VF:40%; IT:35

fixing type: 2p fixed base, 0 transla-

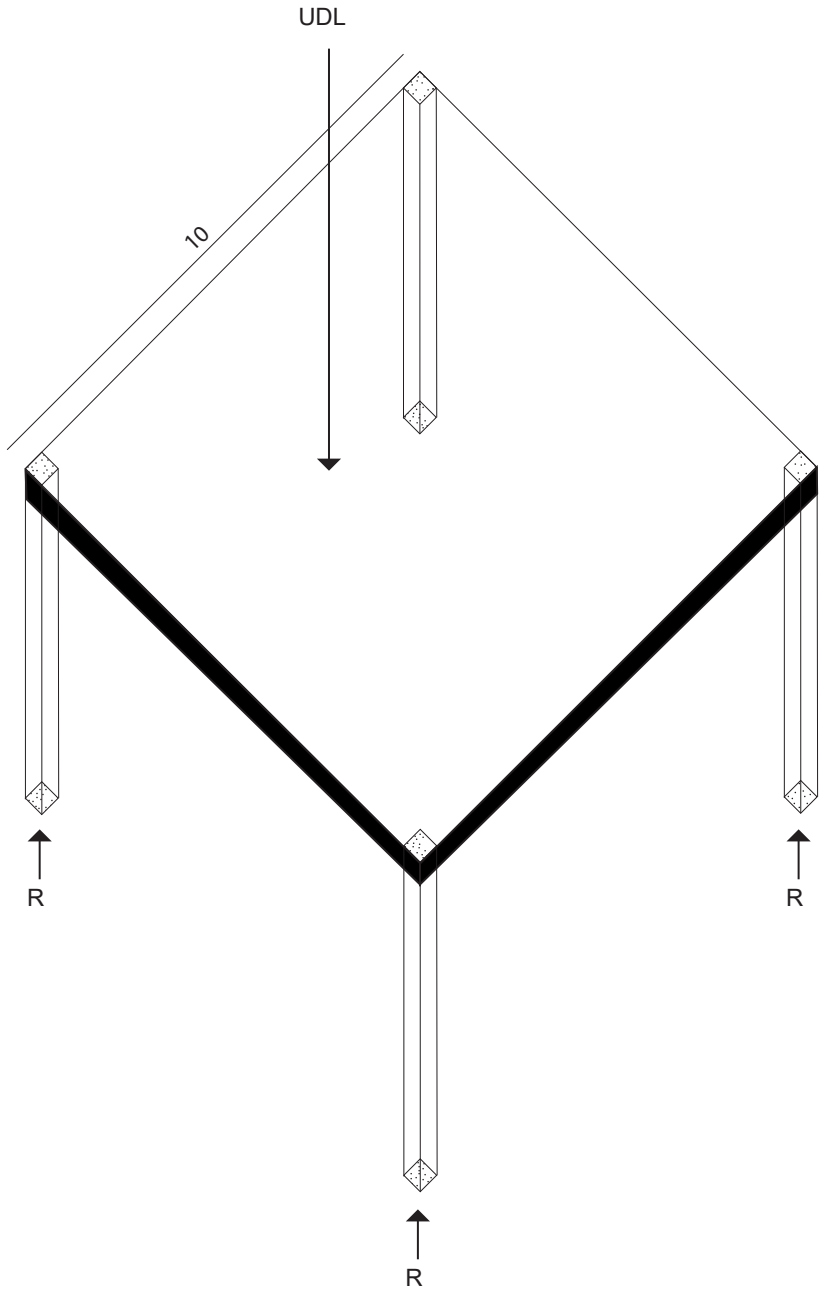
magnitude loading: refer to arrows

material: steel; built ratio: 1/8

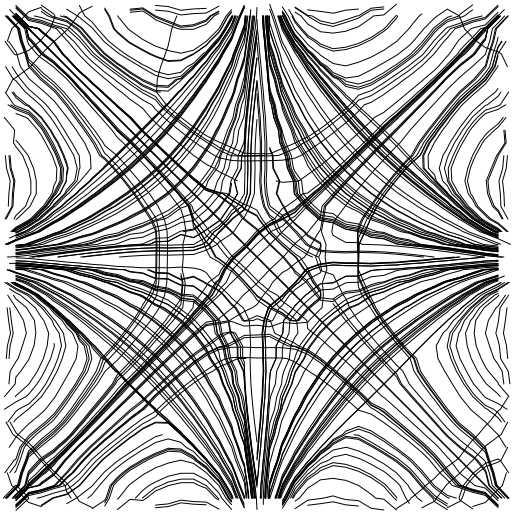
SubD:no; NDD: floor, and cavity



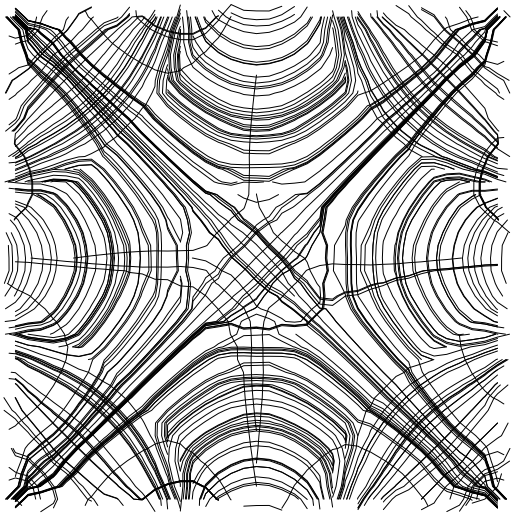
● **1.14** *Orveito aircraft hangers 1935.*
1.15 *Gatti Wool Factory. Nervi. 1952.*



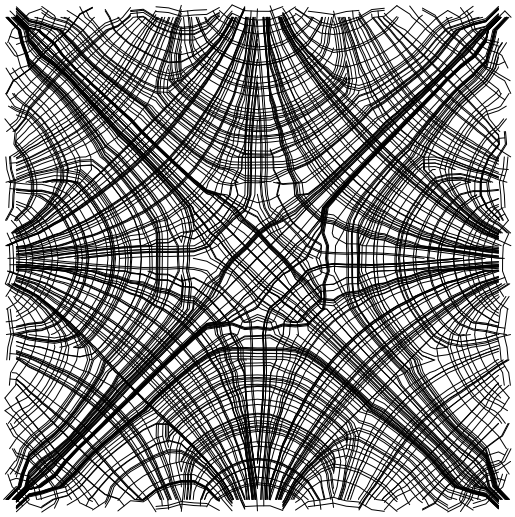
4.15
10 x 10 x 0.2m slab, the starting topology for isostatic optimization



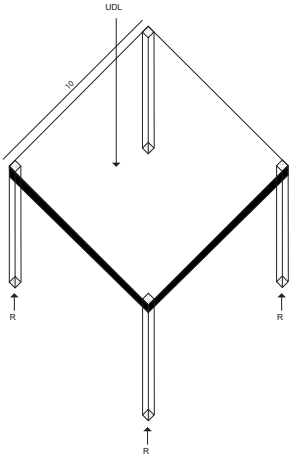
Bending principle line of stress A) for typical 10 x 10 x 0.2m slab

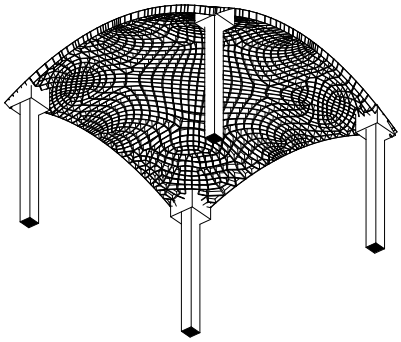


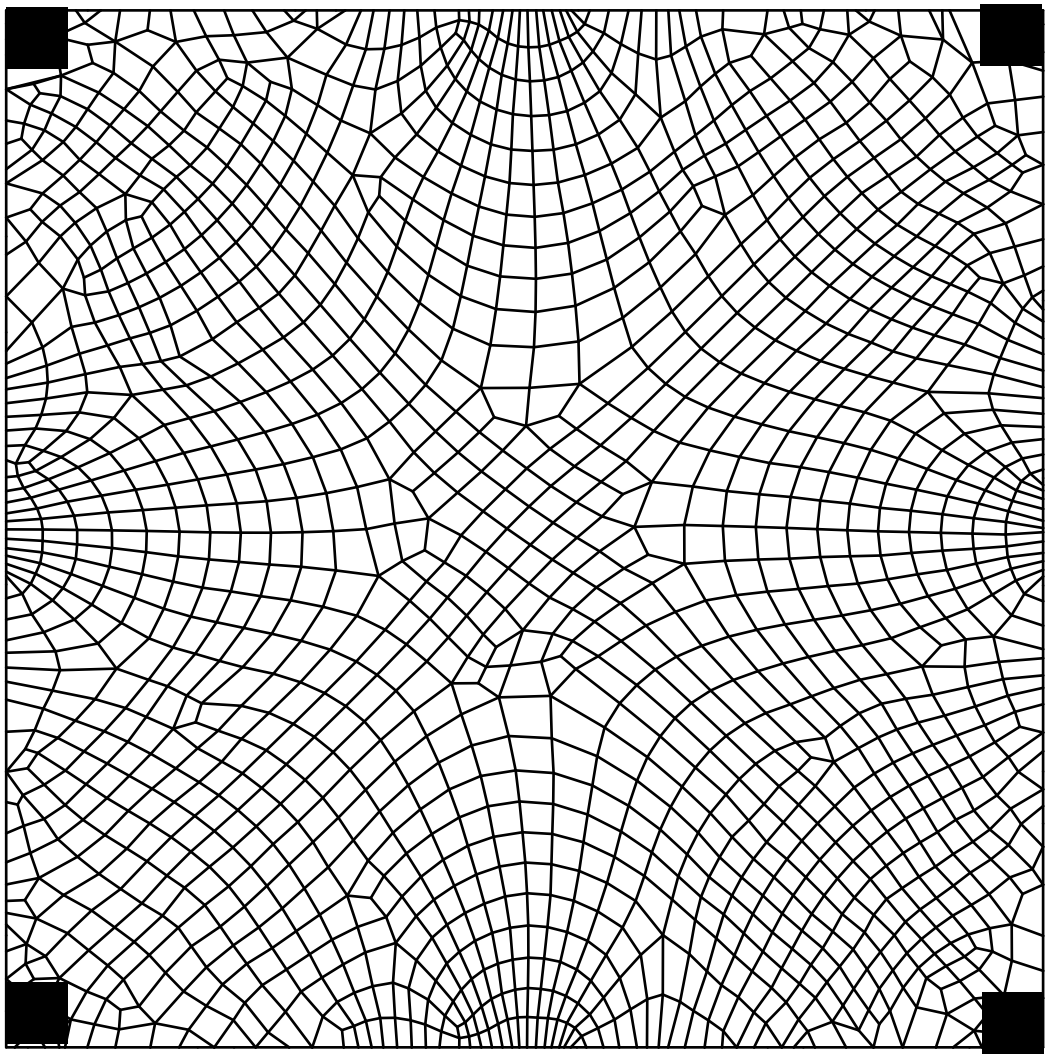
Bending principle line of stress B) for typical 10 x 10 x 0.2m slab



Combined bending principle stress for typical 10 x 10 x 0.2m slab







Quadmesh rationale

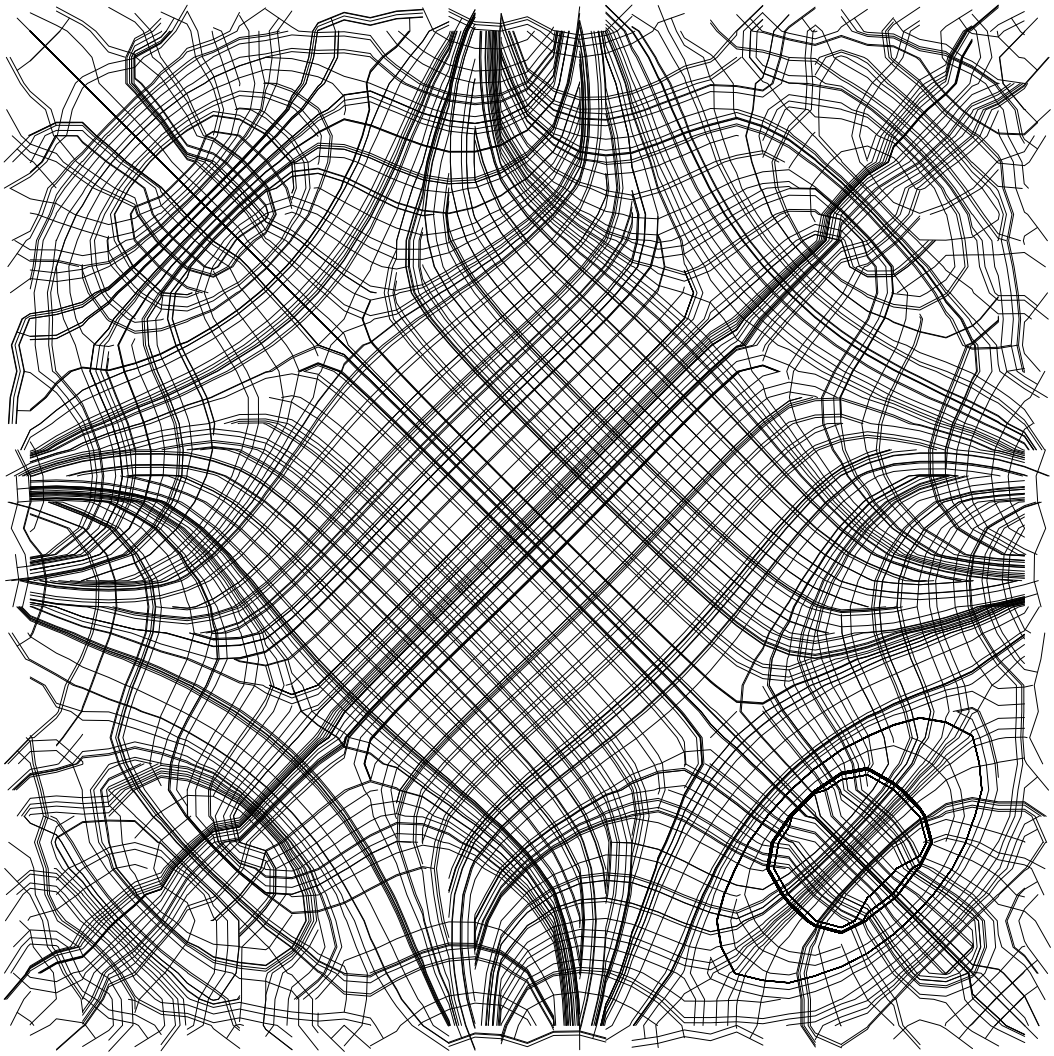


Figure: 4.6 prinicple isotatics at 0.2m

arched 10 x 10 x 0.2 slab

TO: 60%; IT: 10

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes

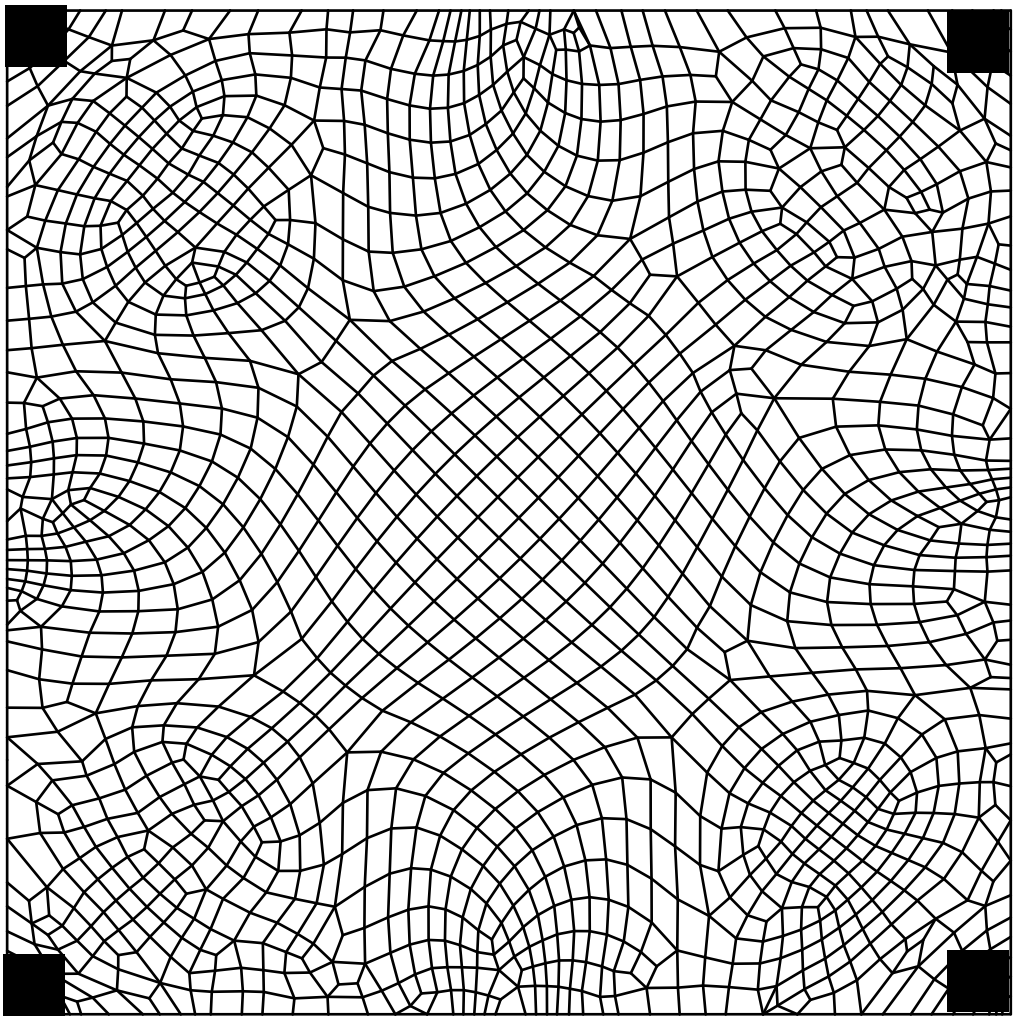


Figure: 4.7 rationalised quadmesh

arched 10 x 10 x 0.2 slab

TO: 60%; IT: 10; RES:1000

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes

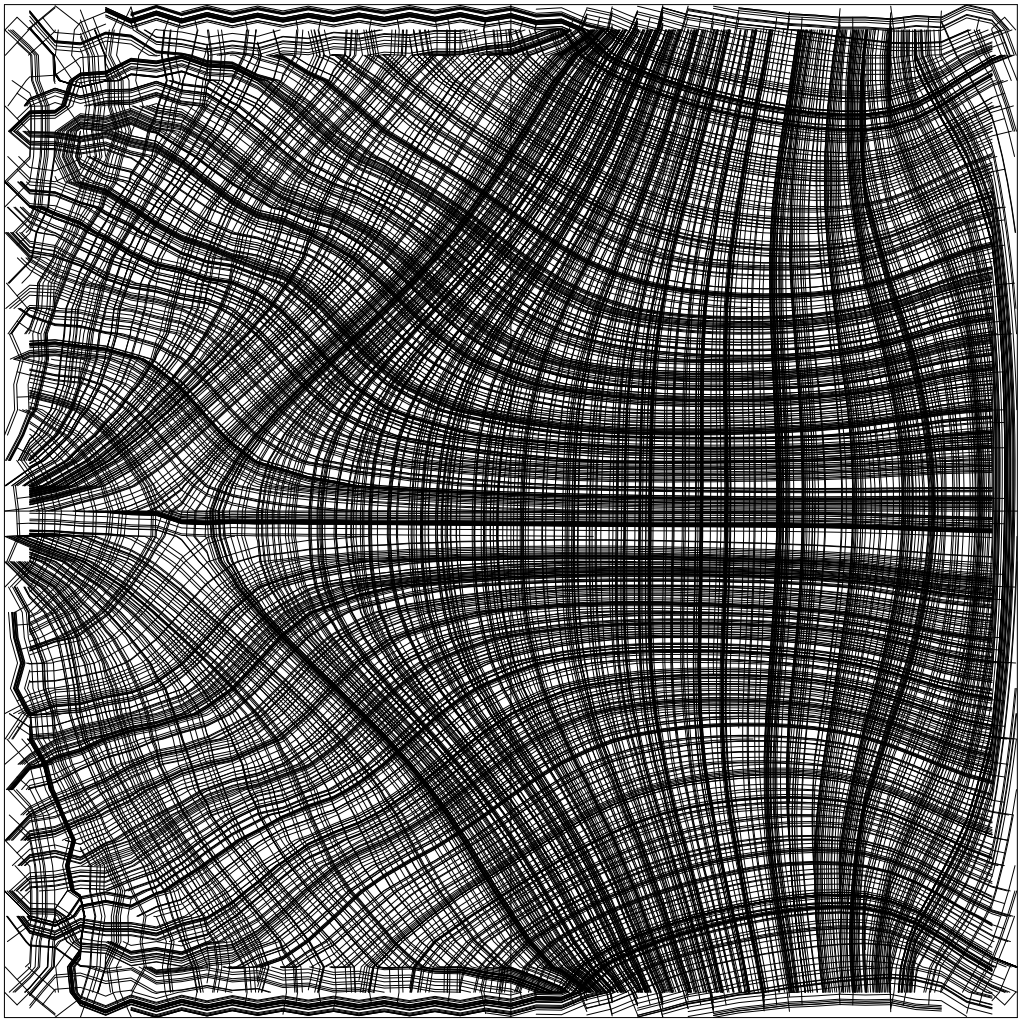


Figure: 4.8 prinicple isotatics at 0.5m
arched cantilver 10 x 10 x 0.2 slab
TO: 60%; IT: 10
fixing type: fixed base, 0 translation
magnitude loading: refer to arrows
material: concrete; built ratio: 1/1
SubD:no; NDD: yes

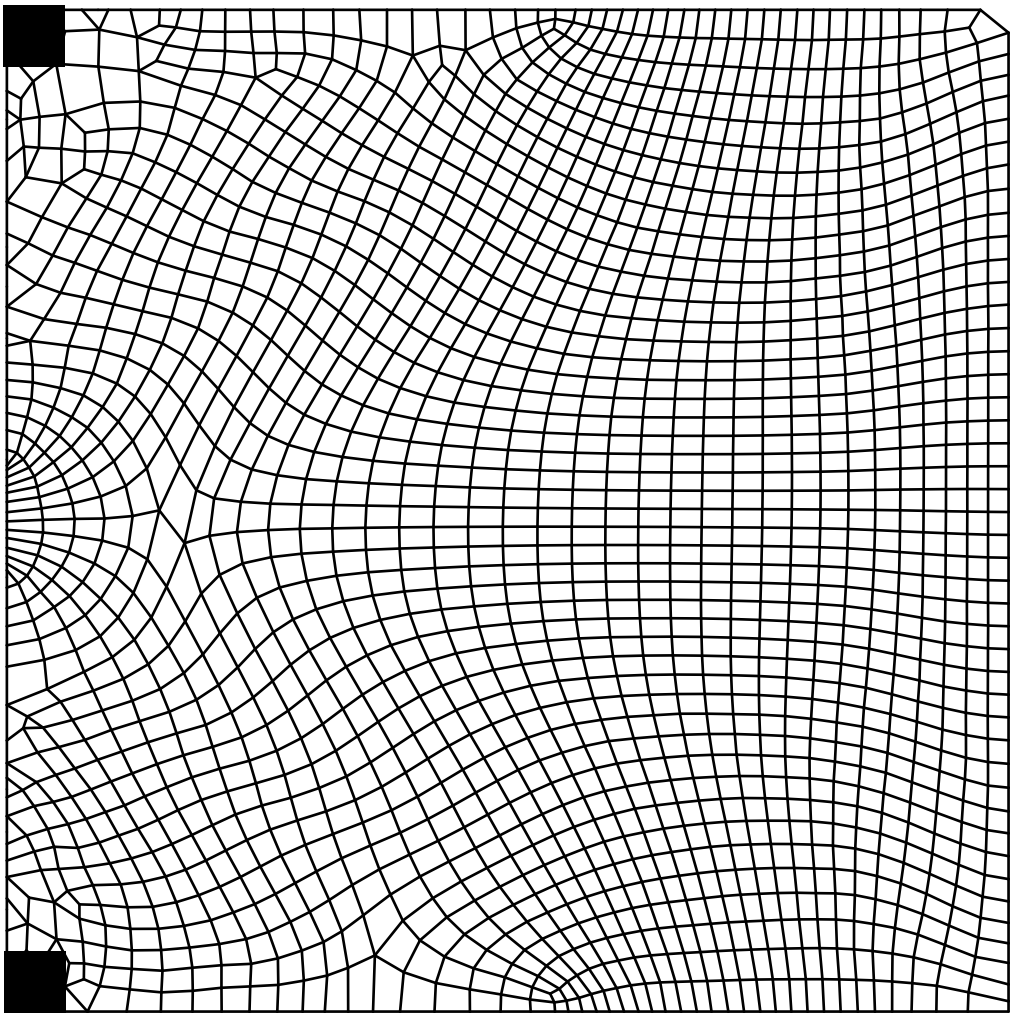


Figure: 4.8 rationalised quadmesh

arched cantilever10 x 10 x 0.2 slab

TO: 60%; IT: 10; RES:1000

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes

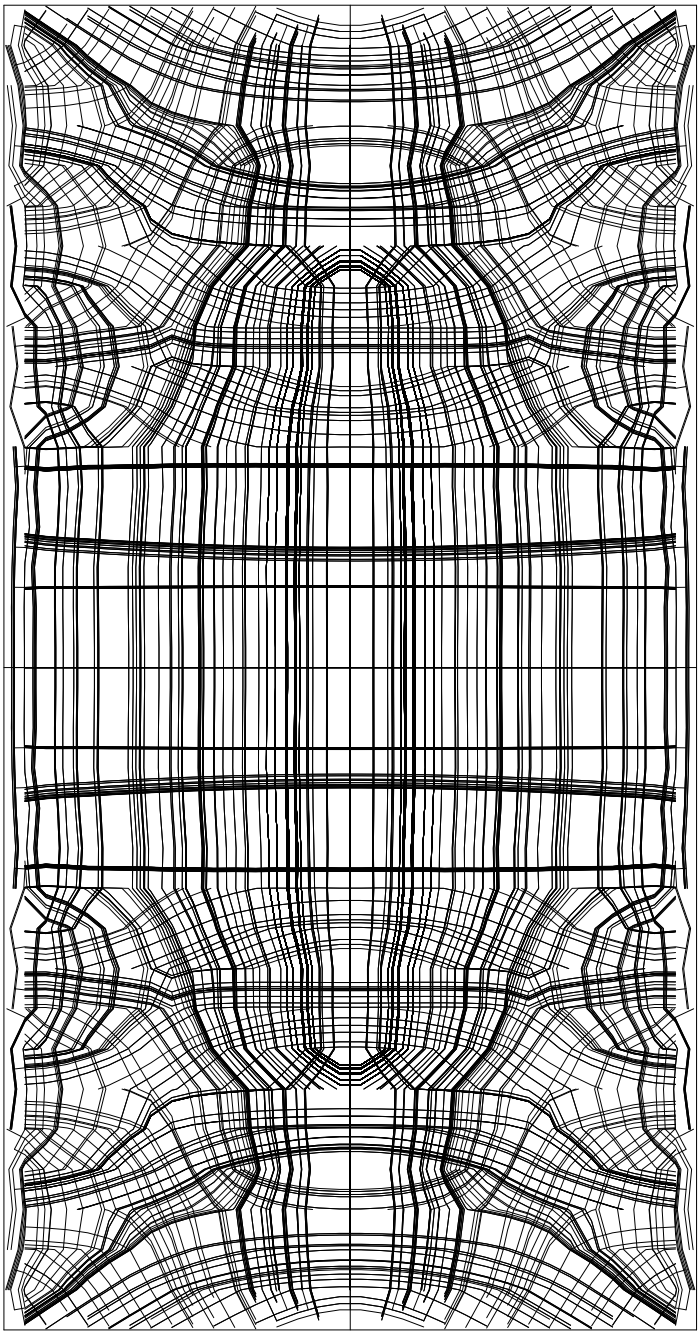


Figure: 4.9 prinicple isotatics at 0.5m

arched 20 x 5 x 0.2 slab

TO: 60%; IT: 10

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes

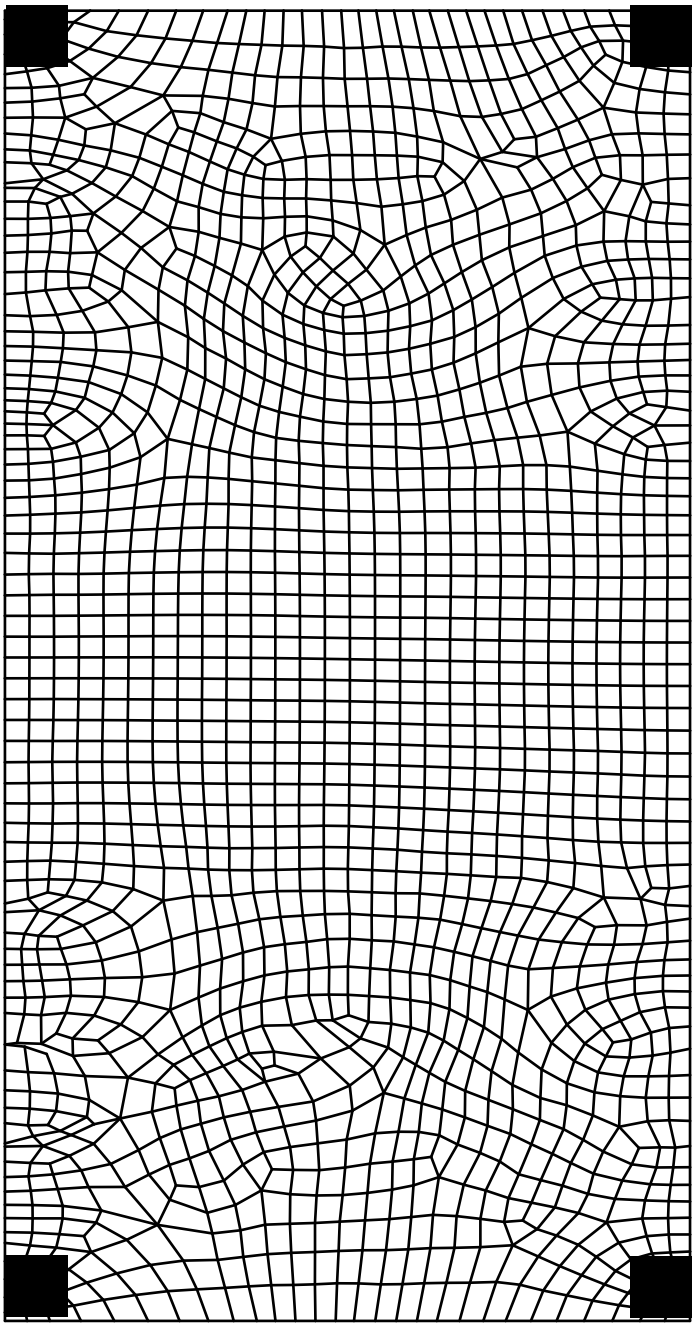


Figure: 4.10 rationalised quadmesh

arched 20 x 5 x 0.2 slab

TO: 60%; IT: 10; RES:1000

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes

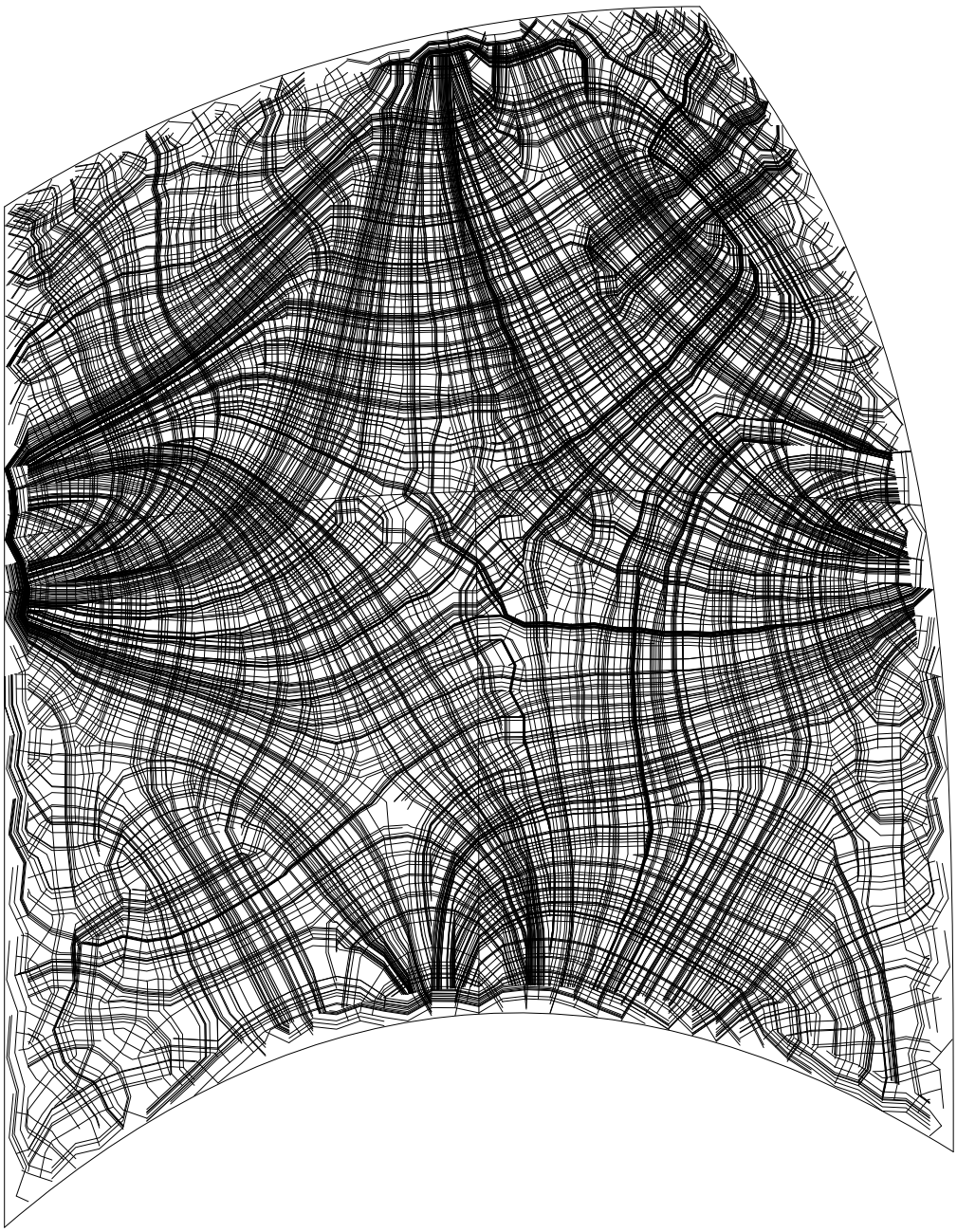


Figure: 4.11 prinicple isotatics at
arched non-orthogonal slab
TO: 60%; IT: 10
fixing type: fixed base, 0 translation
magnitude loading: refer to arrows
material: concrete; built ratio: 1/1
SubD:no; NDD: yes

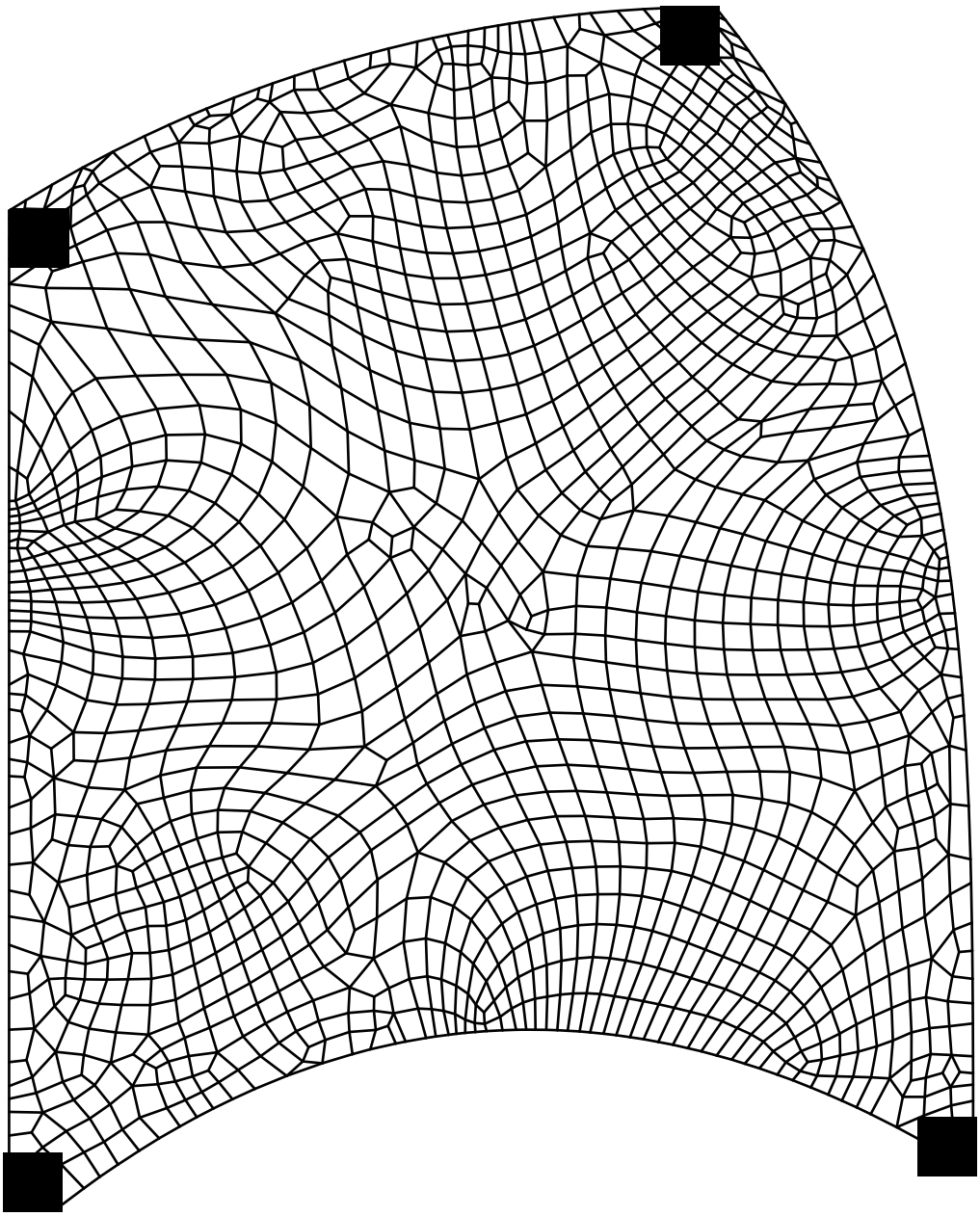


Figure: 4.12 rationalised quadmesh

arched non-orthogonal slab

TO: 60%; IT: 10; RES:1000

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes

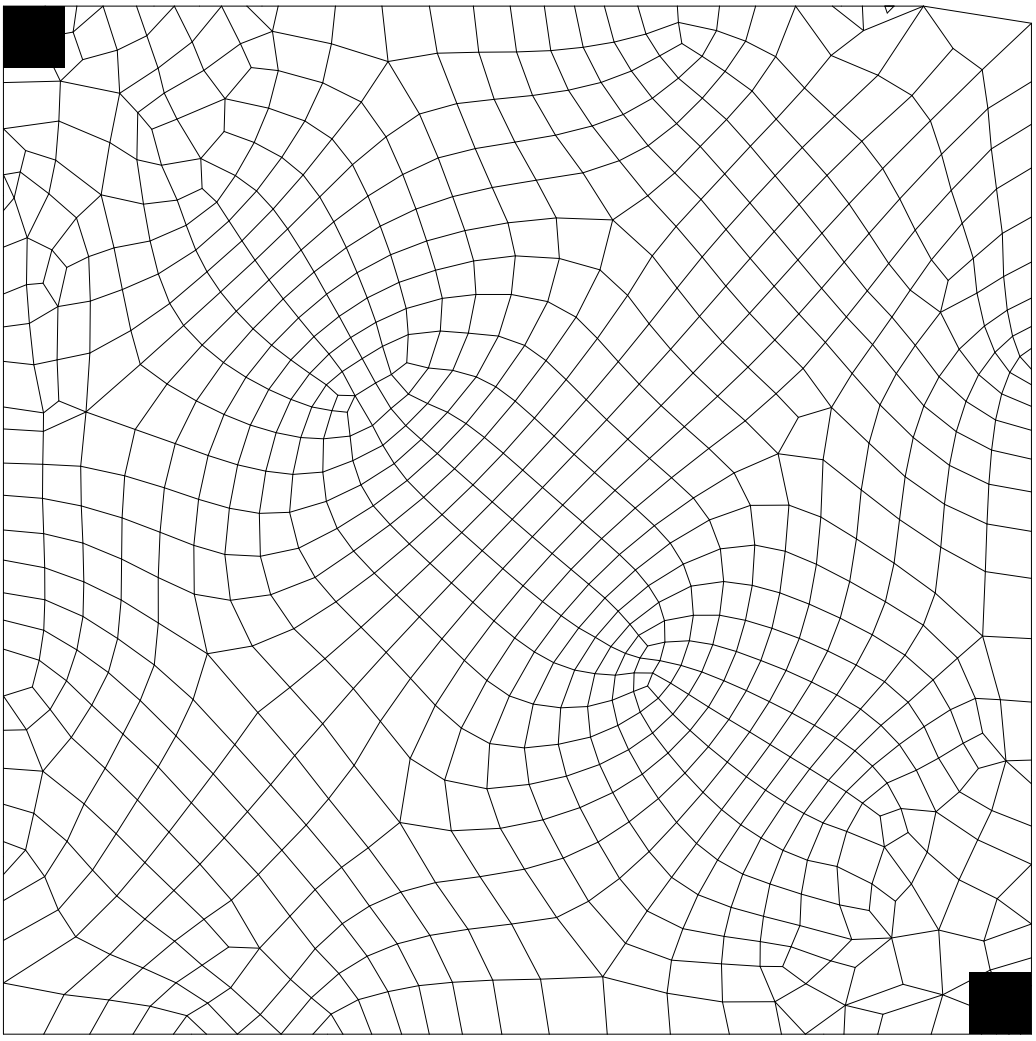


Figure: 4.13 prinicple isotatics at 0.5m

arched 10 x 10 x 0.2 slab

TO: 60%; IT: 10

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes

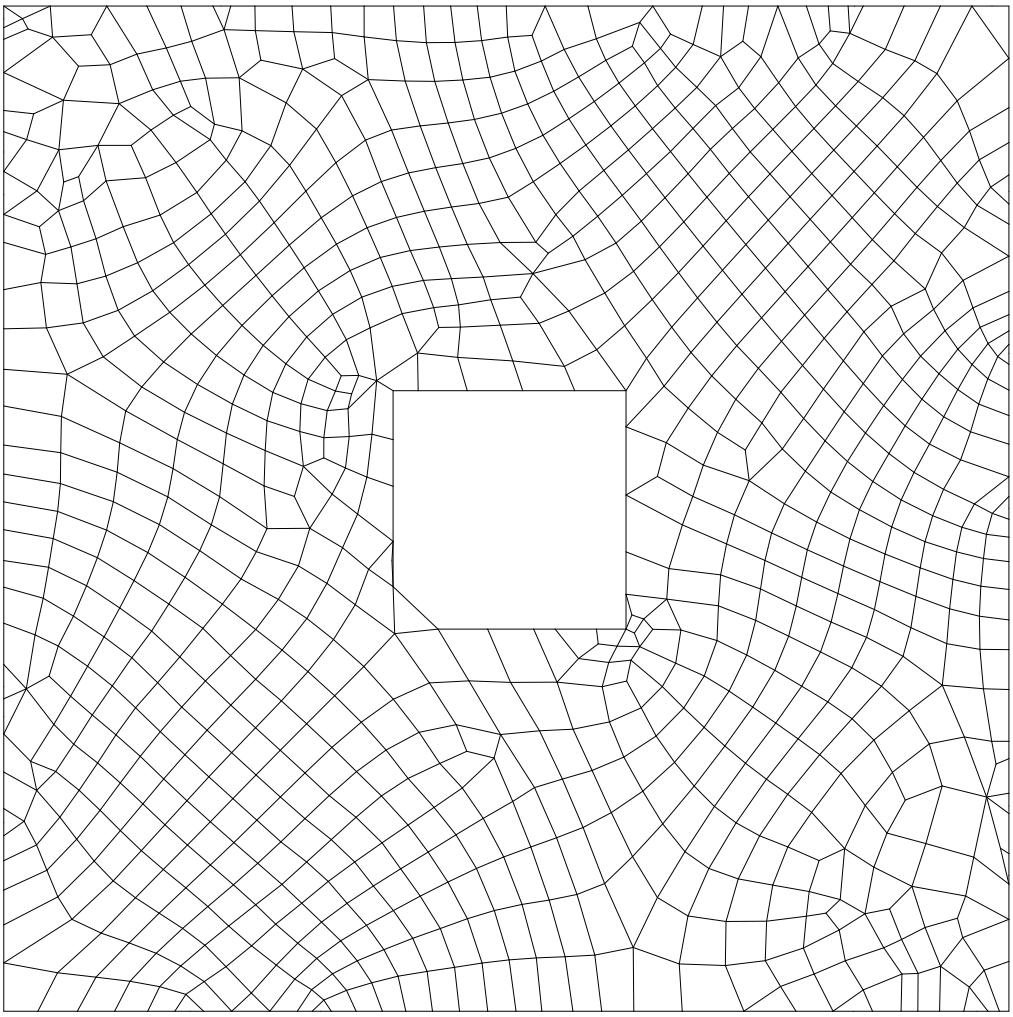


Figure: 4.12 rationalised quadmesh

arched 10 x 10 x 0.2 slab with void

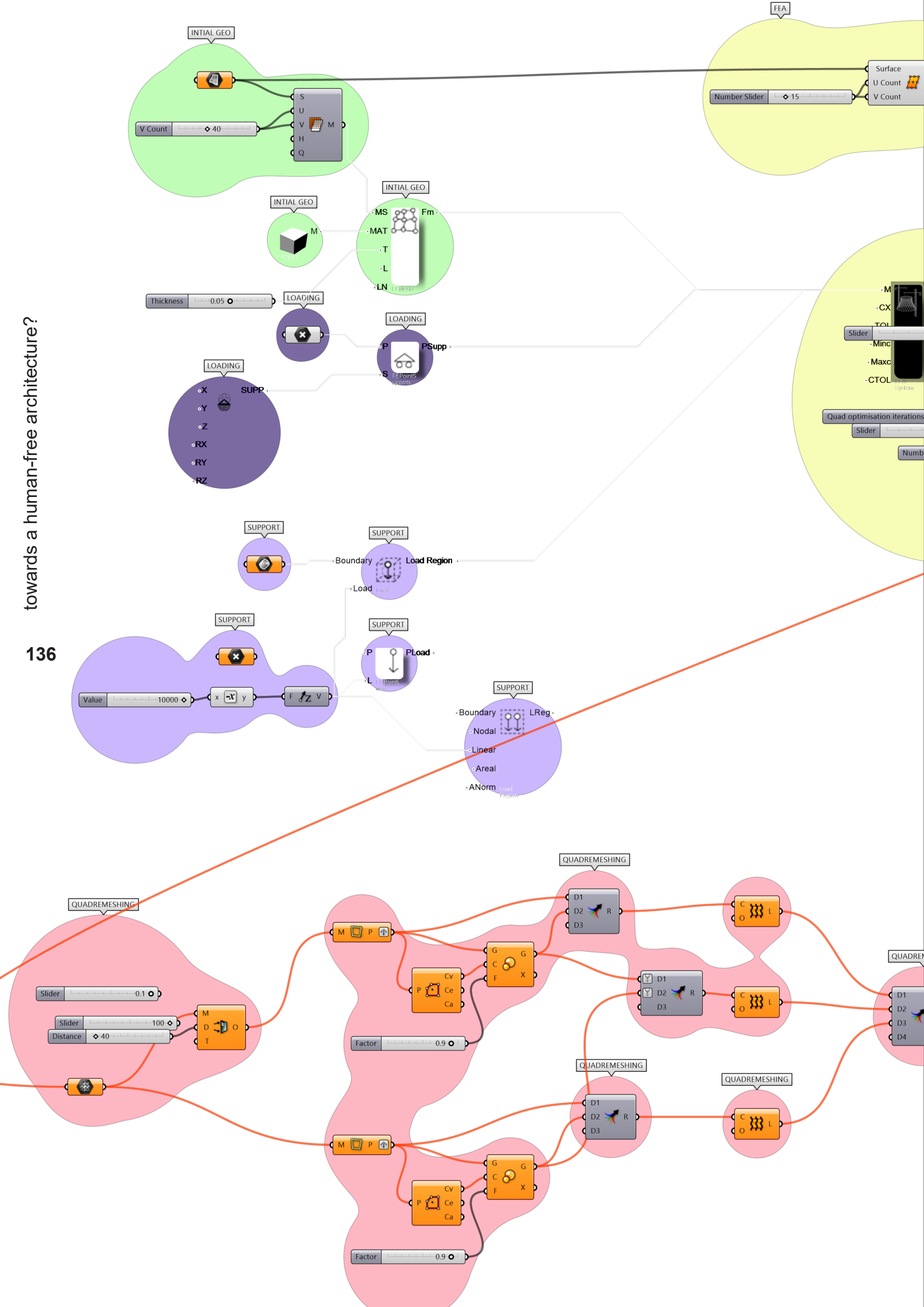
TO: 60%; IT: 10; RES:1000

fixing type: fixed base, 0 translation

magnitude loading: refer to arrows

material: concrete; built ratio: 1/1

SubD:no; NDD: yes


INTIAL GEO
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FEA
Surface
U Count
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Number Slider
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INTIAL GEO
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INTIAL GEO
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T
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Fm
Thickness
0.05
LOADING
LOADING
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LOADING
X
Y
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RX
RY
RZ
SUPP
M
CX
Slider
Minc
Maxc
CTOL
Quad optimisation iterations
Slider
SUPPORT
SUPPORT
Boundary
Load Region
Load
SUPPORT
SUPPORT
P
PLoad
L
Value
10000
x
y
F
V
SUPPORT
Boundary
LReg
Nodal
Linear
Areal
ANorm
QUADREMESHING
Slider
0.1
Slider
100
Distance
40
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D
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O
QUADREMESHING
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Ca
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Factor
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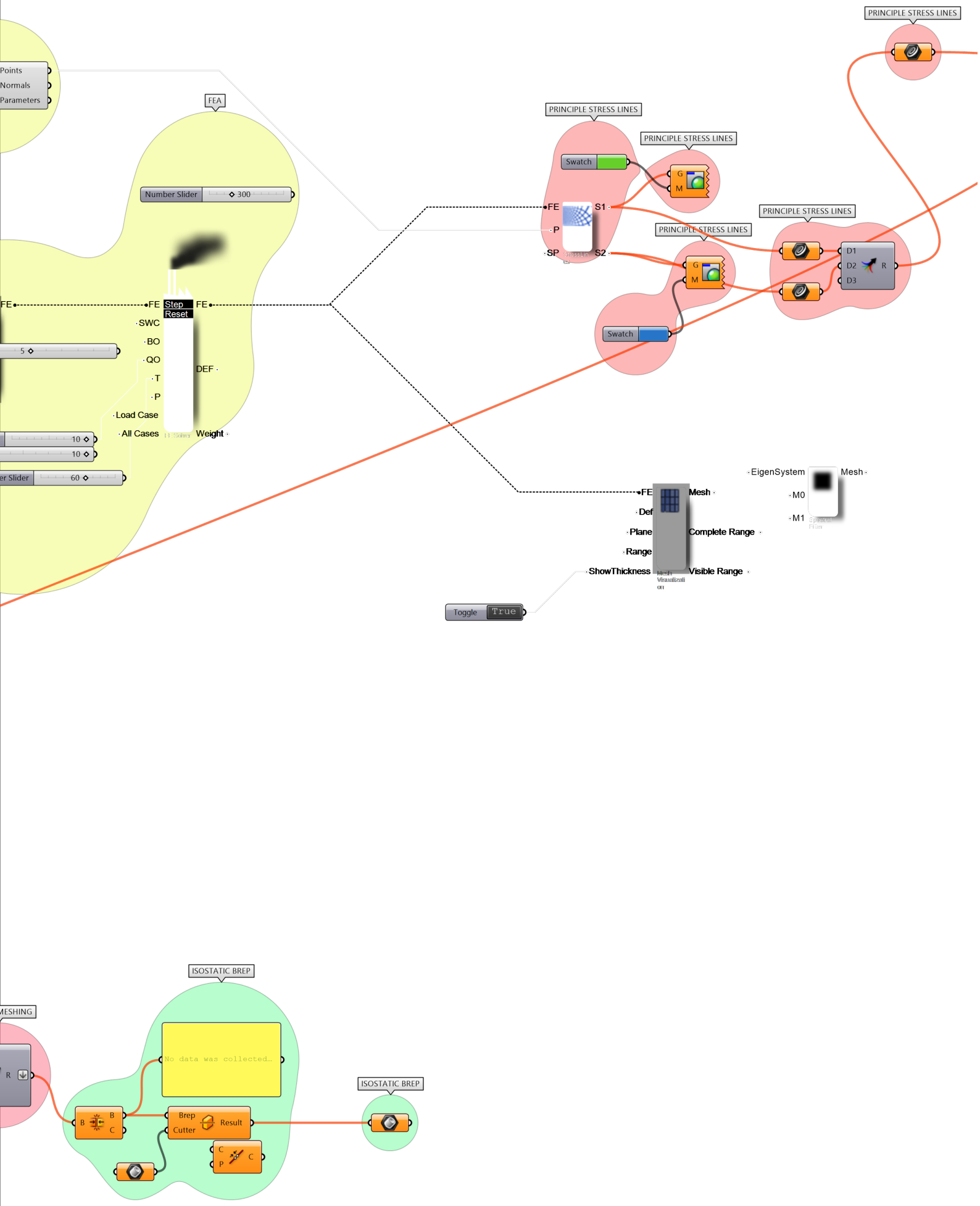
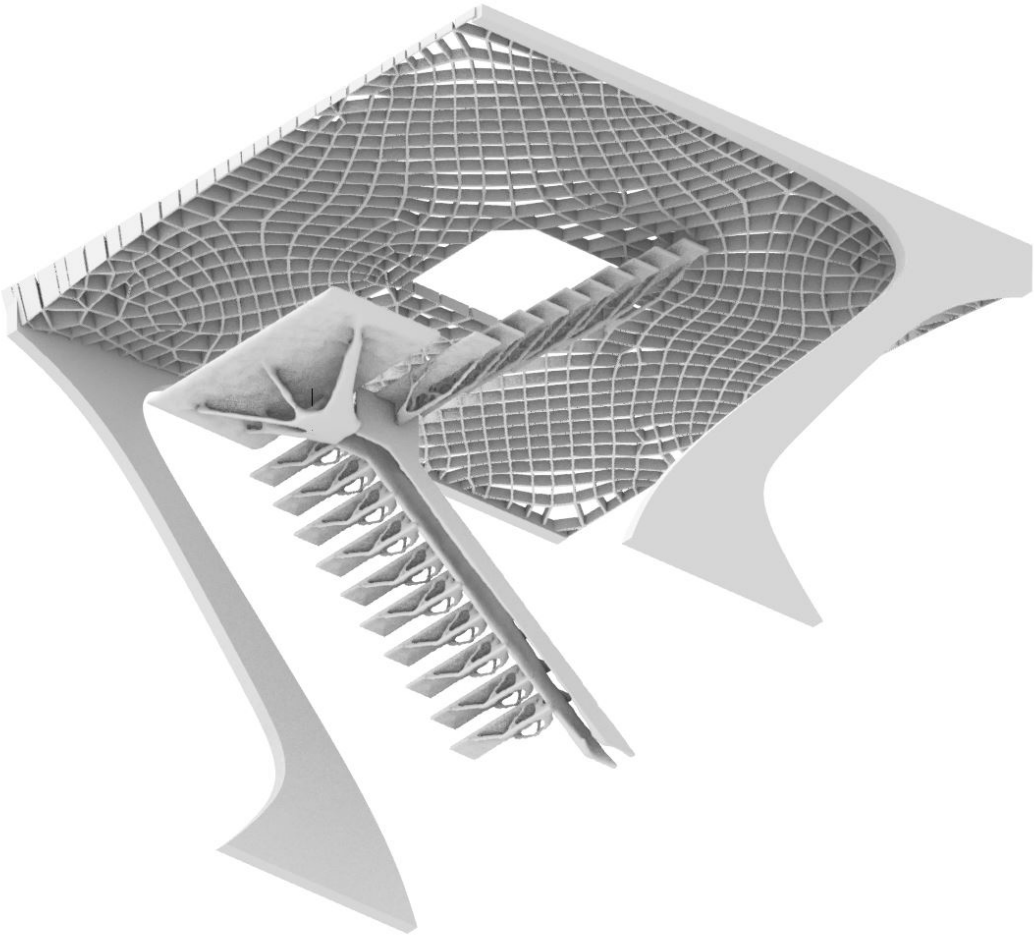
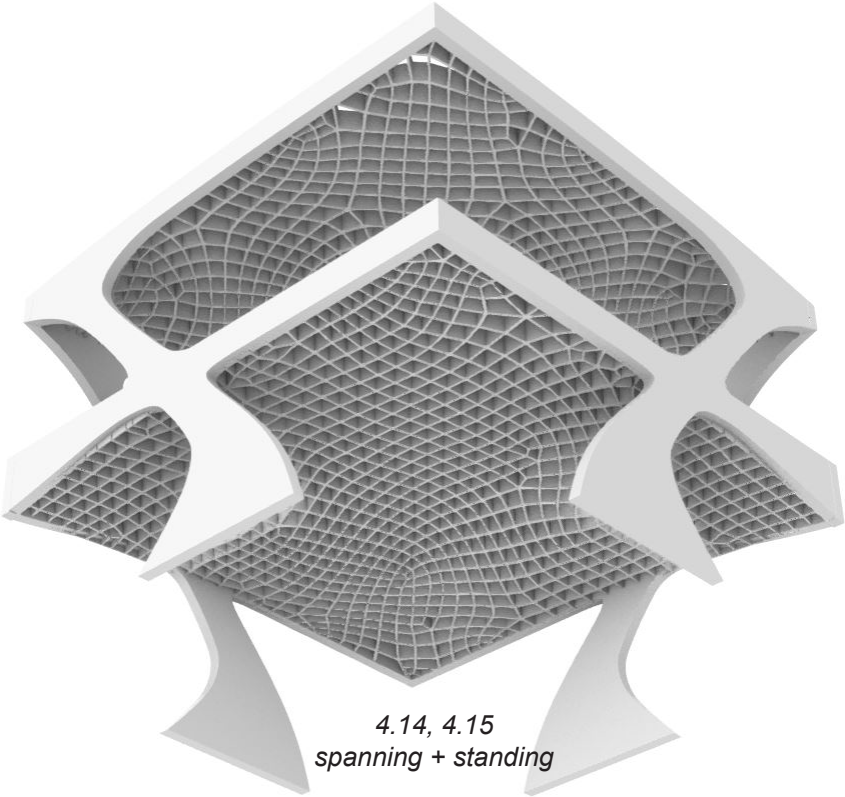
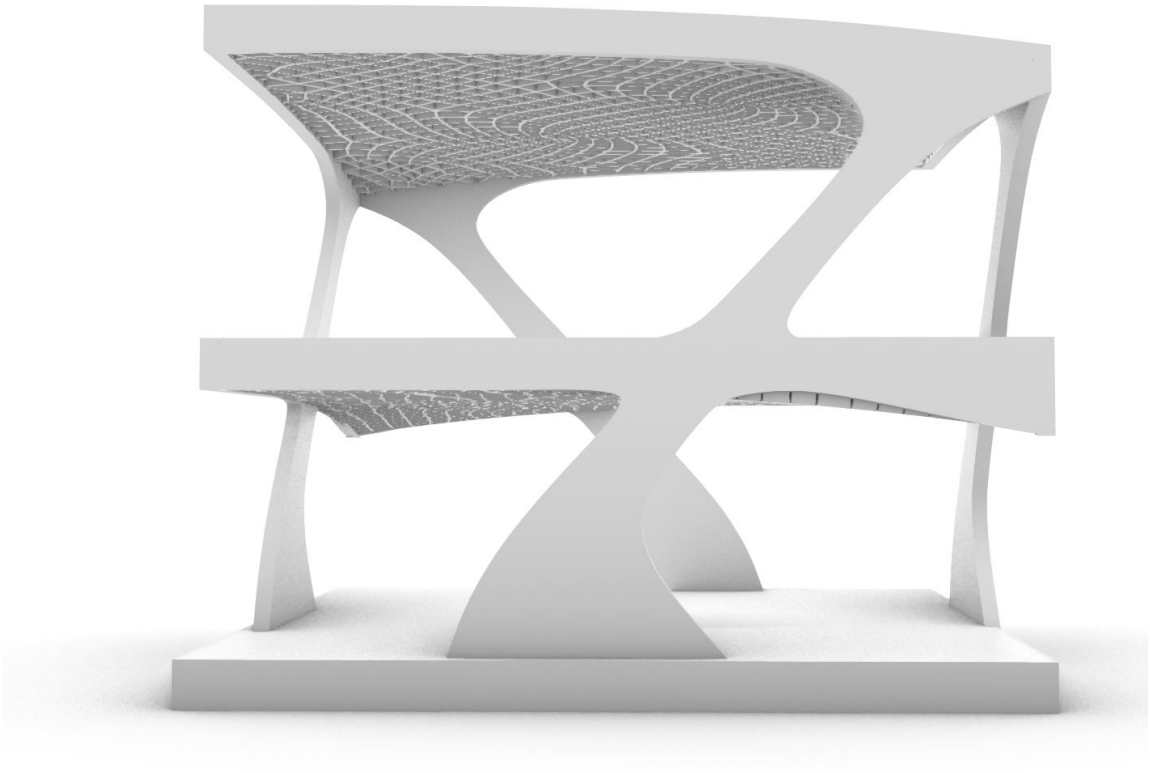


4.13
Millipede scripting adapted from Kirdiekis (2020)

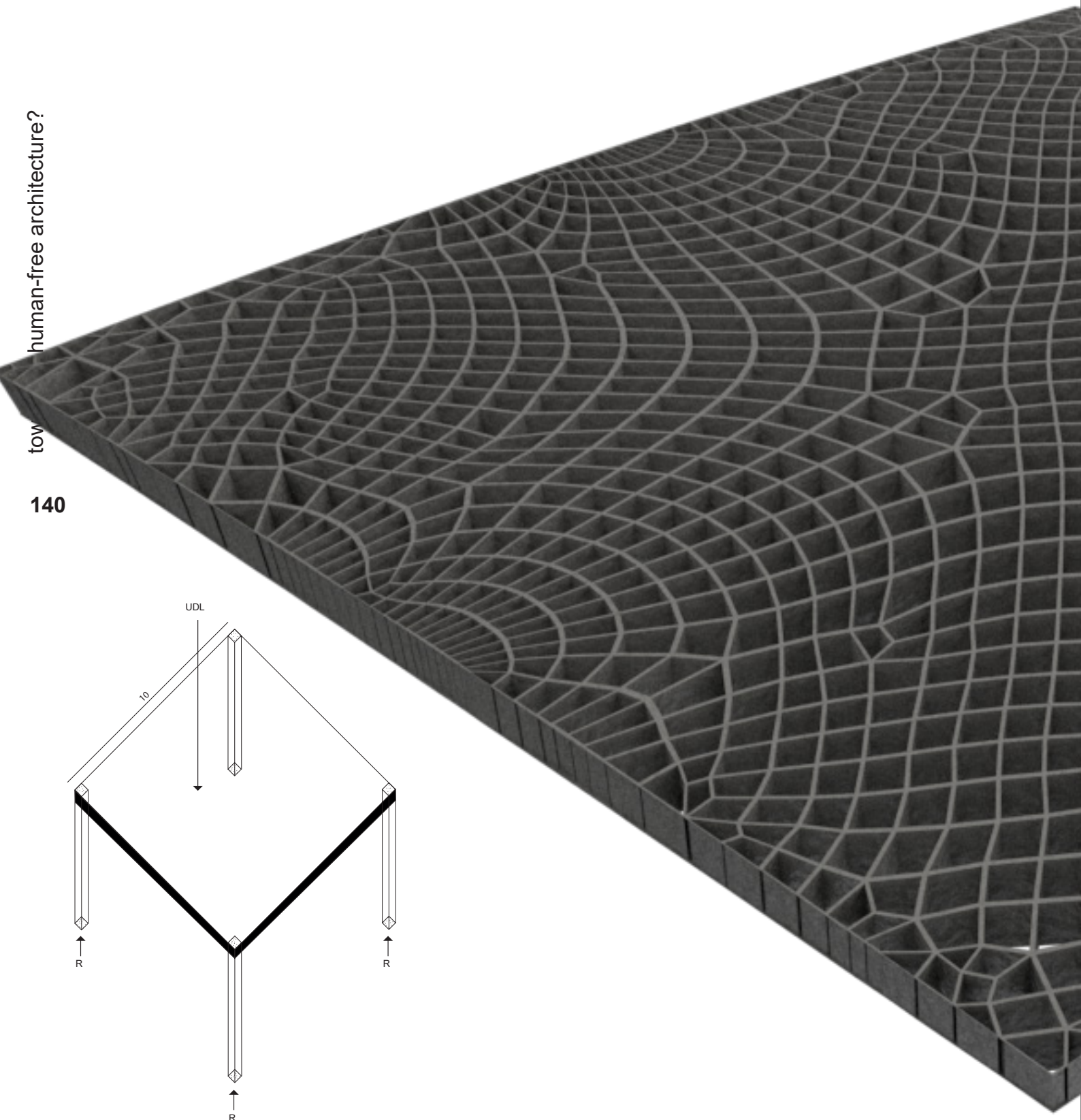




4.14, 4.15
spanning + standing

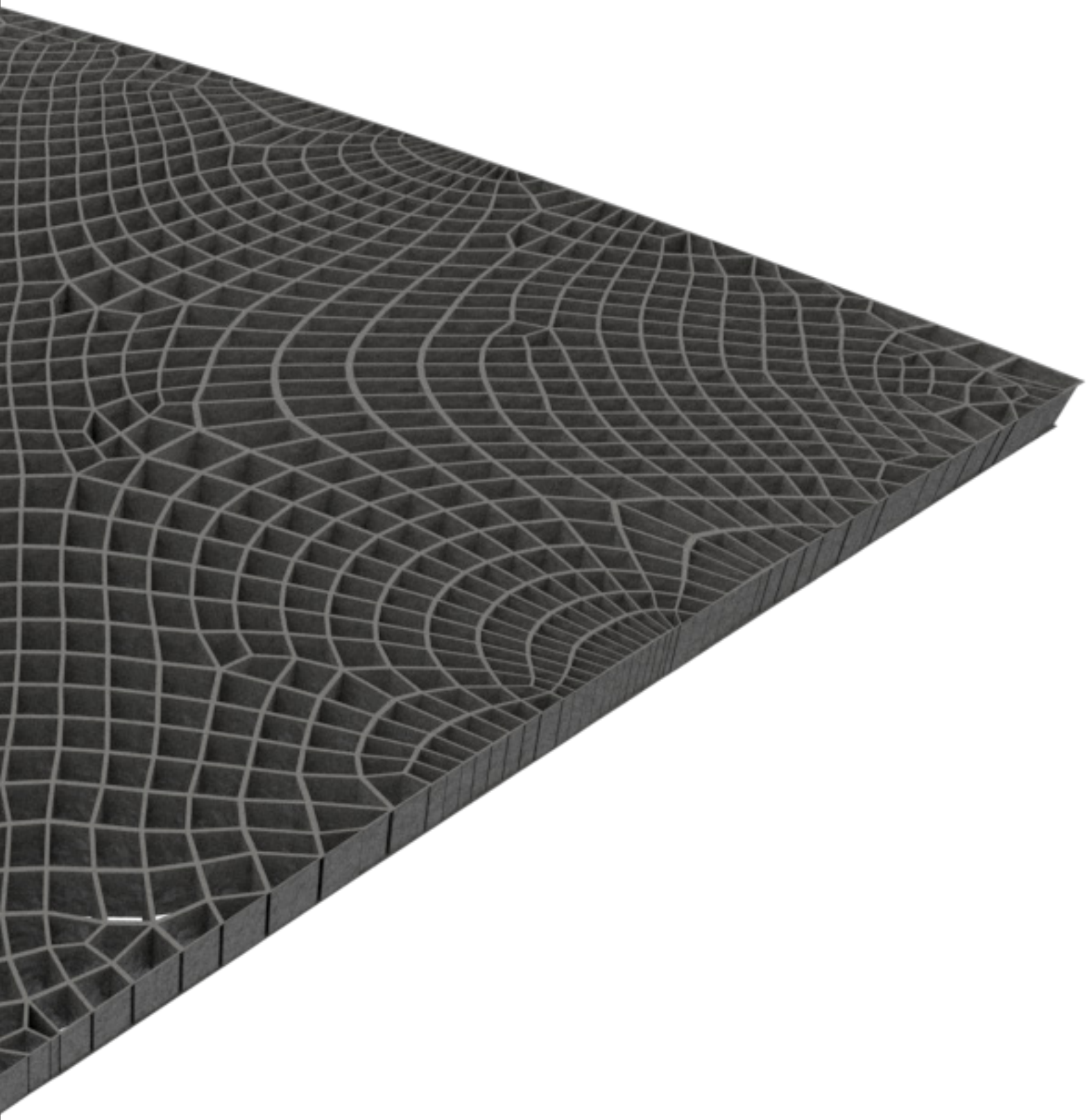


4.16, 4.17
spanning + standing



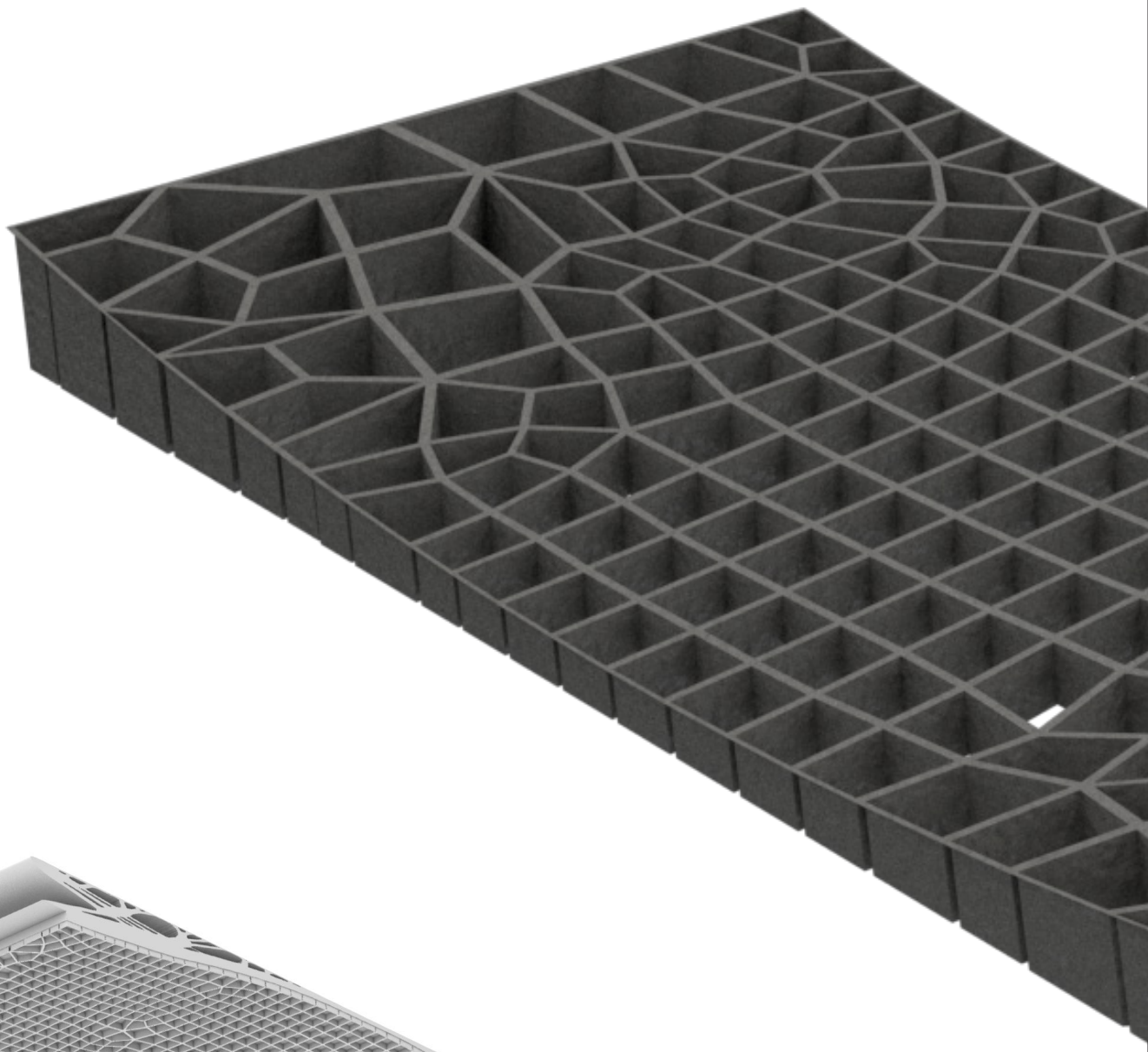
4.15
10 x 10 x 0.2m slab

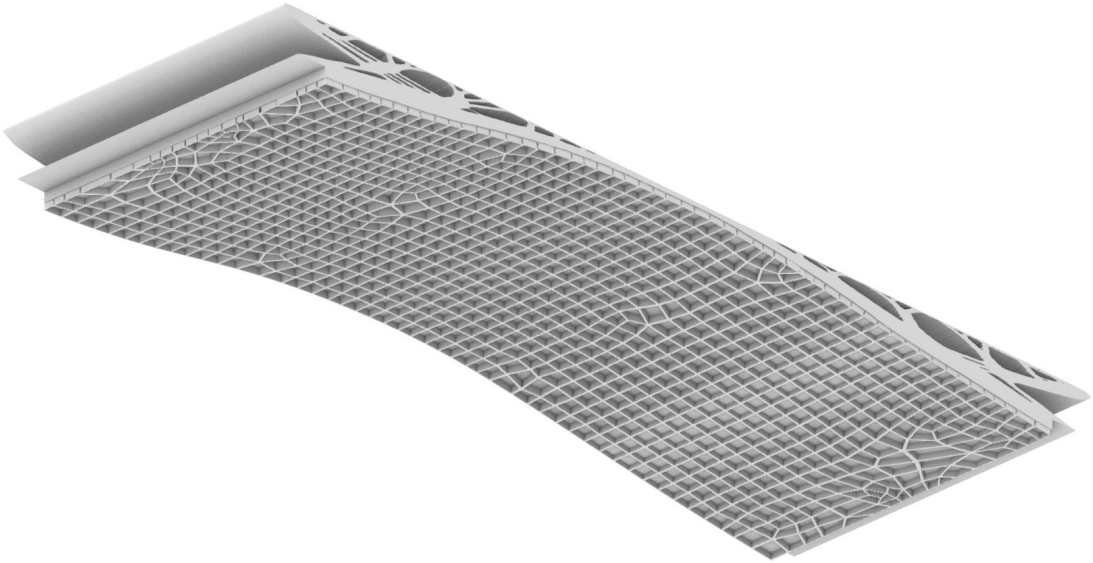
4.1
isostatic slab with ribs folowi



8
ng principle bending stress

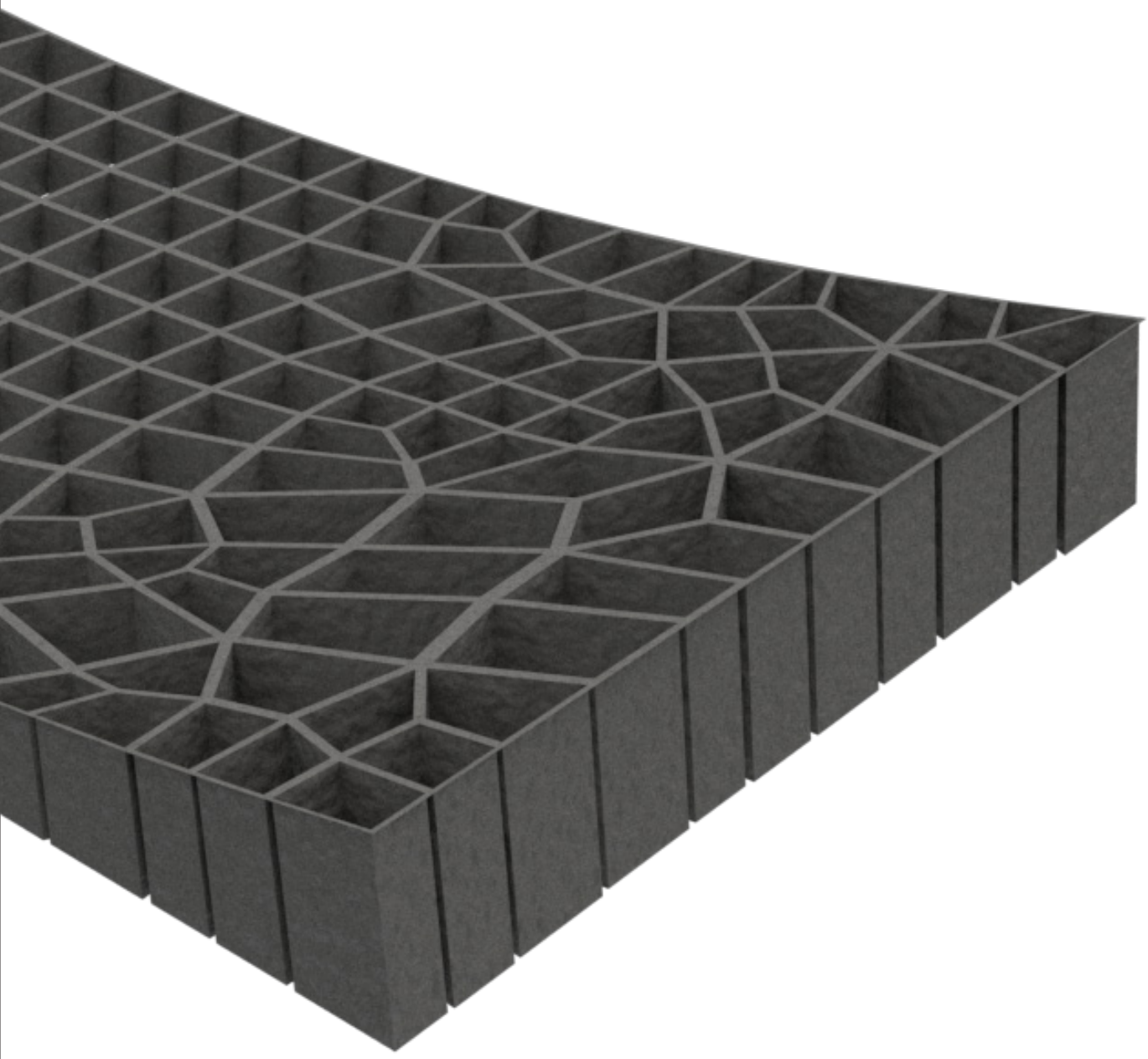
the addition:





4.19
composite isostatic and sectional optimised spanning unit

4.2
isostatic slab with ribs folowi

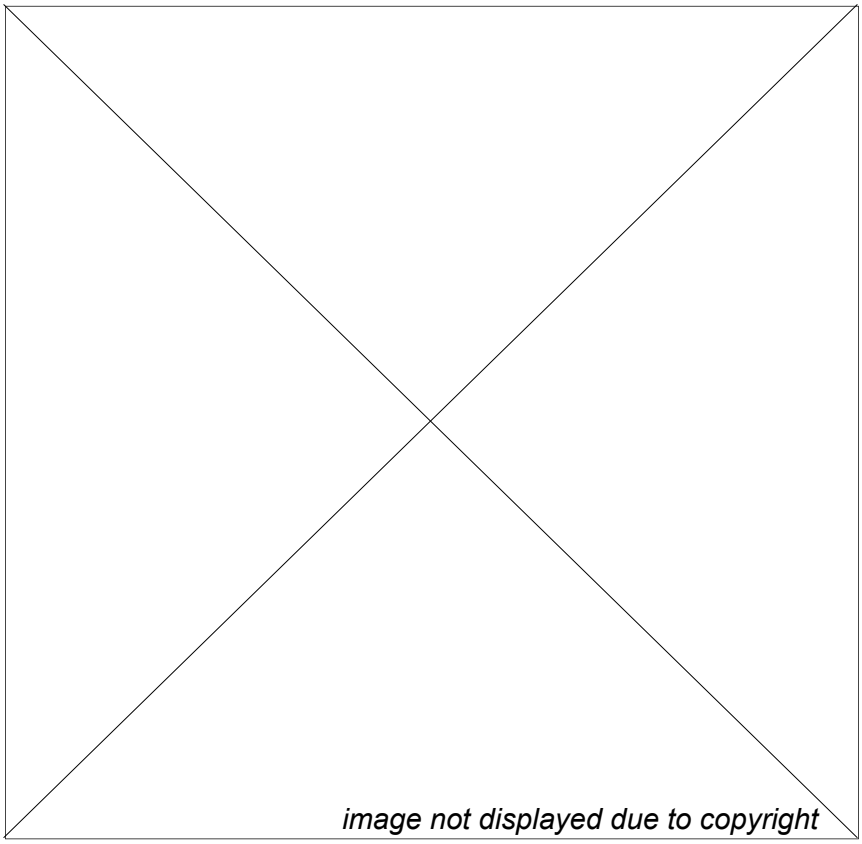


0
ng principle bending stress

CHAPTER V

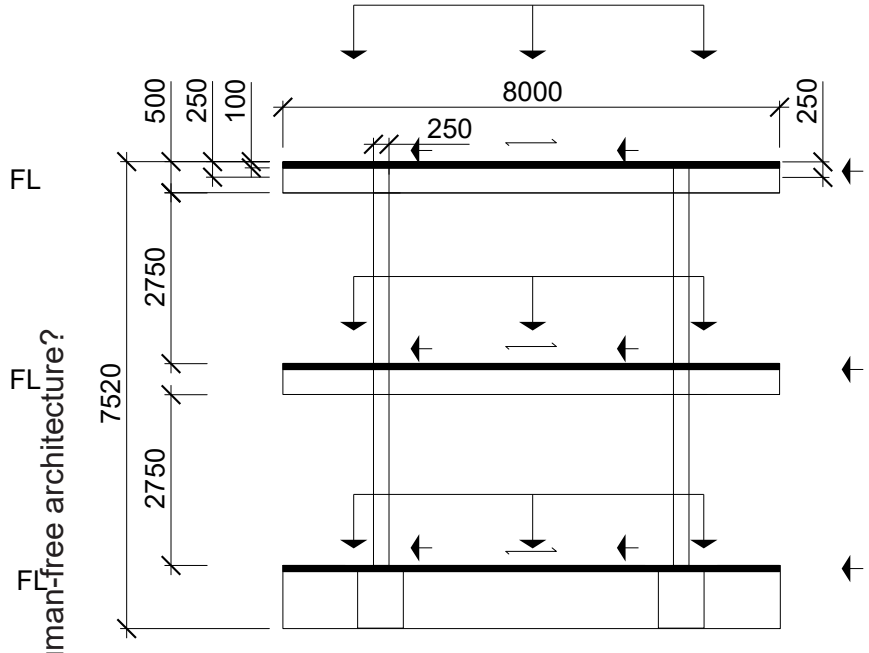
makin

g

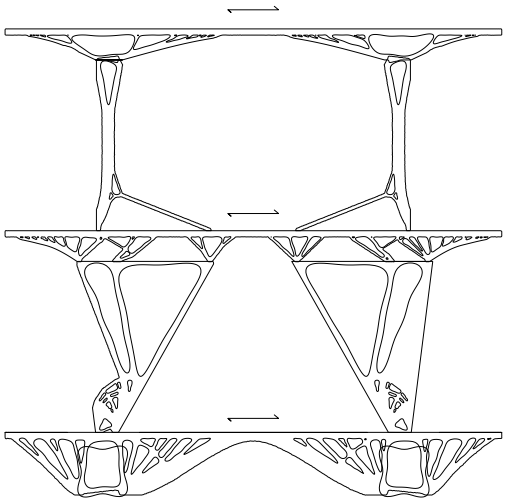


5.1

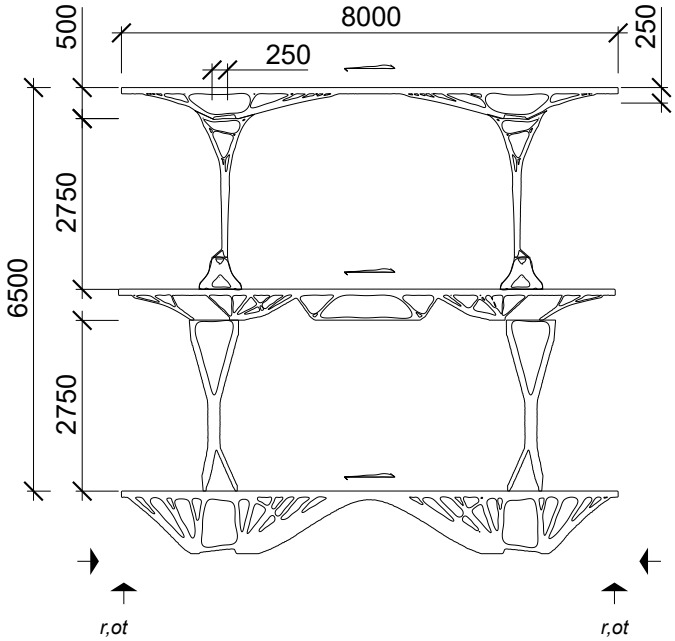
Chapter V rounds of the investigation by taking dimensions and typology of Le Corbiser's Domino House, in order to creating a series of pavilions that attempt to refine such as simple post and slab structure.



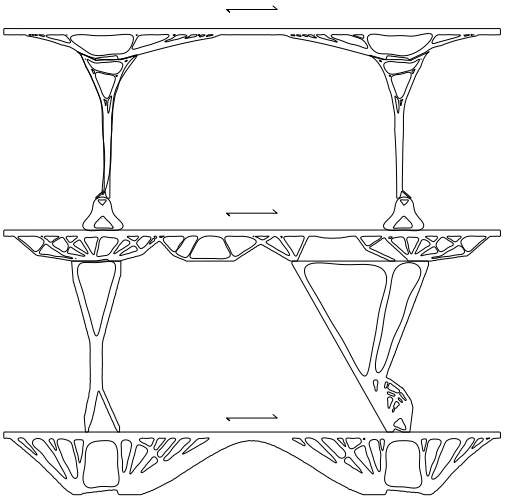
5.2
Domino House existing geometry



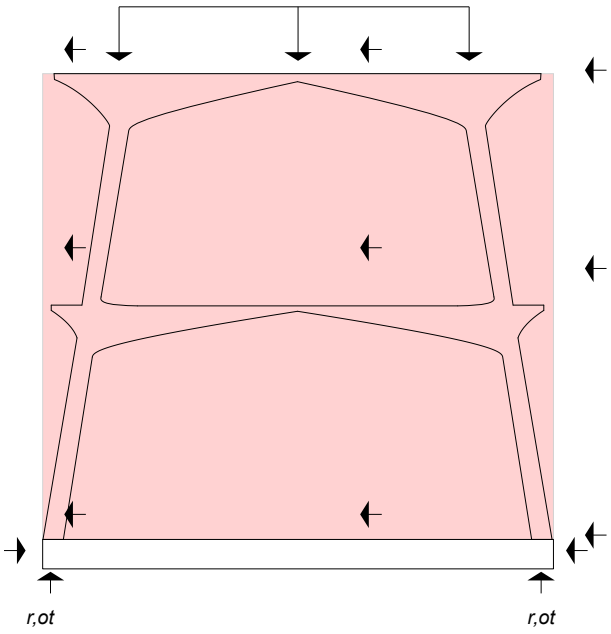
5.3
shape optimisation for members under lateral loading



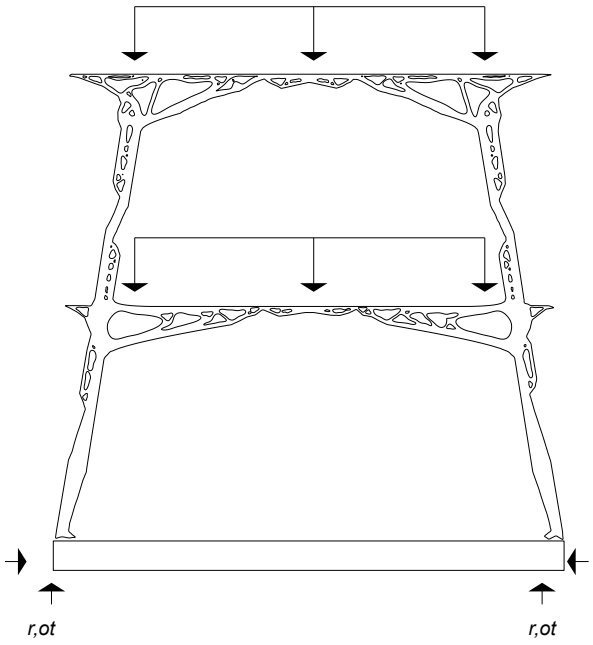
5.4
shape optimisation for members under gravity loading



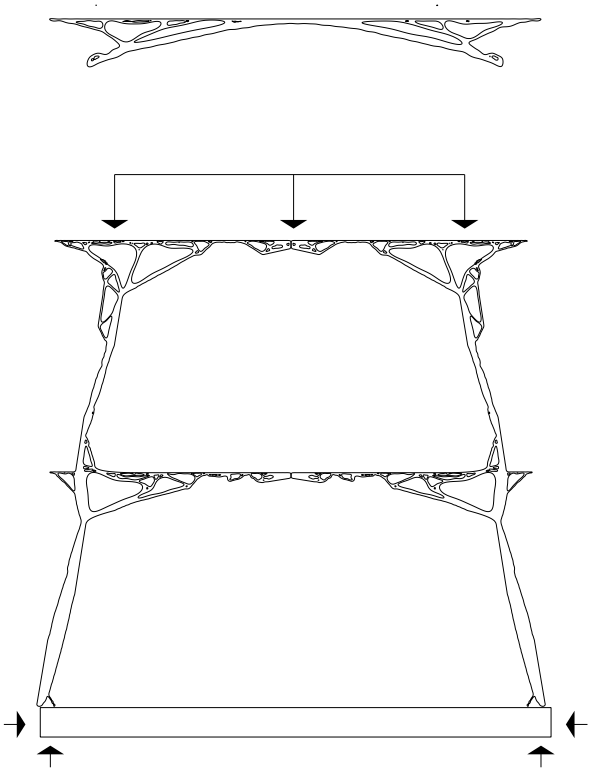
5.5
shape optimisation for members under gravity and lateral loading



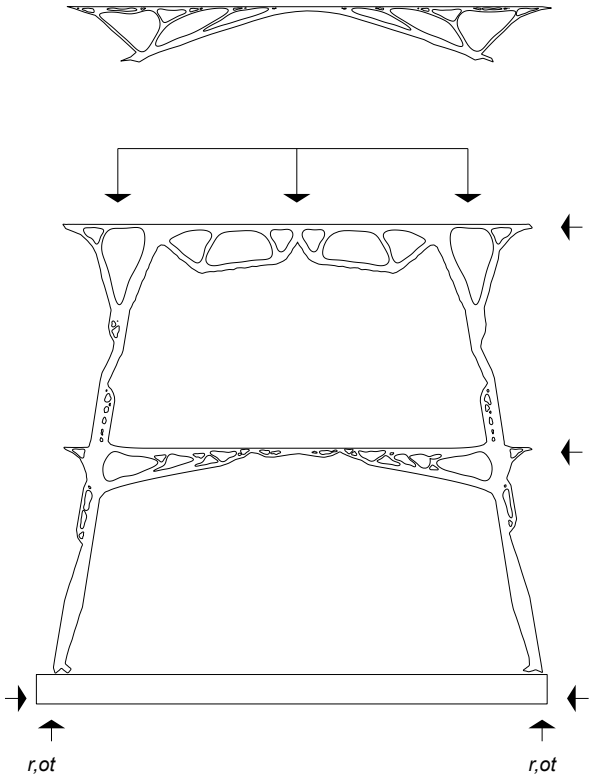
5.6
optimised boundary condition inside boundary



5.7
gravity frame 0.3 VF

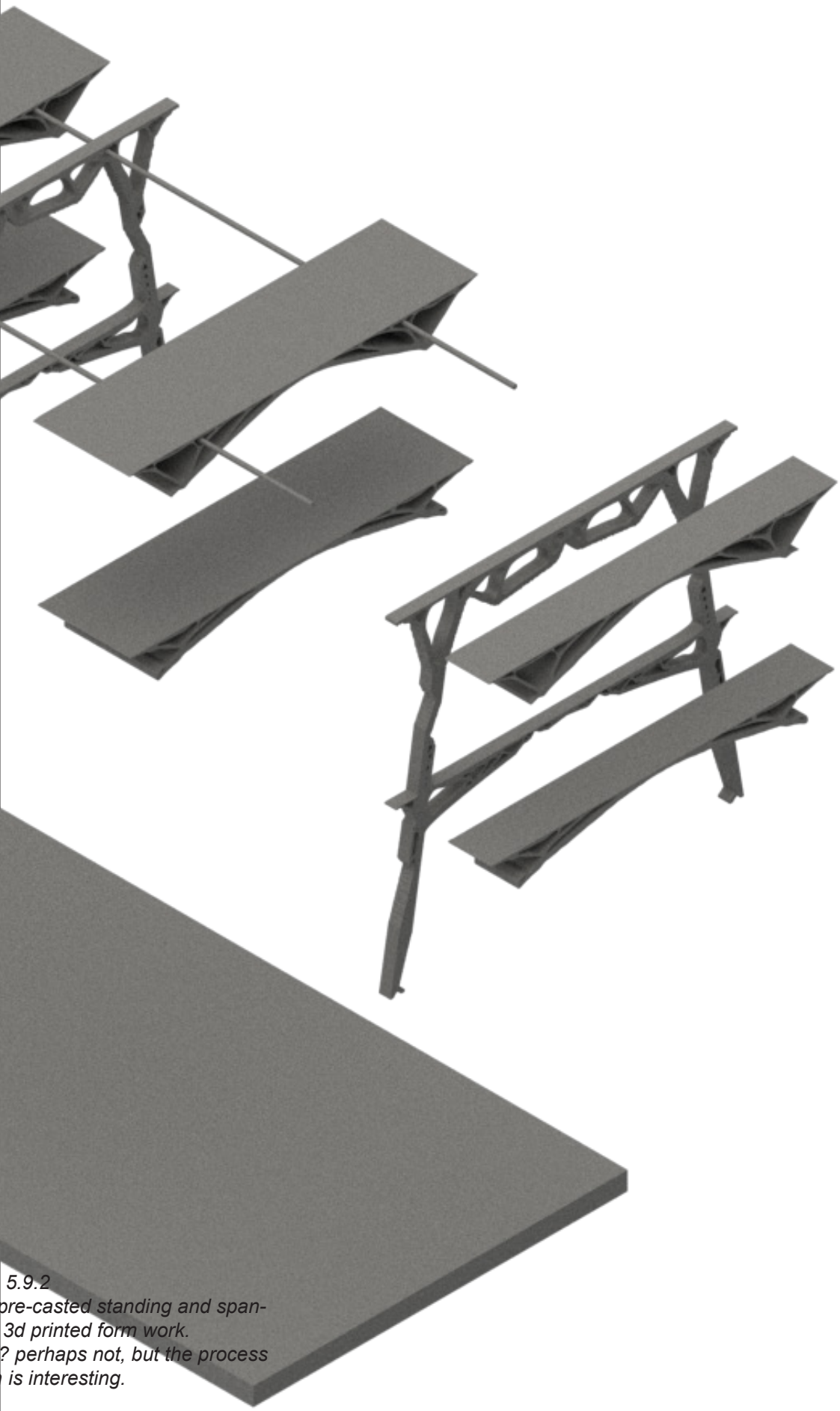


5.8
gravity frame 0.05 VF



5.9
moment frame

figure
a moment frame assembly of
ning items, done with
would this be applied in reality
of optimization



5.9.2
pre-casted standing and span-
3d printed form work.
? perhaps not, but the process
is interesting.

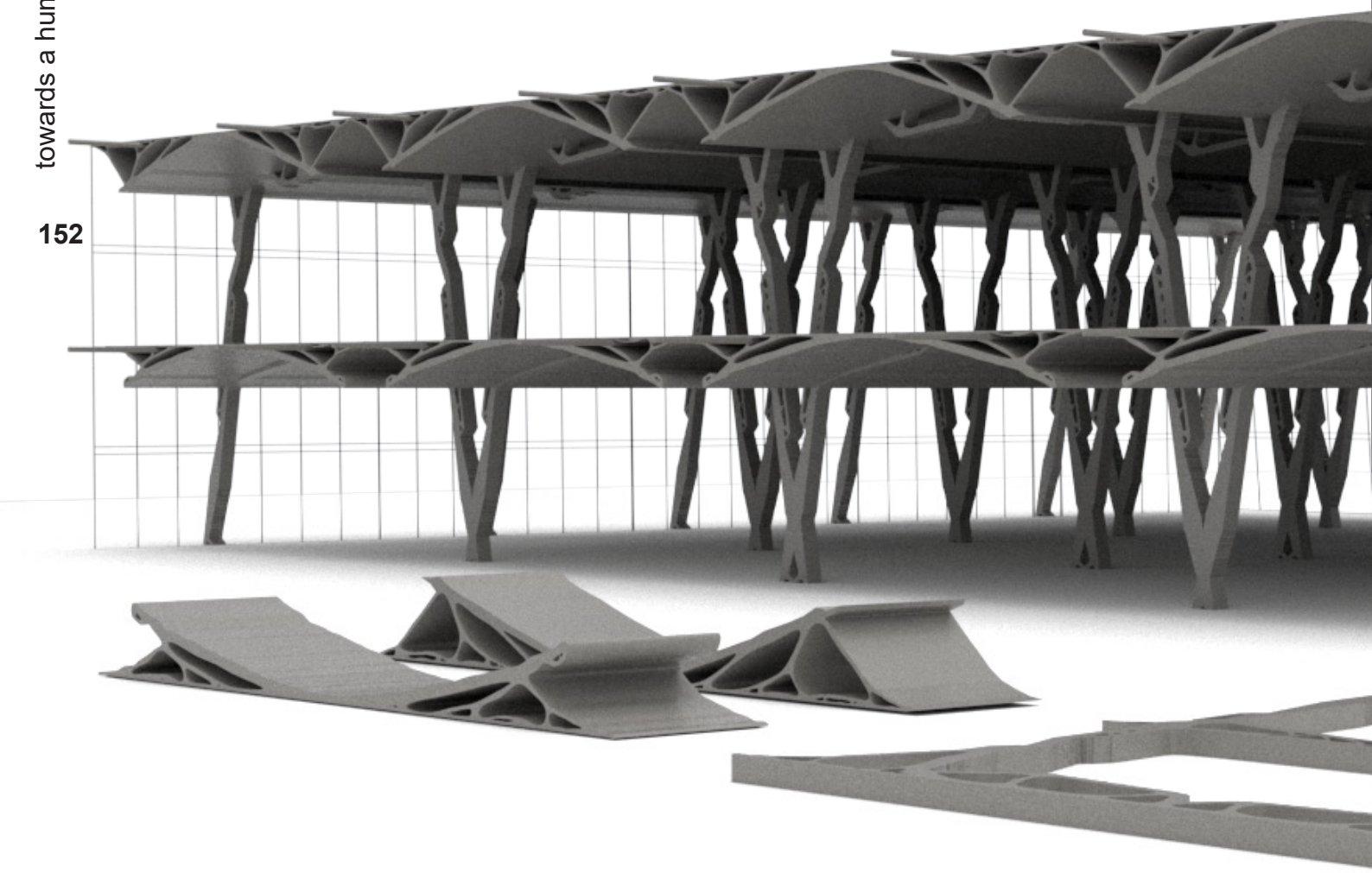
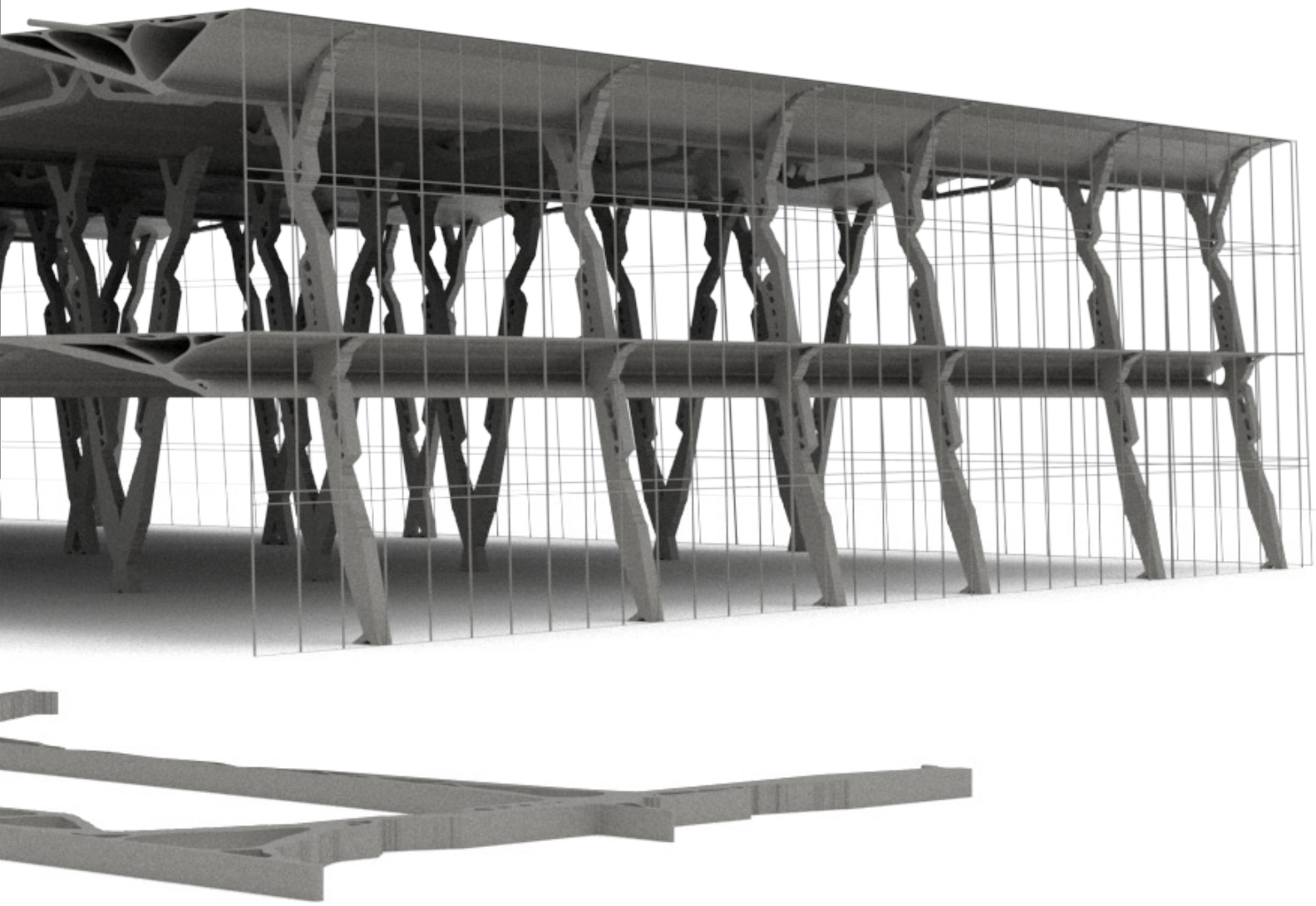


figure
a moment frame assembly of p
ning items, done with
would this be applied in reality
of optimization



5.9.3
pre-casted standing and span-
3d printed form work.
? perhaps not, but the process
is interesting.

SO in TO

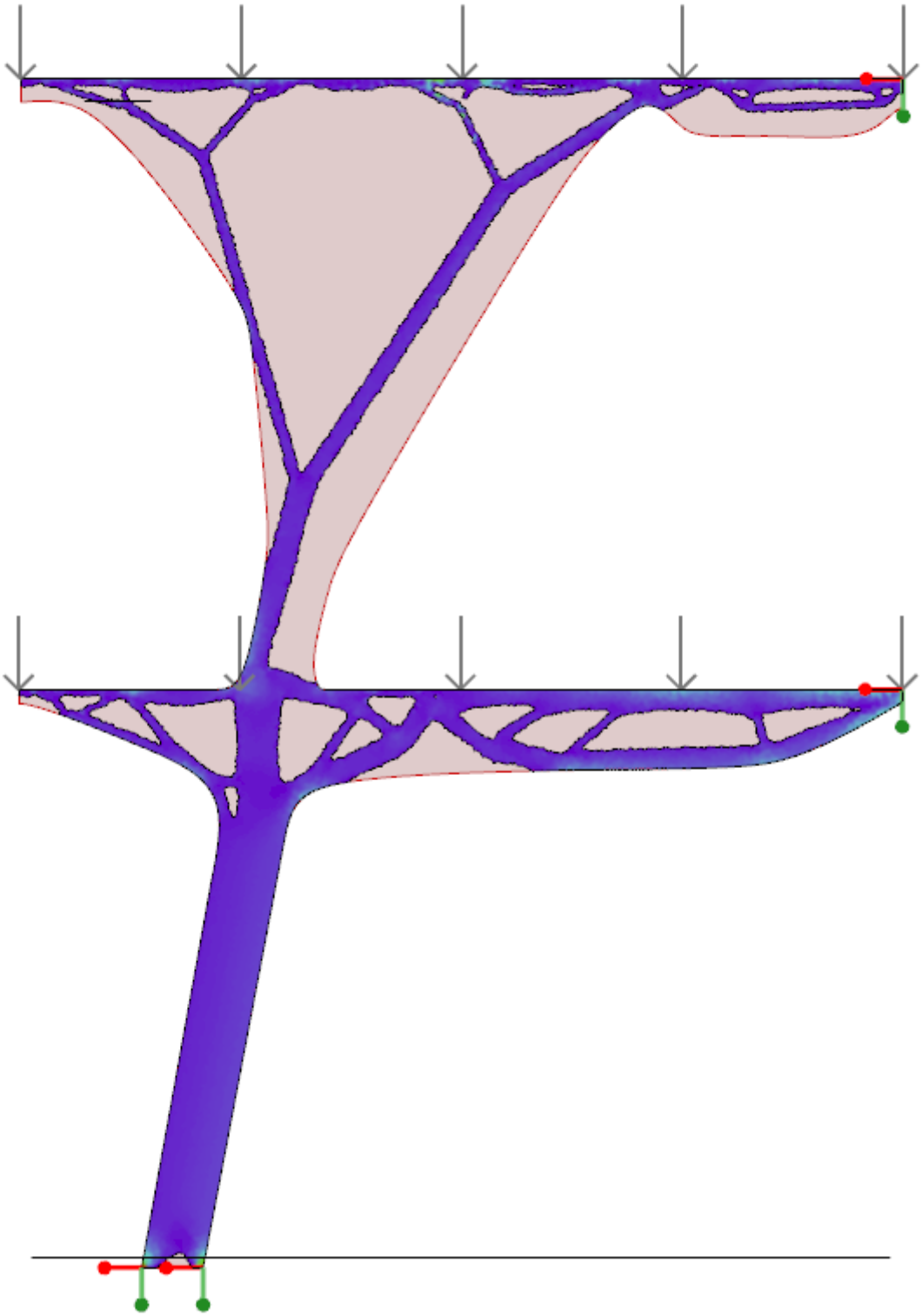
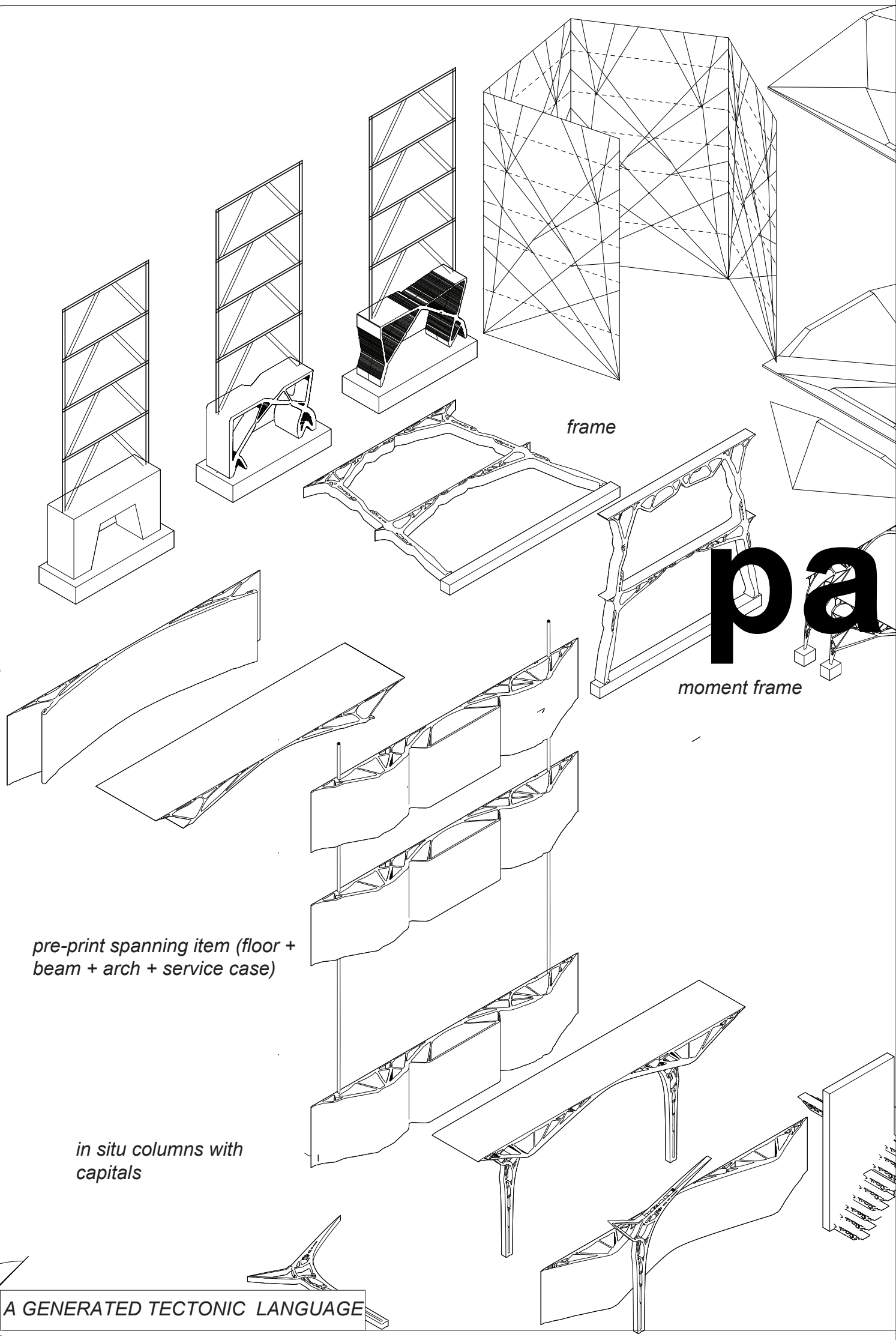


figure 5.9.4
Shape optimization in Topological Optimisation

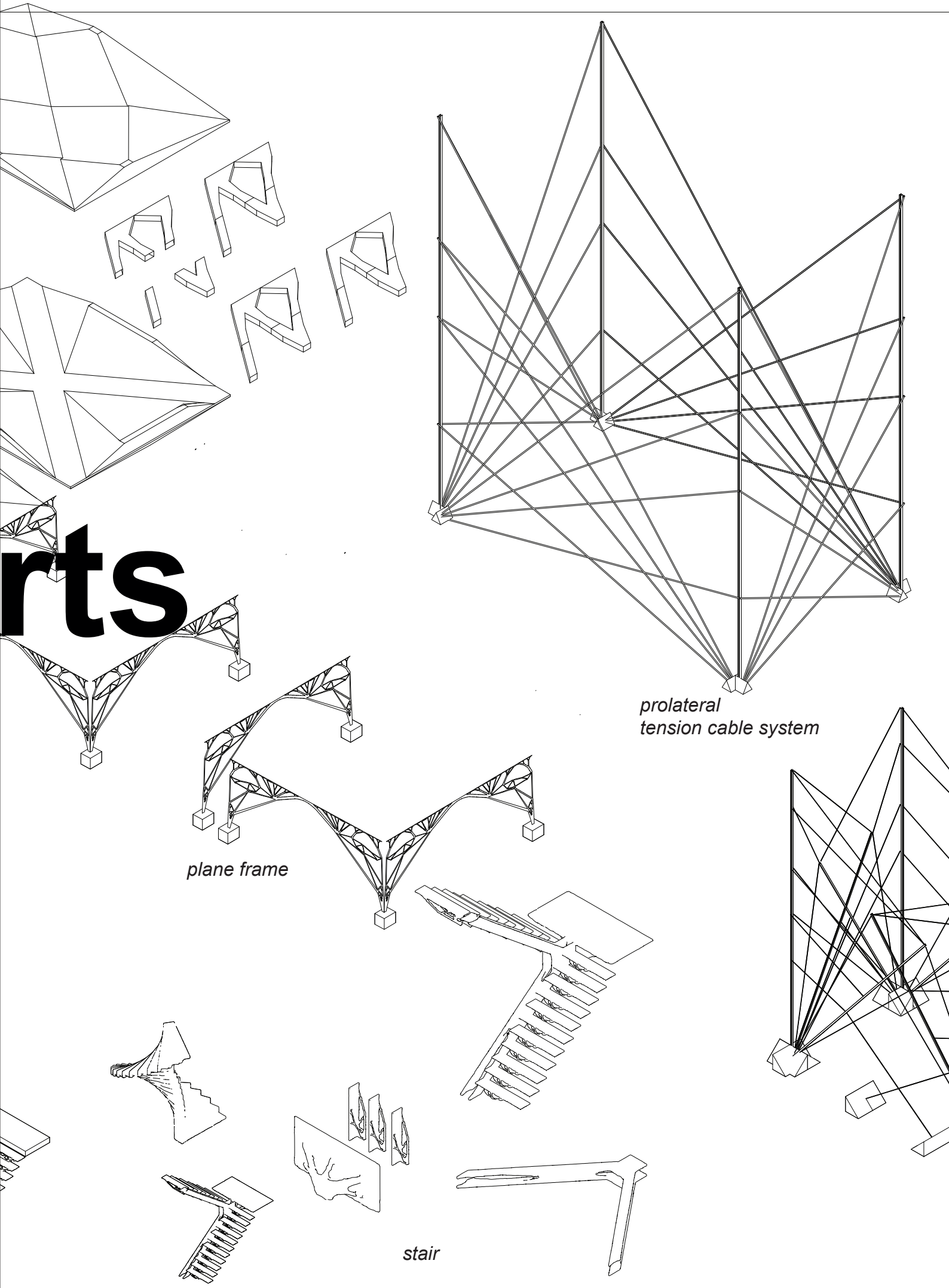
The question which underpinned the dissertation was: how the reprioritizing of material to areas of stress drive the symbiosis of engineering performance and architectural outcome? The thesis concludes that BESO is one tool in the practitioner's kitset (alongside physic modelling, digital modelling, drawing et cetera). The computer and computational script works itself as a designer, side by side the human as an aid with build in artificial intelligence. Resultant meshes are often unprecise due to resolution issues, however the mesh following the direct line of force offers an indication of how to solve the structural problem, how one can go about rationalizing a structural scheme, and offers conceptual typologies that expand the scope of the architect's possibilities for

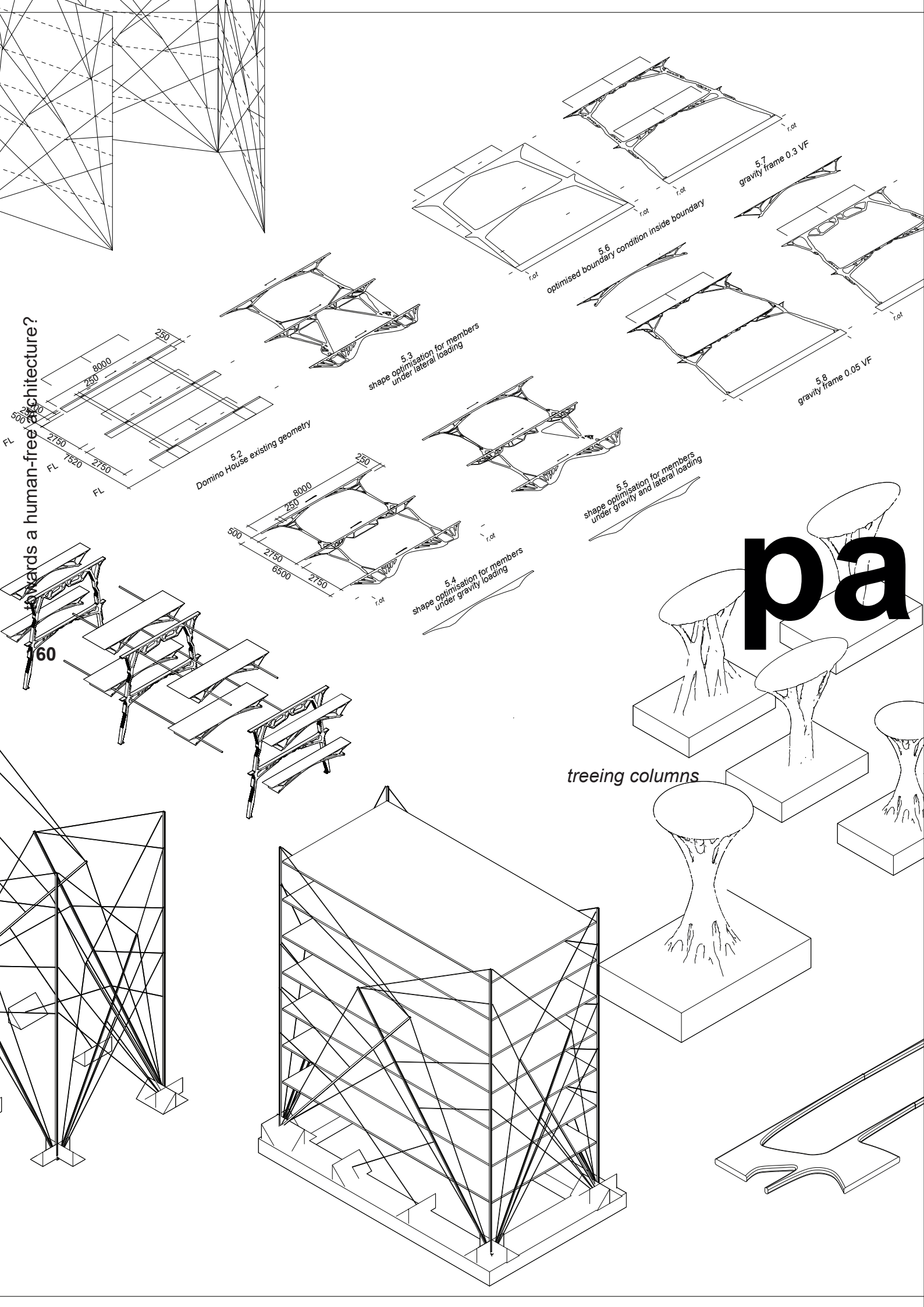
a given project.Outcomes are always novel with BESO as a design driver.

The dissertation researches the methodology for BESO, then realises its use as a tool: an aid with built in artificial intelligence, to provide the designer a broader scope of options when it comes to design. BESO use can become hindered on the meshed output, when, large 3D printing is not feasible and meshes are low resolution. We have something that indicates stress lines and effective force transfer for a given shape and can aid us in designing through it as an aid, as designers we strive for innovation. The generation of design iterations proved interesting structural drafts which can be converted into refined design later. Currently in the broader literature, the output is treated as an end, when it should be regarded as a means. The



A GENERATED TECTONIC LANGUAGE


rts
prolateral
tension cable system
plane frame
stair


5.2
Domino House existing geometry
5.3
shape optimisation for members under lateral loading
5.4
shape optimisation for members under gravity loading
5.5
shape optimisation for members under gravity and lateral loading
5.6
optimised boundary condition inside boundary
5.7
gravity frame 0.3 VF
5.8
gravity frame 0.05 VF
8000
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7520
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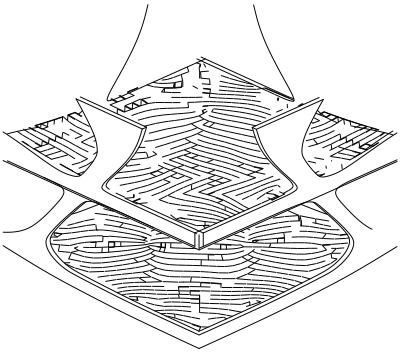
treeing columns



research shows where material needs to be prioritised, and where it is not needed. BESO should be as a starting point (centre line analysis, information where material is located, centre line etc) can be converted to more traditional construction systems and methods, where further tools such as engineering software like Karamba 3D can then automatically size minimal cross section sizes for the entire structural indeterminate system to work. The centre lines are extracted, either internally within Grasshopper or by line drawing on each façade as a 2d plane. Using Native Karamba we can ascertain the axial loading, bending stress, buckling, and shear force on each member, and given that the system within Karamba is taken as a whole system, Karmaba will calculate each size member minimum

requirement, node fixing, et cetera, for the structurally indeterminate system to work as a whole. The translation of BESO to a workable typology/traditional construction is important and original here and not acknowledged in current literature on BESO. How we use the tool might differ from the original use of the tool; a piece of mesh which was simulated to work in compression, may be used for tension; outcomes can be interpreted differently, and this is perhaps just as valuable as the actual mesh itself (assume it is high resolution). There is also the philosophical mantra of form following force, so when the line of force is followed, outcomes will be unprejudiced by humans: we result in standing and spanning items.

The question: *towards a human-free architecture (?) is answered: the designer is a curator of tools at their disposal, so, no.*

Figures
All graphic images, line drawings and renders are the authors unless stated otherwise.

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