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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Architecture in The Lawrence Technological University 2022

by Nicholas Peruski

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INTERNATIONAL MassTimber CONFERENCE
April 12 – 14, 2022

VERTICAL FOLDED PLATE

Simulated Architecture with Mass Timber and Faceted Space

ABSTRACT

Vertical Folded Plate is a historical and technological exploration of folded plate design pushed to its limits. Since 1950s folded plate design and mass timber innovation since the 1990s, the need for these two worlds to collide is apparent in 21st Century design—to reveal scarcely known social and ecological benefits that each would otherwise not bring on their own. A new design approach to multi-story design can expand on the proven benefits of mass timber as a renewable material. To prototype the synthesis of a space created by folded mass timber plates, the vertical span of an inhabitable column (as used for vertical circulation, services and daylight) was structurally analyzed to test both precedent and exploratory forms in order to achieve socially-significant spaces.

The study traces folded plate design from Sergio Musmeci's approach to concrete architecture to Chris Robeller's synthesis of precision routed mass timber panel joinery. The modern combination calls for a modern visual analysis method. In this study, column-like spaces created with folded plate were analyzed using structural finite element analysis (FEA) to visually represent how folded geometry supports both physical and social forces. Prototyped on a site as context for an architectural work, the approach serves as a catalyst for future innovation in material and form. The design of a vertical folded plate-inspired space charts a new expectation for sustainability and tech-driven architecture.

THESIS STATEMENT

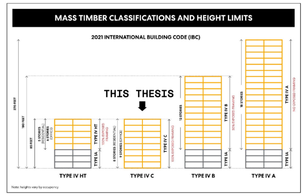
Vertical Folded Plate charts the projection of folded plate construction — realized through the disciplines of mass timber — with the greatest target to reform the spatial logic of modern multistory architecture through structurally efficient, ecologically responsible and tech-driven design.

WHO IS THIS FOR?

FORESTERS NATURAL SCIENTISTS
GEN Z MANUFACTURERS HIPPIES
SOCIAL SCIENTISTS ENGINEERS DNR
STUDENTS LOGGERS
CONTRACTORS EDUCATORS INVESTORS
INNOVATORS DIGITAL FABRICATORS

WHY VERTICAL?

Mass timber is an umbrella term for an array of engineered wood building materials that can be used in structural and non-structural applications to construct beautiful, strong, safe, cost-effective, and sustainable buildings, including taller buildings. By early-adopting the mass timber components of the 2021 IBC, the State will enable the Michigan architecture, engineering, and construction industry to respond to growing consumer demand for buildings that harness the myriad benefits of mass timber, which include:



Source: Perkins+Will, adapted from ICC

Constructing safe, cost-effective buildings, faster

Creating economic development opportunities

Realizing climate and sustainability benefits

Adapted from a template letter to the Bureau of Construction Codes of the Michigan Department of Licensing and Regulatory Affairs calling for early adoption of all of the new mass timber elements included in the 2021 International Building Code.

WHY STUDY THIS?

1. ARCHITECTURE=

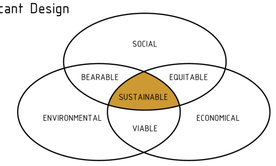
/Related to Built Environments and Human-Experienced Space
/Socially & Culturally Significant Design
/Environmentally Responsible

2. FOLDED FORM=

/Creates dynamic space
/Has rarely been studied multistory/stacked

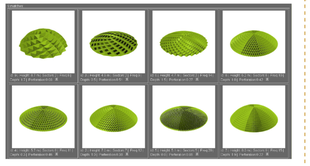
3. MASS TIMBER=

/Has clear ecological and sustainability benefits
/Is one of the greatest disruptors of the 21st Century



PERFORMANCE CRITERIA

MODERN TOOLS



/ This research studies timber-based plate-shell domes by analyzing structural, daylighting and acoustical parameters. With a focus on CLT-based plate elements, the effects of perforations (windows and glazing) within the CLT are analyzed via modeled as a dome.
/ Conducted using Paragen (a parametric modeling tool) designers can take into account multiple performance criteria when designing the folded plate.
/ With the increase in innovation with bio-based building materials such as CLT, designing with such materials is a field constantly explored related to similar wood products and brings attention to energy consumption during production.
Source: Falk, Andreas, et al. Form Exploration of Timber-Based Folded Plate Domes. Proceedings of the International Association for Shell and Spacial Structures (IASS) Symposium, 2015.

OTHER TYPES OF VISUAL STRUCTURAL TOOLS USED FOR THIS RESEARCH:

KARAMBA3D FOR RHINO/GRASSHOPPER
https://www.karamba3d.com/
DLUBAL RFEM
https://www.dlubal.com/en-US

THE PHYSICS BEHIND

INTEGRATED JOINERY

$$n = \left\lceil \frac{\psi_{tot}}{\cos^{-1}\left(\frac{R_{ext} - h_s}{R_{ext}}\right)} \right\rceil$$

$$\tilde{n} \geq \left\lceil \frac{\psi_{tot}}{\cos^{-1}\left(\frac{R_{ext} - h_s}{R_{ext} - (h_s/2)}\right)} \right\rceil$$

$$n = \begin{cases} \tilde{n} & \text{if } \tilde{n} \text{ is even} \\ \tilde{n}+1 & \text{if } \tilde{n} \text{ is odd} \end{cases}$$

/ The edgewise conditions of folded plate are performance-maximized to achieve lightweight structure. By intensely presenting the force comparisons and performance of the classifications of folded plates, the case is made for using the structures on a building scale.
/ This research is presented to those who would do similar calculations for the types of specific joinery on the edge condition to where this research focuses on the gravitational implications of the edge between panels.
/ By designing such prefabricated systems with intentional load bearing considerations, the construction of the system are projected into ecological and sustainable advantages.
Source: Stitic, Andrea, and Yves Weinand. "Timber Folded Plate Structures – Topological and Structural Considerations." International Journal of Space Structures, vol. 30, no. 2, 2015, pp. 169–177., doi:10.1260/0266-3511.30.2.169.

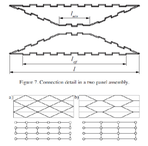
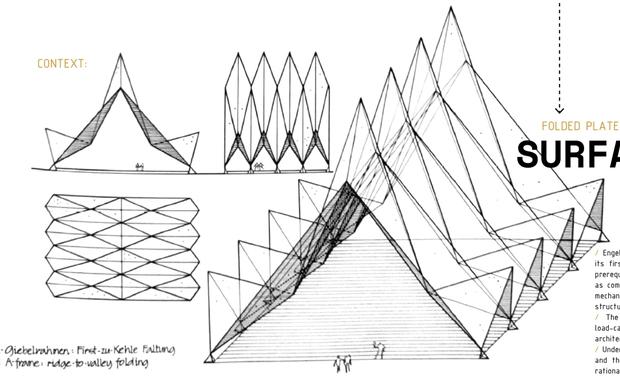


Figure 7. Connective detail in a two panel assembly.

CONTEXT:



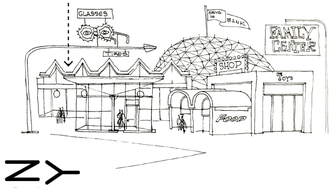
Zweigelenk-Giebelrahmen, Pfost-zu-Kehle Faltung
two hinged A-frame, ridge-to-valley folding

A RATIONALLY-EFFICIENT MACHINE
AN AESTHETIC-SIGNIFICANT FORM

FOLDED PLATE IS A TYPE OF

SURFACE-ACTIVE STRUCTURE

/ Engel defines folded plate, during the period of its first popularity, as surface and form – two prerequisites that today's designers may preserve as common to all design but which are deliberate mechanisms for folded plates as surface-active structures.
/ The knowledge of this self-supporting and load-carrying system is great value to the architect designer.
/ Understanding the system as both the structure and the envelope poses infinite opportunities to rationalize architecture through similarly infinite variations.
Source: Engel, Heinrich. Structure Systems. Praeger, 1968.

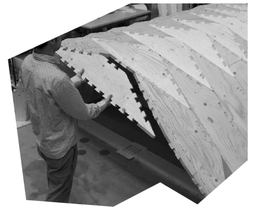


MID-MODERN PHILOSOPHY

AESTHETIC JUDGMENT IS CLOSELY LINKED TO

SURVIVAL

/The 1964 "rulebook" of the aesthetics of folded plate reveal the context of the system within architectural history and Gestalt psychology. Such includes that humans have survived by judging and measuring their environments and that there is a natural self-entity, just like domes, of folded plate.
/ This is a mid-century foundational (almost primitive) look at the typology and application of folded plate from its repetitional nature to its context within the integration of other systems such as structure and daylighting.
/ This source can relate to human and environmental psychology as structure, for example, is not just something to be calculated by an educated designer but something that is justified and verified as good in society.
Source: Heimsath, Clovis B. The Aesthetics of Folded Plates. Dept. of Architecture, Rice University, 1964.

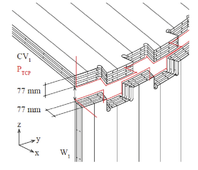


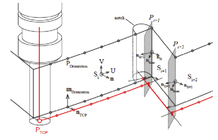
MODERN DISCOURSE

JOINING PROCESSES WILL BE

AUTOMATED

/Robeller comprehensively presents how timber plates can be fastened not with mass-produced mechanical fasteners but with ones that are integral to the plates themselves.
/For those also inspired by European and Asian joinery (in both building and object applications) the automated manufacturing process allows for the same rationalization.
/Innovation with CLT plates is headed toward having their connections automatically designed during the primary process rather than as a secondary process. This is integral to the prefabrication and automated design disciplines.
Source: Robeller, Christopher. (2015). Integral Mechanical Attachment for Timber Folded Plate Structures. 10.5075/epfl-thesis-6564.





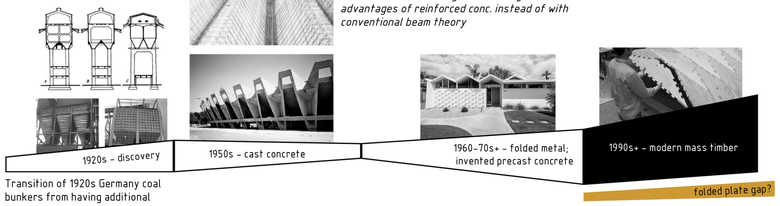
FOLDED PLATE + MASS TIMBER

HISTORY

Fugenlosigkeit [foo-ginn-low-zish-kite]

_the **seamless** connections between the plates that can be achieved with in-situ cast steel-reinforced concrete

First investigated and published by Hermann Craemer in 1929 who argued for using the advantages of reinforced conc. instead of with convenional beam theory



Transition of 1920s Germany coal bunkers from having additional ribbing to performing as a surface-active structure system.

TYPOLOGIES

SURFACES

- linear additions
- combination of additions
- radial additions

FRAMES

- continuous
- two-hinged
- three-hinged
- barrel

SPACES

- pyramidal
- polyhedral
- combinations

	bidirectional folds		anti-prismatic
a / simply corrugated	b / spot or facet	c / rhombus based	d / anti-prism based folded form and its quadrilateral variation

Mass timber folded plate charts a moment of history where the past approaches of folded design is modernized via the application and analysis of a modern material.

Existing typologies of folded plate design were applied to the Methods. The three-hinged was selected for the Proposal.

edge conditions

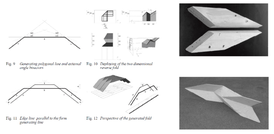


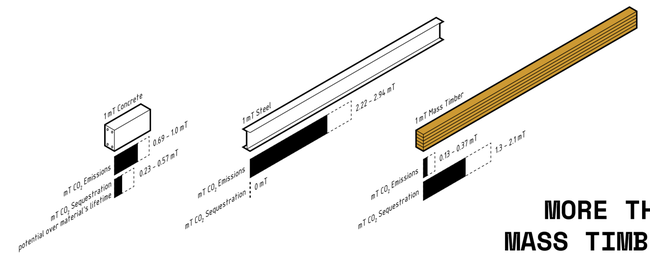
Fig. 9 Generating polygonal line and external angle bisectors

Fig. 10 Overlaying of the two-dimensional control grid

Fig. 11 Edge line parallel to the form generating line

Fig. 11 Perspective of the presented fold

/ To reveal the potential of folded plate, mathematical investigations of the form-finding process are taken through the lens of Origami art and CNC-milled CLT as the material.
/ Origami patterns as designed in collaboration with an architecture office can reveal interest from clients to engage with the generation method for potential projects.
/ Just as a series of folding techniques exist in Origami, similarly defined, complex, folded geometry is quantified for the deployment of forms rationalized for CLT – necessary for understanding through the lens of mathematics.
Source: Buri, Hani, and Yves Weinand. "Origami—Geometry of Folded Plate Structures." Structures & Architecture, 2008, doi:10.1201/b10428-90.



Source: Timber City Research Initiative, Gray Organschi Architecture, timbercity.org

Precedent: MSU STEM Building

/Granger Construction Company, Sasaki, Integrated Design Solutions, Ellenzweig and IDEO, et. al.
Lansing, MI
2021

Claims
_Mass timber is a viable material choice for Michigan. The first Michigan mass timber building brings promise for the advancement and research of the material.

Tactics
_Using CLT floors and glulam beams and columns, this structure is an addition to an existing brick building and carries the architectural expression on the exterior.

Advancements
_This project notably does not express the timber on the exterior due to its building classification. This building maximizes the spaces created on the interior and does not necessarily maximize the material.

3,000
cubic meters of mass timber
CLT Floors, Ceilings, Stair Towers, Glulam Columns, Beams, Girders

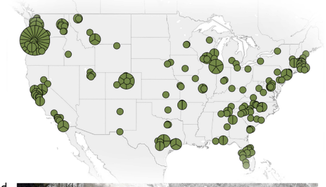
Carbon Storage
1,856 mT CO_2-e

That's like:

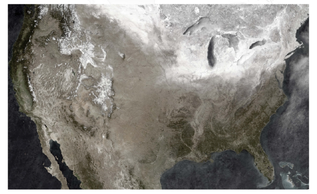
Not driving nearly 4.7M miles

Not burning more than 2 million pounds of coal

MORE THAN 1,384 MASS TIMBER PEOJECTS IN DESIGN (2022)



Mass timber has finally reached comparable engineered capabilites to steel and concrete. It can span and

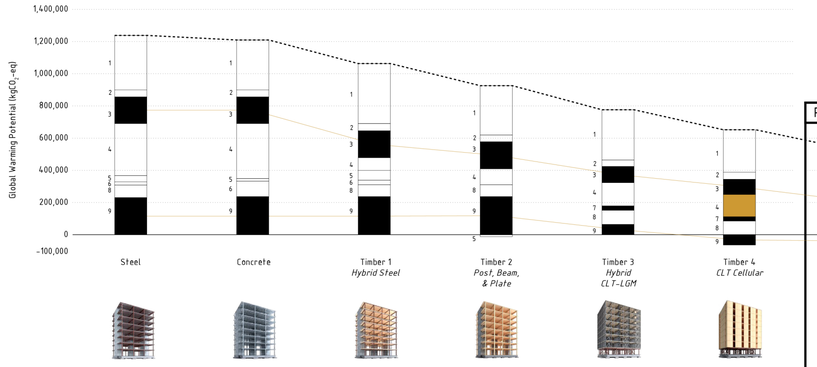


how sustainable is mass timber?

GLOBAL WARMING POTENTIAL (GWP)

(Per Building Assembly)

1. Interior Fit-Out
2. Glazing
3. Exterior Walls
4. Floor Slabs
5. Beams
6. Columns
7. Podium
8. Foundations
9. Structural Walls



Projections.doc

TALLWOOD IS THE FUTURE

With the increase in innovation with bio-based building materials such as CLT, designing with such materials is a field constantly explored with sustainability measures.

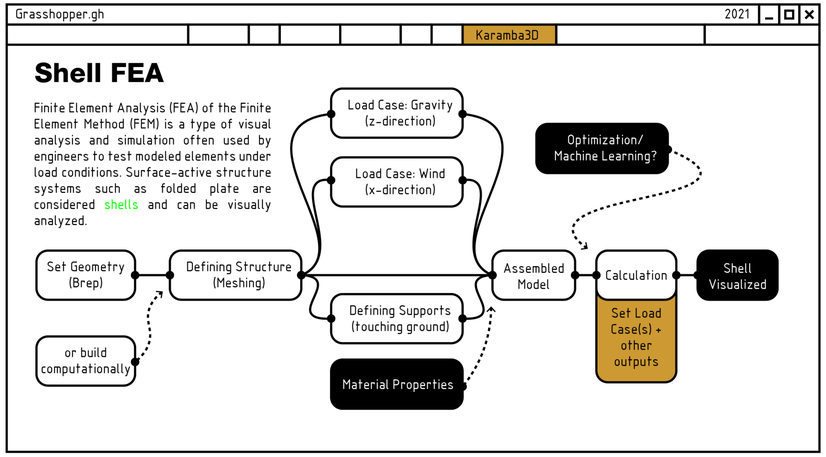
This thesis charts on folded plate CLT as synthesizing floor, walls and structure for for increased efficiency in design and potential reductions in redundancies—all while using a renewable product.

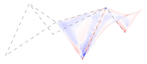
?

PRACTICE+ INNOVATION

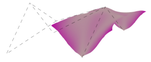
Shell FEA

Finite Element Analysis (FEA) of the Finite Element Method (FEM) is a type of visual analysis and simulation often used by engineers to test modeled elements under load conditions. Surface-active structure systems such as folded plate are considered shells and can be visually analyzed.

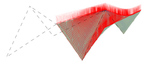




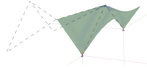
Utilization



Displacement/ Deformation

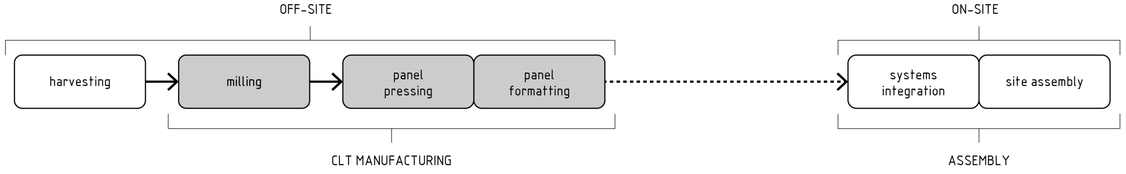


Loads applied to surface meshing (z-direction)

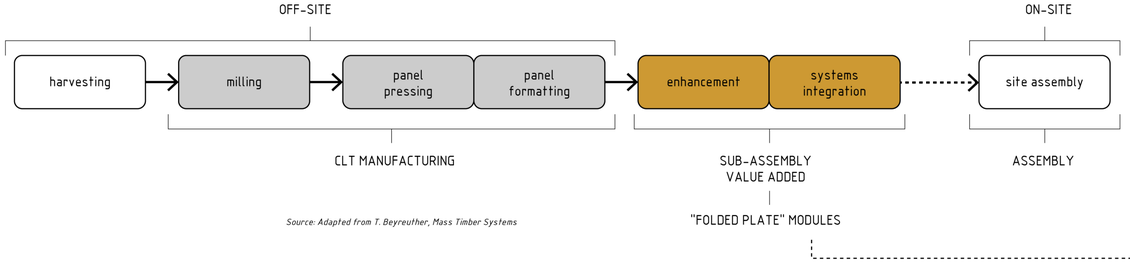


Reactions at Supports

MASS TIMBER PRODUCTS



MASS TIMBER SYSTEMS



Source: Adapted from T. Beyreuther, Mass Timber Systems

"WE CAN INNOVATE WITH MICHIGAN HARDWOOD"

– Shannon Lott, Michigan Natural Resources Deputy

"Manufacturing capacity of CLT in the US is currently 1/10th of the demand expected within 10 years," says Mark Rudnicki, professor of practice in forest biomaterials at Michigan Technological University. "CLT is, therefore, a prime opportunity for increasing the economic resilience of our rural communities".

Architecture as a physical historian

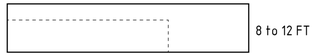
EMBODIED CARBON
The emissions from manufacturing, transportation and installation of building materials

OPERATIONAL CARBON
The emissions from a building's energy consumption

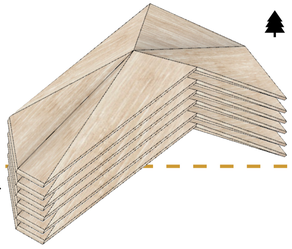
5-10% savings on construction costs

20% CO_2 emissions reduction

AMERICAN CLT MANUFACTURERS
are capable of producing panels:



...which is a basis for American-made folded plate designed panels.

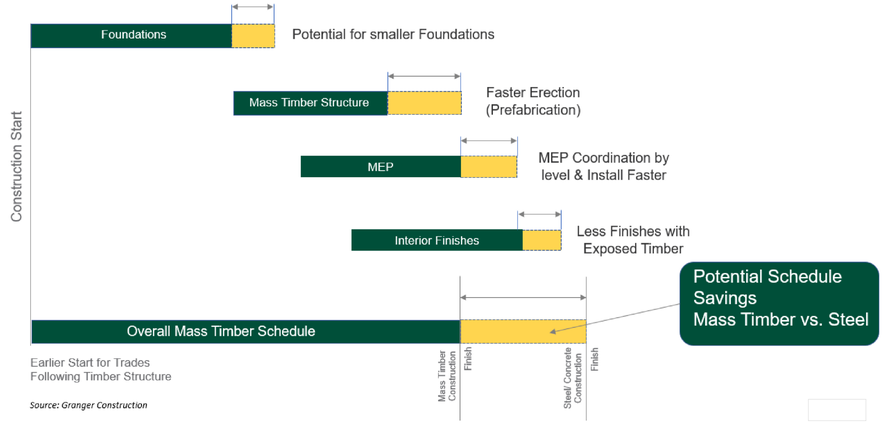


Architecture as a social investment

RETURN ON INVESTMENT (ROI)
Return is based on value engineering of the property and its viability in its context to generate revenue and maintain tenants. The social impact of this thesis is a socio-economic one.

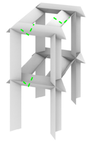
USER GROUPS
Early adopters have introduced mass timber buildings in the creative office sector. Part of what has attracted developers is the aesthetic value: the exposed mass timber helps create a cool, environmentally conscious office alternative that is proving to be a hit with tenants, especially a younger generation of *millennials and generation Z workers*. New generation consumers are willing to purchase or pay 15-27% more in spaces that are timber-enclosed or other biophilic spaces.

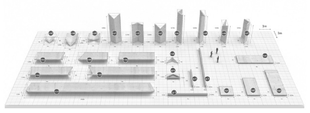
Occupants say wood is
honest, real and sustainable.
Which is a revenue-generating attractor. Combined with the spaces created with mass timber folded plates, tenants and dwellers will enjoy having unique spaces that is inclusive of multiple levels of affordability.



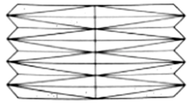
Source: Granger Construction

PROTOTYPES

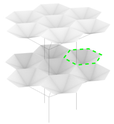


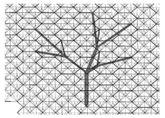


_01 kit-of-parts approach to sub-assemby

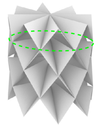


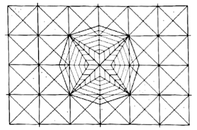
_02 hinged folds



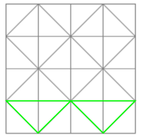


_03 canopy on branches





_04 radial



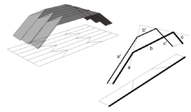
_05 pyramidal

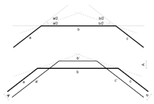
APPROACHES

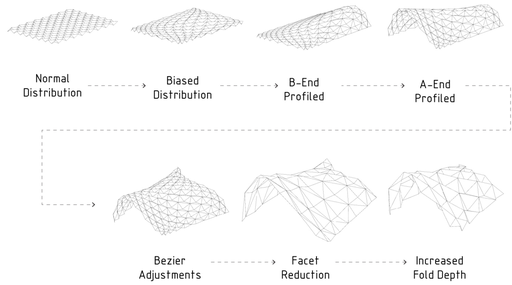
/approach A

Fold Generation Methods

_A polygonal profile designs the general shape in section. The initial accordion folding follows this line and reverses at each inflexion point. All lines reflect on the external angle bisectors of the segments.
_A second profile designs the corrugation of the accordion folding. It defines amplitude and extension of the parallel folds.



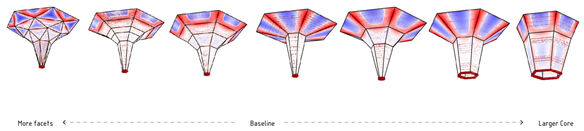




/approach B

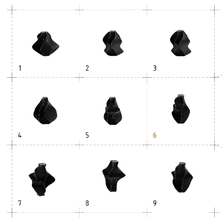
FEM Analysis of an Umbrella Column

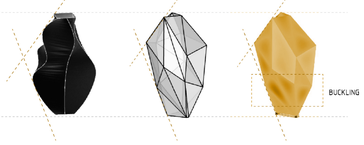
_Finite Element Analysis (FEM) of a column is visualized under uniform vertical loads.
_Percent of ridge and surface strength are visualized.

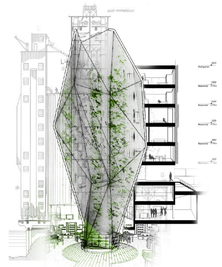


TRIALS

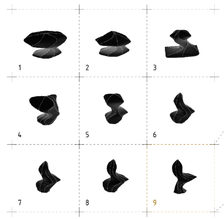
_01 circulation

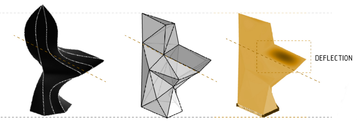


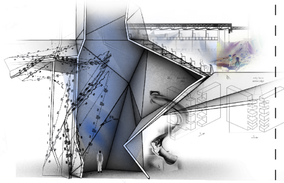




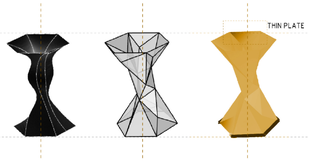
_02 program

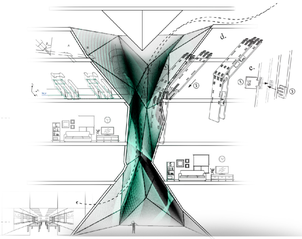






_03 venturi





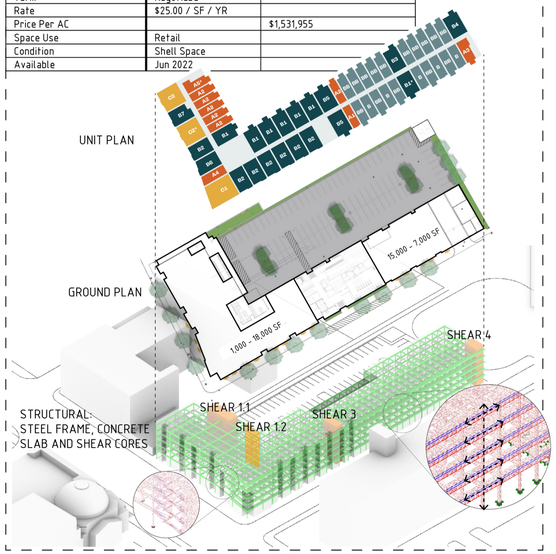
COMPARATIVE STUDIES

BASELINE_0

MID-RISE BASELINE

PROPERTY BASELINES FOR COMPARISON

PROPERTY FACTS	WOODWARD WEST	BRUSH PARK OPPORTUNITY
Rental Rate	$25.00 / SF / YR	
Price		$380,000
No. Units	204	
Min. Divisible	1,000 SF	
Property Type	Multifamily	Land
Property Subtype	Apartment	Commercial
Apartment Style	Mid Rise	
Building Size	188,000 SF	
Construction Status	Under Construction	Under Contract
Sale Type		Investment
No. Lots		1
Total Lot Size		0.25 AC
Opportunity Zone		Yes
AVAILABLE SPACE / LOT		
Space	1st Floor	
Size	1,000-25,000 SF	0.25 AC (approx. 10,805 SF)
Term	Negotiabe	
Rate	$25.00 / SF / YR	
Price Per AC		$1,531,955
Space Use	Retail	
Condition	Shell Space	
Available	Jun 2022	



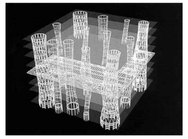
METHOD_1

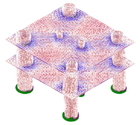
_MAXIMIZE RENTABLE SPACE AND TIMBER SURFACE EXPERIENCE
_PRIMARY UNIT: AREA (sqft)

OCCUPANT-DRIVEN AREA

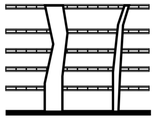
PLATES

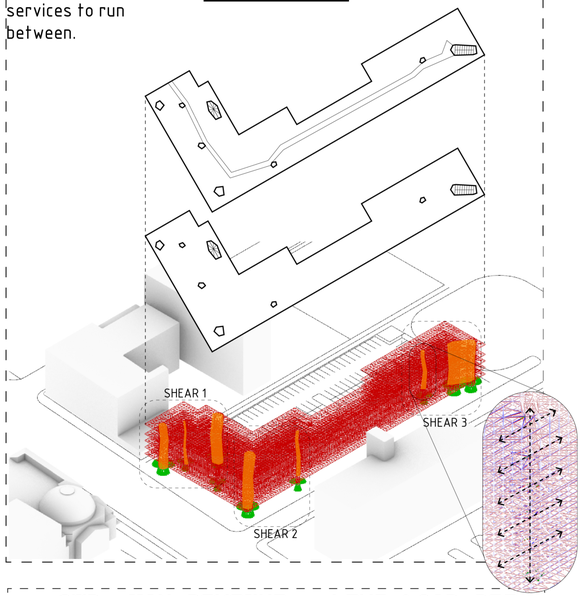
Sendai Mediatheque by Toyo Ito is a basis for occupant-driven floor area with vertical spaces that service all floors.





The cassette floor system is a hollow and lightweight system for 'normal' floor spans between spatial columns. It allows services to run between.



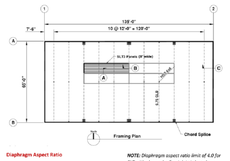


METHOD_2

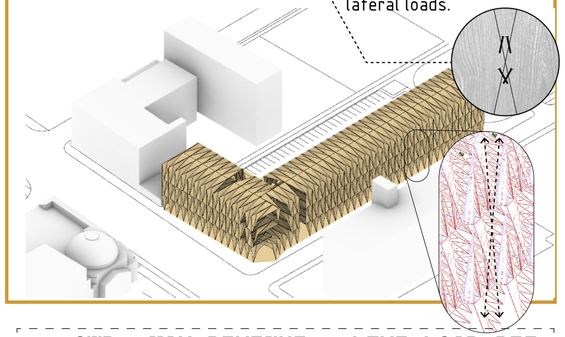
_MAXIMIZE RENEWABLE MATERIALS
_PRIMARY UNIT: GLOBAL WARMING POTENTIAL ($kgCO_2$-eq)

HORIZONTAL DIAPHRAGM

Although seemingly more open-plan compared to Method_1, the floor depth is much larger due to the deeper depth of the folds resulting in an overall building floor area to less to that of a building of similar height.



A diaphragm is a flat structural unit acting like a deep, thin beam. The term 'diaphragm" is usually applied to roofs and floors. A shear wall, however, is a vertical, cantilevered diaphragm. These construction systems can be used when designing a building for wind or seismic lateral loads.

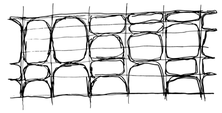


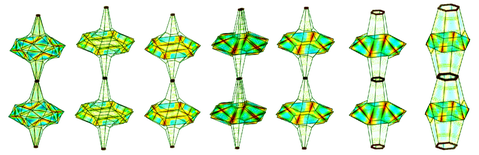
METHOD_3

_MAXIMIZE SPACE POTENTIAL
_PRIMARY UNIT: NATURAL FORCES (kN)

SPATIAL ECCENTRICITY

A doubly-inverted umbrella approach creates a unique typology of faceted space. A shell FEA analysis can be unitized/modular.





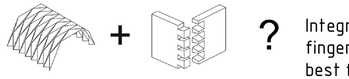


Figure 4.5 – Can an Antiprismatic Folded Plate be assembled with single-degree-of-freedom (1DOF) joints, combining the advantages of the shell geometry with those of the joints?

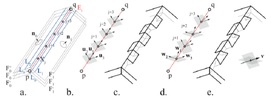
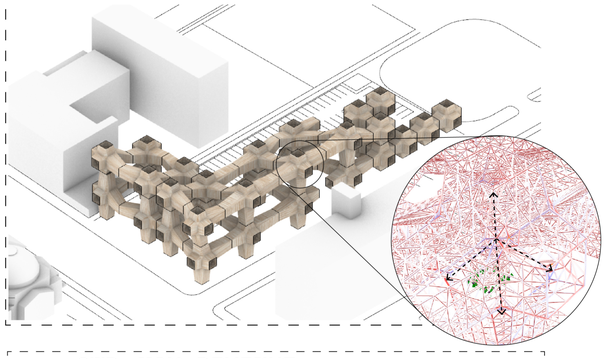


Figure 4.7 – Joint geometry. a: Basic parameters, b: Intersection planes (grey) normal to $\vec{p}|\vec{q}$, c: 3DOF joint, d: Rotated intersection planes (grey) normal to $\vec{n}'_1$, e: 1DOF joint

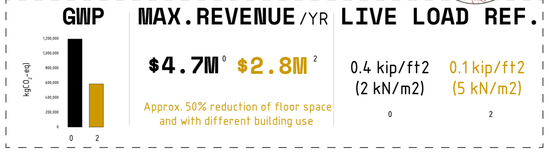
Without additional connectors, finger joints are *planar joints* with three degrees of freedom

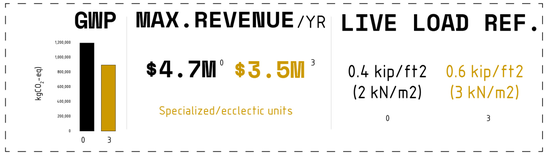
Integrated finger-joinery is best for this proposal because eccentric form and space can be simultaneously designed into the engineering of the joinery incl. number of fingers per edge length.



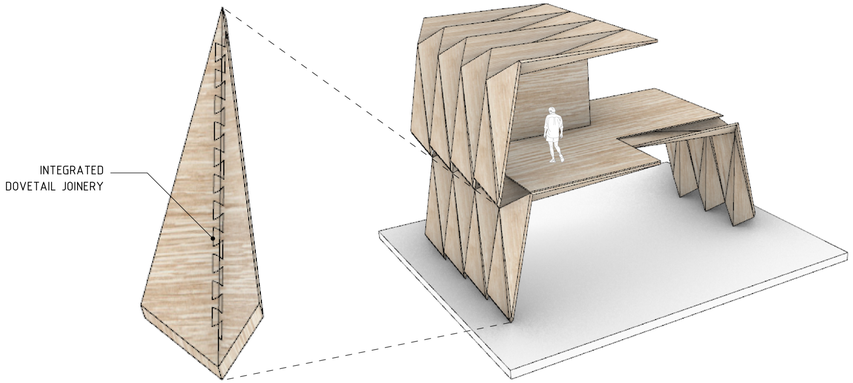
DATA

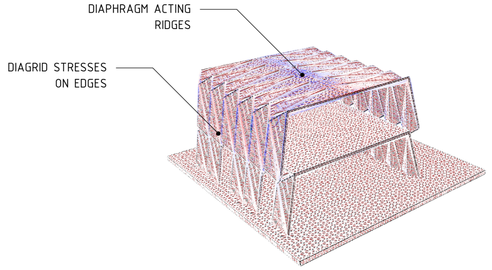
A comparative data approach to a timber-based design was struck against a site in Detroit, MI. Global Warming Potential (GWP), maximum revenue based on local property baselines and live load structural references based on structural approaches each hold a unique benefit to that of concrete/steel construction.

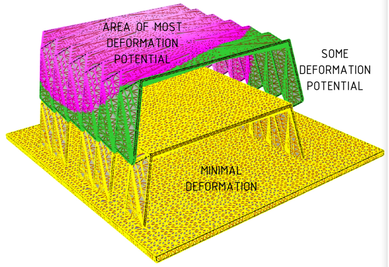




PROPOSAL



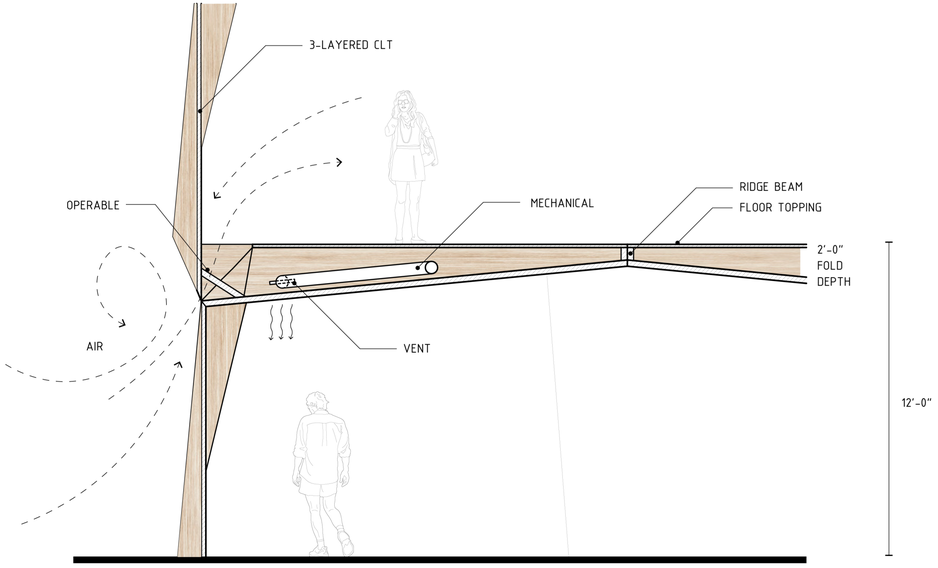




MIDTOWN - DETROIT

WOODWARD WEST
3439 Woodward Ave,
Detroit, MI 48201

An in-construction 5-story mixed-use development with 200 units and a leasable ground floor

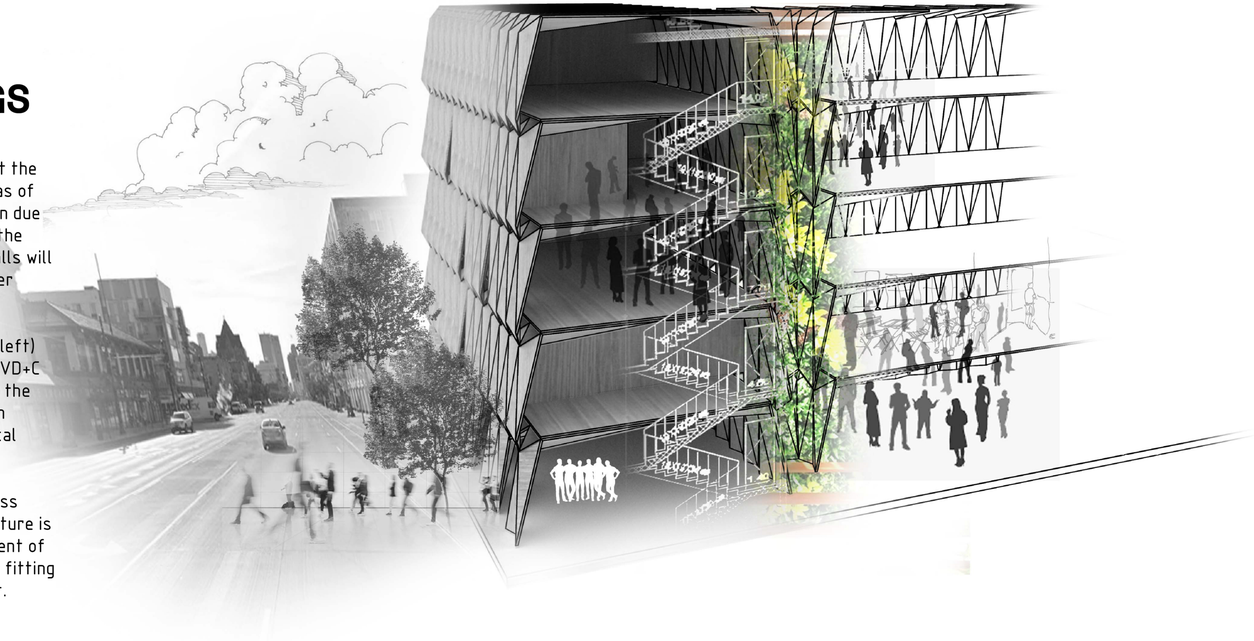


FINDINGS

This proposal is structurally viable at the schematic level. Areas of potential deformation due to spanning without the modeling of shear walls will need to consult timber frame shear design.

Critical connections (left) will need to undergo VD+C efforts but provides the folds to perform with passive and mechanical systems.

The three-hinged mass timber vertical structure is an ecological statement of dynamic architecture fitting in its Detroit context.



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