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# CONSERVATION METRICS FOR THIN SHELL STRUCUTRES: CASE STUDIES IN THE PACIFIC NORTHWEST

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**Abstract.** *The rise of thin shell concrete structures in the mid 20th century marked a globally significant era for both architecture and engineering. Born from a mutual desire for material efficiency, and formal variation, these structures epitomized the close collaboration of building professions of the time – creating dramatic, yet efficient structures. Master builders like Felix Candela in Mexico, and John V. "Jack" Christiansen in the USA blurred the line between structural engineering and architecture.*

*Unfortunately, many projects of this era – even ones that marked the apex of this building technique – are currently being neglected or destroyed. As products of a recent past, they are often not acknowledged as significant work, and their fate is left subject to changes in economic priorities, political maneuvering or simply uneducated indifference.*

*Therefore, it is of increasing importance to communicate the significance of these works, and quantify the multiple, tangible benefits of their conservation in the public realm. This paper presents preservation metrics that help communicate spatial, structural and sustainable considerations, and can be used to effectively argue for the conservation of these iconic thin shell structures. These metrics are intended to build off previous studies, yet reflect the changing landscape of building assessment, with the goal of fostering a new appreciation for these icons of an earlier time, and allowing them to remain active participants in the contemporary built environment.*

*This paper discusses three signature thin-shelled concrete structures in the Pacific Northwest (USA), and demonstrates the real benefits of their conservation. All three buildings were designed and built in the late 1950s/ early 1960s, and all are currently in use. From their structural efficiency and flexible divisions of space, to energy use and embodied carbon, this paper proves that thin-shelled concrete structures are not only worthy of preservation, but can continue to serve as responsible, operative buildings into the future. While focusing on the Pacific Northwest, this methodology could be applied to thin-shell structures around the world.*

## 1 INTRODUCTION

On February 19, 2014, the Seattle Landmarks Preservation Board considered the Nomination of a thin shell concrete warehouse for Landmark status. [1] The building was built in 1955-56, as a collaboration between the architect John W. Maloney and renowned thin-shell engineer John V. "Jack" Christiansen. The structure consists of a series of repetitive, concrete barrel vaulted forms – each one arching 33 feet between columns, yet spanning over 128 feet in the longitudinal direction. These vaults, and the immense long-span space they created, were the product of a coordinated building effort, combining priorities of architecture, engineering and construction. Spatially dynamic, structurally stable, and economical to build, the warehouse has functionally served as an operable warehouse for sixty years, with no significant deterioration or damage.

Figure 1. Seattle School District Warehouse

A new owner of the building, anxious to capitalize on the now-valuable real estate that the building occupies, presented the building for consideration – interested in removing possible obstacles to future uses of the site. The Landmark Preservation Board listened to a well-prepared historical description of the building, and initially voted in favor of the Nomination, by a vote of 8-2. The Board celebrated the building's construction technique, and recognized its form as a significant characteristic of the architecture and engineering of the region. Several Board members commented on the ambitious and innovative structural design and the "sensuous" quality of the undulating roof - both indications of a thoughtful, carefully constructed building. This positive vote spurred a second meeting, with a second vote as to whether to formally designate the building a Seattle Landmark.

However, at this second meeting, opinions began to shift. As an industrial building, the original design included solid concrete walls around the perimeter of the structure. These columns were inset from the supporting columns, with only strip windows above the wall to allow natural light into the space. While reasonable for the warehouse function of the building at the time, these walls presented a hard edge to the surrounding neighborhood – which had changed significantly since the time of construction. Also, with limited visual access to the interior space of the building, Board members argued that "no one" would be able to appreciate the long span spaces within, or understand the constructive innovation that the building displayed. At this second meeting, after an animated discussion, the Board voted 5-4 opposing Landmark Designation.

The Board discussion, and reasons for the change in voting provide an interesting perspective on the state of historic thin shell structures in the United States. On one hand, the building had effectively succeeded in demonstrating its value as a work of engineering and construction. Once made aware of the building's attributes, the Board recognized the ingenuity of its designers in their use of structure to shape the architectural space within. In fact, the board noted how the architectural features on the exterior derived from building's structure – with an undulating roof cantilever extending over minimally detailed columns and flat walls. In a reversal of roles, the engineer was celebrated as the more significant designer, over the architect.

Yet on the other hand, as a utilitarian building, the Board felt it failed to communicate its significance in its contemporary urban condition. Without visible, public access to the interior of building (never an intention with the original design), the Board felt it would remain widely unappreciated and interesting only to knowledgeable architects and engineers.

In this manner, the Landmarks Preservation Board effectively ruled that the significance of the building remained hidden behind its own functional exterior. The expressive engineering design of the long-span roof was too concealed by the original, programmatic elements of the building's use. Several Board members implied that if expressed more, the building would have perhaps been Designation worthy.

## 2 EARLIER LITERATURE

This discussion however, displays a promising shift in thinking with regard to the conservation of thin shell structures. In 2005, Boothby et. al. described the "principle threats to thin-shell concrete buildings" as "functional obsolescence, changing architectural tastes, and lack of understanding of the technical issues in their design and maintenance." In this case, the Board came to appreciate the technical achievements of thin shells, and the persistent values they promote – primarily material efficiency, the interconnection of architectural space and structural form. In 1977, David Billington had earlier stated that "The general public gets the idea that imaginative uses of concrete always involve immense overruns of estimates for cost and construction time." [2] At the time, expressive thin shell forms were type-cast as flamboyantly wasteful of material, and impractical - a sentiment that thankfully appears to be waning. Even on the issue of "architectural taste", the Board remained appreciative of the expressive geometry and architectural implications of the thin shell roof – seen as an aesthetic feature of a past era. The curvilinear forms expressed on the roof's edge were highlighted as favorable characteristics.

The primary hindrance to Designation apparently fell to an interpretation of the "functional obsolescence" of the warehouse building – a common difficulty in the preservation of historic structures of many different construction types. With rising real estate costs, the need for an operable warehouse in that particular neighborhood was waning, despite the fact that the building continued to operate effectively in its original intended use. It was not that the building failed to support warehouse activity, but rather warehouse activity itself had become not essential.

Ironically, the statements by board members seem to indicate that the building was deemed significant *independent* of its architectural program and use. For this building, the typical designation of historic buildings as a program space from a particular time (ie. warehouse from the 1950s) is not as important as the structure and construction method from a particular time (ie. a thin-shell structure from the 1950s). In fact, its specific use seemed to almost hinder the appreciation of the significance of the building.

## 3 ADAPTATION

This current condition presents an interesting question – is it possible to intentionally adapt historic thin-shell structures to suit modern building use? Do the significant elements that define thin-shell structures allow for a reinterpretation of use in the contemporary era, such that these buildings can retain their significant characteristics, while remaining active and useful buildings? Prompted by the ruling of the Seattle Landmarks Committee, these are the questions this paper hopes to address.

In the past, other scholars have had their doubts. In the 1990s and 2000s, many large-scale structures, originally intended to support grand civic uses – like the Seattle Kingdome – have indeed been torn down for their perceived inability to new uses. Boothby noted "The commercial and industrial buildings built in this style are also poorly prepared to accommodate modern commerce and the demands of modern industry."[3] He further stated that with thin-shell structures, the "integrated architecture and structure becomes an obstacle to effective adaptation of the building. [4]

Yet a series of mid-size thin shell structures in the Pacific Northwest may challenge this notion. With long clear span spaces, adaptable enclosures, and a growing appreciation of their formal presence, these thin shell structures appear prime candidates for adaptive re-use strategies – strategies that celebrate the past ingenuity of the structural form while revitalizing the space with designed programmatic changes.

## 4 QUANTITATIVE METRICS

Previous preservation efforts have focused purely on the historical significance of these buildings, describing the important values they embody. Others have described important repair techniques for thin shell concrete necessary for these building to maintain their structural integrity. [5] This article acknowledges the challenges of repair for poorly constructed or poorly waterproofed concrete structures, challenges that may jeopardize the integrity of the structure. However, the structures included in this study have endured for 50 years so far, with an intrinsic durability that is not in question. This study seeks to add a layer of assessment to the preservation argument by addressing issues of spatial adaptability, structural capacity, water proofing, energy consumption and embodied energy/carbon. By addressing three, midsized structures as case studies for evaluation: first, the barrel-vaulted Seattle School District Warehouse, then a hyperbolic-paraboloid umbrella Seattle City Light warehouse, and finally a gabled, hyperbolic paraboloid office building. These buildings present a range of thin shell concrete roofs – the significant element of their construction - at a small variation in scale.

(1) (2) (3)

Figure 2. Aerial View of Barrel-vaulted warehouse (1), hyperbolic paraboloid umbrella warehouse (2), and gabled hyperbolic paraboloid office building (3). (Not to scale)

## 4.1 Spatial Adaptability

Designed to support industrial or lightly programmed spaces, the layout of these buildings was driven by repetitive structural considerations, and have few impediments to an adapted use. With the significant thin shell roof serving as an overhead plane and a varying head height, their plans primarily consist of a repetitive grid of columns, with only limited walls inbetween. While the typical bay size and clear span varies, each structure offers its own set of flexible possibilities for new uses.

Table 1. Spatial Adaptability

| | Total Sq. Footage | Typical Bay Size | Overhead Clearance | # Interior Columns | Wall Locations |
|---|---|---|---|---|---|
| | | | | | |
| (1) Barrel Vault | 5,574 $m^2$ | 10 m x 39 m | 4.86 m | 4 | Perimeter |
| (2) HP Umbrella | 1,858 $m^2$ | 10.9 m x 10.9 m | 3.04 m | 15 | Perimeter |
| (3) HP Gable | 929 $m^2$ | 8.8 m x 4.6 m | 2.66 m | 12 | Interior Core |

Though these dimensions vary in each structure, each suggests a highly flexible interior space, easily adaptable to a variety of future uses. The typical bay size and overhead clearance are similar to those of newly constructed office, residential or retail spaces – with the expansive 39-meter distance of the barrel vaulted structure being particularly adaptable. These metrics indicate the possibility of a variety of future uses, with minimal disruption to the existing structure.

## 4.2 Structural Capacity

### 4.2.1. Gravity Loading

These thin-shell structures are all designed as single-story buildings, with the thin-shell utilized as only an overhead roof configuration, supported by vertical concrete columns. They all have a clear gravity load paths, easily divisible into tributary areas – a product of their repetitive construction system. All were designed an constructed to safely resist the in place gravity loads (dead loads, roof live loads, limited utility), and have indeed done so over the past 50 years. In addition, these thin-shell concrete structures were commonly over designed for their given strength considerations. The thickness of the concrete shell was determined by the size of the available aggregate, the diameter of the minimum reinforcing steel in perpendicular directions, and the required clear cover. These construction concerns ultimately created stronger shells than required by the code, and suggest the ability to resist some amount of increase in load in the future.

### 4.2.2. Lateral (Wind and Earthquake) Loading

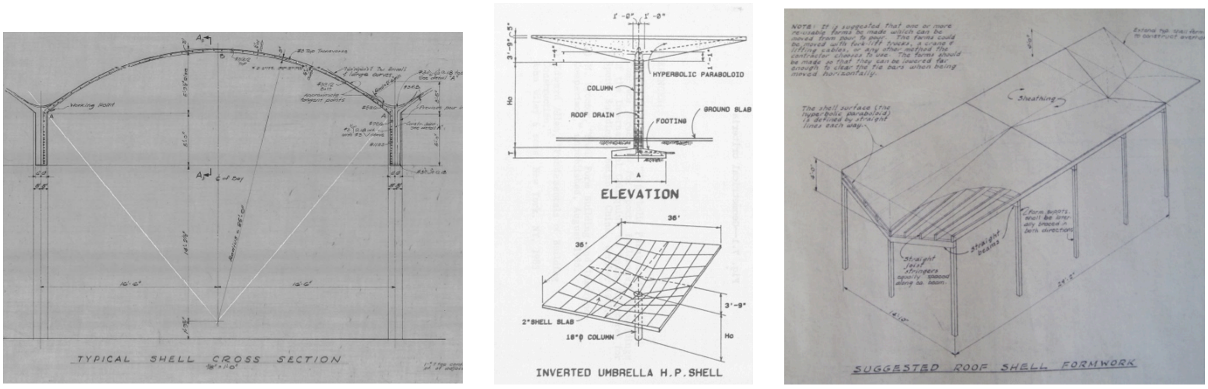
Despite the fact that these structures predate the majority of contemporary seismic design considerations and detailing requirements, they appear to be well configured to resist lateral loads, with often only minimal interventions needed. As largely horizontal elements –with a vertical variation less than 1.5 meters - the thin shell concrete surfaces do not attract large out-of-plane forces during seismic or wind events. Other structures, with more exaggerated vertical dimensions to the shells, require more consideration to ensure that buckling or out-of-plane bending does not cause detrimental effects. But in this type of structure (primarily horizontal configuration), the thin-shells act as large continuous diaphragms, with adequate stiffness to distribute forces to lateral-force resisting elements.

These types of structure are also aided by their material efficiency. With the primary roof structure consisting of only 2-3 inches of concrete, across the entire elevated level, the elevated seismic mass is relatively small. Under expected ground accelerations, this limited mass generates limited lateral forces that are easily resisted by small, strategically integrated walls or frames. Small forces and a rigid diaphragm allow significant discontinuities to be easily handled.

Table 2: Structural Capacity

| | **Shell Thickness** | **Vertical Variation** | **Roof Weight** | **Designed Live Load** | **Design Wind Load** |
|---|---|---|---|---|---|
| | | | | | |
| (1) Barrel Vault | 76 mm | 1.5 m | 3.16 $kN/m^2$ | 1.20 $kN/m^2$ | 0.72 $kN/m^2$ |
| (2) HP Umbrella | 51 mm | 1.2 m | 1.20 $kN/m^2$ | 1.20 $kN/m^2$ | 0.72 $kN/m^2$ |
| (3) HP Gable | 64 mm | 1.2 m | 1.53 $kN/m^2$ | 1.20 $kN/m^2$ | 0.72 $kN/m^2$ |

These structural capacity metrics suggest a robust system capable of supporting some variability in future loading and different configurations.




(1) (2) (3)

Figure 3. Structural System Details for Barrel-vaulted warehouse (1), hyperbolic paraboloid umbrella warehouse (2), and gabled hyperbolic paraboloid office building (3). (Not to scale)

## 4.3 Water Proofing and Drainage

The geometric variation in these thin-shell roofs, derived from structural and construction-based concerns can provide a challenge to the drainage of water, depite the fact that each of the case study buildings were designed with a waterproofing and water-flow strategy from the beginning. This took the form of an impermeable membrane bonded to the top surface of the concrete, and drains provided at the areas of depression. In the barrel vaulted structure, water flows to the perimeter of the building, and down to street drains. In the hyperbolic paraboloid structures, these drains continued through the interior of the supporting column to the foundation below. When clogged, this can cause a large volume of water to collect in the depressed region. With excess strength, there is little danger of structural failure form the water weight, but water intrusion must be carefully guarded against. These structures must be maintained to permit proper drainage of water – especially when contained within a structural column. While drainage is a chief concern, no single metric was found capable of helping assess potential for adaptive reuse.

## 4.4 Energy Use Considerations

With pressing concerns of sustainability and energy use, it is important to consider the operational behavior of these thin shell structures. Thin shell concrete is aided by beneficial thermal properties, particularly in terms of insulation and thermal mass. While, the specific benefit of these properties depends greatly on the particular location, climate and use, in general, concrete provides a relatively high thermal storage capacity (compared to other roofing compositions) that can help moderate the exterior temperature fluctuations and help reduced overall demand for heating and cooling. [6] Concrete can be considered to have a thermal storage capacity of 1800 kJ/m$^3$-K. As an overhead plane, the concrete has constant exposure to the sun, acting as a thermal storage well for most times of the year. Concrete also has some inherent insulating properties (measured by R-values, in kelvins square-meters / per watt) that increase with the thickness of concrete. Despite the thin application of concrete, both of these properties are beneficial to the energy performance of the building.

In addition, two of the case study buildings have perimeter walls of concrete that serve as an enclosure between inside and outside space, as well as providing seismic resistance. These walls add to the thermal mass of the building and help create a passive system for temperature regulation.

Table 3. Energy Use Considerations

| | Shell Thickness | Roof R - value (insulation) | Roof Thermal Storage Capacity | Perimeter Wall? |
|---|---|---|---|---|
| | | | | |
| (1) Barrel Vault | 76 mm | 0.0528 K-m$^2$/W | 136.8 kJ/m$^2$-K | Y |
| (2) HP Umbrella | 51 mm | 0.0352 K-m$^2$/W | 91.8 kJ/m$^2$-K | Y |
| (3) HP Gable | 64 mm | 0.044 K-m$^2$/W | 115.2 kJ/m$^2$-K | N |

The actual energy use of the case study buildings varies greatly, heavily dependent upon the activities and energy use of the occupant. Average and peak monthly energy usage was recorded for each building, however these values were highly dependent upon the conditioning of the space and the electrical demand from the building users. For example, a software company occupies the office building, with a server load that dwarfs any heating or cooling system for the building. In the absence of more use-specific analysis for specific uses and configurations, thin shell concrete structures can be considered to have beneficial thermal and insulating characteristics.

### 4.5 Embodied Energy/ Carbon

The preservation or reuse of buildings is being widely understood as an act sustainability. Rather than tear a building down, expending energy and dispersing carbon into the atmosphere, the use of existing buildings takes advantage of resources already in place.[7] The usefulness of an embodied energy or embodied carbon calculation, in the consideration of thin shell structures for preservation, presents an interesting predicament. While methods for calculating embodied energy and carbon are being developed and debated, in preservation these metrics are largely used to quantify energy or carbon already "spent" on the current building. Using approximate values, concrete is considered to have 1.110 MJ of embodied energy per kg, and 0.159 kg of $CO_2$ per kg. As these metrics are based, among other things, on the volume of material in the existing building, thin shell structures inherently have lower embodied energy/ carbon numbers than other building types. These numbers suggest that the material efficiency of these buildings makes them less valuable than a more massive, carbon intensive building. The usefulness of embodied energy/carbon in the adaptive reuse of thin shell structures lies in their ability to communicate the effectiveness of a low-carbon building, to hopefully inspire future consideration of thin shell applications.

## 5 CONCLUSION

While no single number can communicate the complex considerations that go into the adaptive reuse of thin shell structures, several metrics presented in this article indicate favorable characteristics. With flexible spaces, low structural forces, manageable water and energy traits, these buildings can be considered highly functional and adaptable to future use. Through simple design interventions, like the removal of several exterior wall panels, or the reconfiguration of interior partitions, these buildings can exhibit the innovative structural systems on which they were conceived and capitalize on their hybrid role as both architectural and engineering forms. The building metrics presented here can begin to shift the public understanding of thin shell structures, and help the historic building be seen not as static objects of arbitrary forms, but as adaptable, performative structures with intrinsic value.

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