Consolidating pedagogies

Between architecture and engineering

Citation for published version:
Pedreschi, R, Serefoglu, I & Paredes Maldonado, MIGUEL 2022, Consolidating pedagogies: Between architecture and engineering. in M Frier Hvejsel & PJS Cruz (eds), *Structures and Architecture. A Viable Urban Perspective?: Proceedings of the Fifth International Conference on Structures and Architecture (ICSA 2022), July 6-8, 2022, Aalborg, Denmark.* Proceedings in Structures and Architecture, CRC Press, pp. 1042-1049.

Published In:
Structures and Architecture. A Viable Urban Perspective?

Consolidating Pedagogies: Between Architecture and Engineering

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ABSTRACT: The paper presents and raises discussion on a new pedagogical approach, that combines computational modelling with careful use of precedent in architectural and engineering education. This study is a part of a larger PhD research project investigating the workflows of the rationalization of form from the initial design phase to realization of structure, manufacturing and assembly. A range of efficiency criteria has been formulated and discussed to enable the derivation of a methodology to analyze and reevaluate existing complex forms through the use of learnings from precedent. A series of projects have been evaluated. This paper presents a re-evaluation of the Dynamic Earth project in Edinburgh serving as an exemplar project to facilitate a novel pedagogy being tested and implemented through a research project.

1 INTRODUCTION

The exploration of the relationship between form, structure and construction has been an area concerning many collaborators: architects, engineers, manufacturers and contractors, from the initial stage of conceptual design to the construction and completion of a project. The ongoing shift to digital design and computational modelling is continuing and encourages the designer to envision more complex forms, sometimes disregarding boundaries of architecture, engineering and construction. However, conceptual designs, facilitated by modelling, may result in form driven complexity and lead to projects that are inefficient in terms of geometry and structure. This affects the overall project workflow with a consequent impact on efficiency and sustainable use of material and lead to difficult manufacture and construction, high initial and high lifetime costs of the building.

The urge to achieve non-orthogonal structures that are defined by complex double curvature is not a new concept, forms such as vaults and shells designed by masterbuilders and early pioneers of the industry are considered. Influential engineers and architects of the past have created innovative and efficient ways of resolving complex forms due to the material, manufacturing, and assembly limitations of the time. Their means of generating form, design and analysis of complex structures were dominated by mathematics, form finding techniques, material and building knowledge, and the experience of the designer. The forms that were derived from structural principles had an overt concern for the use of materials and practical construction with a simple workflow. Requiring a unified understanding of engineering and construction knowledge combined with an architectural sensitivity towards expression., the realization of these complex forms would not be achieved efficiently without the collaborative knowledge through architectural design, structural engineering and construction.

Moving away from the rectilinear paradigm, modern trends in design, facilitated by digital tools, can create abstract complex geometries independent of structural and construction constraints, which are resolved and developed in the post-concept stage of the workflow. (Bechtold, 2011). Nevertheless, technical and material limitations in manufacturing complex freeform structures still remain excessively inefficient in terms of time and cost. Recent examples like curved titanium cladding of Guggenheim Bilbao, the iceberg and sails of Fondation Louis Vuitton or isometric wireframe curves with moldable aluminium of BMW Welt demonstrate the complex production and assembly of both customized and standardized components of a generic digitally fabricated building. Modern architectural expression in projects as such demonstrates a challenge that forces a trade-off between conventional design (with standardized parts, ease of construction, cost optimization, less flexibility in architectural expression) and showcase examples that demonstrate with highly bespoke manufacturing, more flexible design and extremely cost and time intensive (Papanikolaou, 2012).

Efficiency in this sense becomes a notion to be considered in two ways: efficiency in materials and process. For instance, although concrete shells had a worldwide appeal at the beginning of the 20th century, the popularity declined due to the extensive use of formwork, construction methodology and emerging materials with lightweight building systems (Tang, 2015). Concrete and masonry shells reappeared around the 2000s with the prospect of gaining popularity when the materials and processes are used appropriately (Bradshaw et al., 2002). A recent attempt at displaying the efficiency of funicular forms by the Block group intended to integrate architecture and engineering in dry-stone construction with the Armadillo Pavilion (Block et al., 2017). The need for zero-tolerance fabrication contributed to the significant waste in stone and which can be challenging even if modeled precisely (Schurer, 2010). The same software, RhinoVault,,was used to develop the funicular Catalan vault of Mapungubwe Interpretation Centre (Ramage et al., 2010), where efficiency in process and material is achieved using modern ways of deriving shell form together with a construction process that uses local labour and materials and requires minimal formwork, resulting in a pragmatic, low cost solution. Thus the development of form uses the same tools and principles but the resulting effective construction processes depend on the integration of material knowledge and process

2 AIMS AND METHODOLOGY - PRECEDENT AND PEDAGOGY

In Architectural education the use of precedent is intrinsic to and embedded across the various modes of teaching, in history and in the design studio, however often fails to dive deep into deconstructing the projects to answer specific questions regarding the rationale between chosen structure, material and construction methodology.

Structural engineering education is based on scientific principles for structural analysis and material behaviour directed towards designs based on codes, standards and regulations. This latter point inevitably defaults attention towards the standard, often to the rectilinear and the plane. Precedents are very rarely used, seemingly somewhat less tangible that calculation and code verification.

This study introduces an evolving pedagogical approach that reviews the way precedent can be used in engineering education to address the issues mentioned in terms of efficient design, development and production. The approach uses digital modelling combined with precedent studies through concentrating on the relationship between form, technology and production primarily from an engineering perspective. A range of MEng Structural Engineering with Architecture (SEA) dissertation students were involved to understand the possible impact of using digital tools and precedent studies and identify the relationship between architecture, structure and construction.

Throughout history and particularly from the late 19th C, from Gaudi onwards finding efficient forms for structure have preoccupied many engineer and architect, such as Nervi, Candela and Dieste, physical models, mathematics and geometry. Whilst their work may lie and be well understood in the broader context of architectural and construction history in this study, we apply directly from their methodology, their design and construction workflows. This is to facilitate an in-depth understanding in deriving efficient form considering technical and material limitations and potentials to produce complex structures.

Digital modelling and form finding allows operations that are beyond the convention to be developed, linking to FEA programming through Karamba3D and other structural solvers. The problem arises in finding ways to import the notion of intuition and the sense of process, which cannot be modelled through parametric software.

Exploring digital trends to extract relevant information from appropriate precedent is the first step of understanding form and its implications in conceptual and detailed design. Along with developing an understanding of both structural and architectural considerations in the conceptual design of complex buildings, this study assesses the impact of using precedent in education on design efficiency and construction awareness. This notion is explored through deconstructing an exemplary efficient complex form as precedent and understanding the digital ways of achieving the same form evaluating its performance. The process involves applying this knowledge to re-consider an existing project. In effect this creates the idea of an alternative design narrative, seen through the eyes of the engineer or builder as a tool to re-evaluate the original concept and propose alternative solutions to enhance the architectural concept whilst simplifying structure and construction.

A set of criteria has been introduced to understand and conceptualise the ideas behind efficient design and ways of addressing the problem. The preliminary analysis of Dynamic Earth points out the main themes that arise from questioning the efficiency through the way computation and digitization of the form is perceived and alternative means of production in the modern construction of free-form geometries. The two buildings are then re-evaluated learning from Eladio Dieste's work on brick vaults. These criteria are outlined below in terms of a Sustainability Matrix.

3 INNOVATION AND SUSTAINABILITY MATRIX

The diagram below demonstrates the three key elements that are identified through scrutinizing what efficiency implies when taking account of architectural expression, structural intent and construction awareness. The designer's role should be to achieve functionality regarding aesthetics, cultural and performative needs in a sustainable environment. Construction Declares and current themes discussed in COP26 call for immediate action in attending global emergencies like climate change and biodiversity with a paradigm shift in professional behaviour within the construction industry, the largest consumer of raw materials and resources, and accountable for 6% of global GDP (Gerbert, 2016). Reducing waste and regenerating self-sustaining systems in the built environment can be established through a deliberate strategy of collaboration between key players to deploy possible digital tools to adopt regenerative design principles for more efficient, innovative and sustainable structures. This study approaches efficiency and 'good structural form' with a holistic approach defined with following parameters, including the environmental concerns: Architectural Expression, Structural Intent and Construction Awareness.

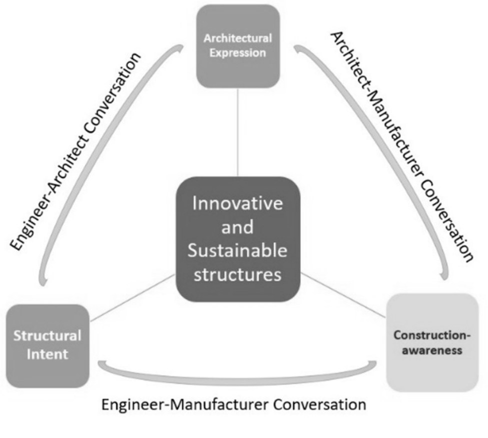


Figure 1. Innovation and Sustainability Matrix

4 RE-EVALUATION FROM PRECEDENT CASES

The redesign exercises conducted in this study highlight the importance of structural understanding and the incorporation of sustainability matrix at the preliminary stages of design through creating a design fiction narrative for using precedent. A number of different projects have been studies this project present a reflection of the design of the Dynamic Earth Building in Edinburgh.

4.1 *Dynamic Earth (Hopkins Architects) and the brick vaults of Eladio Dieste*

Dynamic Earth opened in 1999 in Edinburgh. It is a major visitor attraction intended to provide a better understanding of earth sciences and geology. The site on the edge of Salisbury Crags is particularly significant. 'Dynamic Earth is located on the exact spot where James Hutton, the father of modern geology, lived and worked during the 18th century. Visitors can experience earthquakes, volcanoes and the processes that formed natural settings just like Edinburgh's.' Hopkins Architects website (Figure 2).

Figure 2 Dynamic Earth Building at the foot of Salisbury Crags in Edinburgh

The building is constructed on the footprint of the Abbey Brewery and retains the existing stone wall. In this study focus was placed on the main external roof, a masted tent structure. The overall dimensions are 70 by 35 metres and opens to an external terrace. The roof is a PTFE coated glass fibre membrane, stretched over curved steel trusses and tied down around the perimeter. The trusses are supported by pairs of masts that penetrate the trusses and the roof through a series of glazed panels. The perimeter is enclosed using a free standing self-supporting glazed façade. The project was studied using a variety of means including site visits, digital scanning and available literature. The project seems to follow a sequence of projects using similar tensile systems by the practice: The Schlumberger Research Centre, Cambridge 1984 and the Inland Revenue Building Nottingham, 1994, following the tradition of High Tech.

Figure 3. Julio Herrera y Obes Warehouse, showing use of vault for lighting

The particular form of the Dynamic Earth (DE) is shell-like and could easily be envisaged as concrete shell, internally this could be spatially re-interpreted as a cavern, an obvious geological metaphor. The combination of shell like form and geological metaphor clearly point towards the work of Eladio Dieste, now well known (Pedreschi, 2000 & Anderson, 2004). Dieste worked almost exclusively using brick and sought to 'resist through form', leading to highly efficient doubly curved Gaussian Vaults. The fictional narrative is then to re-envisages the design through the work of Dieste with careful attention to concept, context, performance and construction. The relevant precedents involve three of his projects, Julio Herrera y Obes Warehouse 1979, Montevideo shopping, 1984 both Montevideo and Citrus Caputo Fruit Packing Plant, Porto Alegre, 1972 (Figures 3 and 4).

The Julio Herrera y Obes warehouse is the primary precedent of the study and demonstrates a number of key points.

- It is a has a clear uninterrupted span of 45 metre, significantly greater than DE, with a thickness of only 13cm (Pedreschi and Theodossopoulos, 2007) thus clearly structurally feasible
- It was also constructed on existing walls of an earlier building
- It was low-cost, despite its complex doubly curved surface- the roof comprises a sequence of vaults each made with the same formwork used 14 times.
- The overlapping vaults form glazed openings that provide diffuse light and avoid glare

Reimagining the DE there are potential strengths in this approach:

- Resistance through from, greatly simplified structure, eliminates need for steel masts and curved beams and with completely clear span internally
- There is an established
- Inherently more durable, the Teflon coated membranes have a notional service life of 30 years
- Better quality of light, the glazed roof lights in DE allow direct sunlight and create glare
- In the context of Earth Science and geology the brick is clearly expressive of its geological source.

Figure 4. Citrus Caputo, showing the edge condition and Montevideo Shopping showing the combination on Barrel and Gaussian Vaults

The Citrus Caputo (CC) project adds a particular feature that could be developed. In DE the glazed perimeter wall provides an opening to the outside. In CC this was also necessary along the two sides of the building. The springing of the Gaussian Vaults is connected to continuous inclined edges that collect and transfer the thrusts from the vaults to a series of intermittent buttresses with large opening s in between.

A criticism of DE is the roof design does not actually facilitate a view of Salisbury Crag, the very place that Hutton made his remarkable discoveries. Montevideo Shopping project suggests a way of dealing with this by a hybrid of vaulting systems, incorporating barrels and Gaussian vaults, which together create different opportunities for light and view. The direction of the vaults can be re-oriented with the barrel vault directing towards the view of the Crags.

4.2 *Alternative Design Schemes*

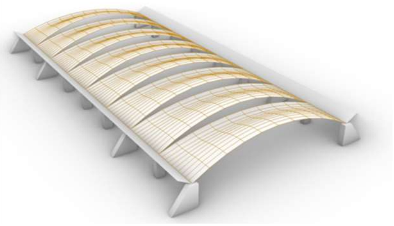
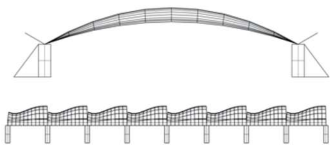
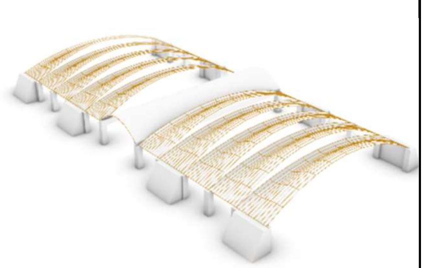
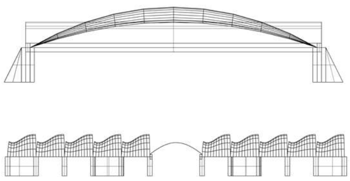
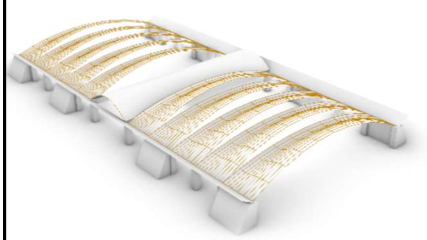
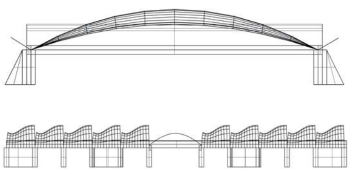
ALTERNATIVE SCHEMES		PRECEDENTS
		Julio Herrera y Obes Warehouse and Citrus Caputo farmers market.
		Julio Herrera y Obes Warehouse and Montevideo Shopping.
		Julio Herrera y Obes Warehouse, Citrus Caputo farmers market and Montevideo Shopping.

Table 1. Alternative Schemes

The first alternative scheme uses the Montevideo Warehouse and CC using similar span to depth ratios and abutment supports. The roof openings let in natural lighting and the sides open up to provide a view of the surroundings as well as a shelter for the glazing. Second design introduces a combination of Gaussian and Barrel Vaults from Montevideo Warehouse and Shopping to accommodate the internal planetarium dome. The Barrel Vaults spans 10m in cross-section and 30 m longitudinally acting as a beam. Gaussian Vaults span the same way as the North Light provides a better lighting condition and reduces glare. The third option is combining the three precedents allowing for maximum visibility, view and shelter. Clearly, the costs and complexity rise with the different vaulting systems, using the computational modelling and analysis tools, it is possible to develop these schemes quickly to identify optimal solutions.

4.3 *Structural Analysis of the Alternative Schemes*

The software used for modeling the precedents and the new schemes is Rhinoceros 3D V6 which is a popular NURBS-based software in architectural design that allows the creation and editing of freeform surfaces (Rogers, 2011). Grasshopper is a plug-in that is the visual programming language embedded in Rhino3D allowing for real-time parametric changes to be implemented through sliders. The parametric values can be modified in various ways including evolutionary solvers like Galapagos built-in the software. Kangaroo is used as a physics solver, designed to simulate the physical interaction by dynamic relaxation (Adriaenssens et al., 2014) allowing to observe deformation through ‘goals’. The FEA analysis is carried out using Karamba3D, another plug-in for Grasshopper allowing for parametric analysis and optimization. It illustrates the structural behavior in response to loading and demonstrates accurate values of deformation where members are likely to fail due to increasing loads.

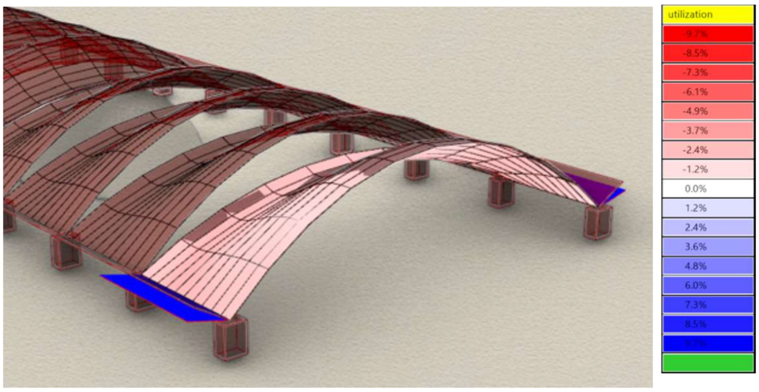


Figure 5. Utilization of Materials in first scheme

Figure 5 shows the utilization values evaluating the areas of tension and compression. As the brick is difficult define in Karamba3D, an arbitrary section of 350mm concrete shell (grade C30/37) is used in this study. As seen on the figure, the utilization is between 1.2% and 3.7% which indicated that the stresses in the vault are between 0.44MPa and 1.37MPa. Previous studies pointed out that the stresses in Julio Herrera y Obes Warehouse are calculated between 1.0 and 1.5 MPa using ABAQUS (Pedreschi, 2006). The results are similar taking the difference in span into consideration, validating the output of the Karamba analysis.

5 CONCLUSION

The Dynamic Earth building is studied as an example showing how to use digital modelling to provide alternative schemes drawing from different precedents. The three precedent studies are combined to present a series of alternative solutions to a landmark building referring back to the sustainability criteria that this study initially outlined. Seeing that Dieste’s projects are noted for their architecture, structural ingenuity and low cost, a series of alternative and more effective schemes have been proposed.

This work is a part of a series of ongoing studies in order to identify the themes and propose a new workflow to the way we design and teach in engineering. Using the computational modelling through parametric design that is conditioned and informed through precedent. The major advantage in using the parametric tools is to be able to quickly generate different forms and options and analyse them for better optimization.

The opportunities in using the precedent are being able to apply the tacit knowledge obtained from deconstructing the successful projects in terms of the sustainability matrix criteria and implement parameters to test the possible range of suitable options. The technical insight gives grounds for the efficient form and design for feasible construction. This new narrative of the workflow and the pedagogy developed allows a different understanding of design cooperation that is absolutely necessary for the most responsive design needed to reduce the impact on the environment.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support and contributions of MEng Structural Engineering with Architecture student, Rahul Prakash.

7 REFERENCES

Adriaenssens, S., Block, P., Veenendaal, D., Williams, C. (2014). *Shell structures for architecture: Form finding and optimization, Shell Structures for Architecture: Form Finding and Optimization.*

Anderson, S. & Dieste, E. (2004) *Eladio Dieste : innovation in structural art / Stanford Anderson, editor.* New York: Princeton Architectural Press.

Block, P et al. (2017). *Beyond Bending: Reimagining Compression Shells*. Edition DETAIL.

Bradshaw, R., Cambell, D., Gargari, M., Mirimiran, A. and Tripeny, P. (2002). *Special Structures: Past, Present and Future*. American Society of Civil Engineers 150th Anniversary Paper. Journal of Structural Engineering June 2002, pp. 691–709.

Bechthold, M. (2011). *Surface Structures : digital design and fabrication*. acadia.

Fu, Feng. (2018). *Design and Analysis of Tall and Complex Structures*. Saint Louis: Elsevier Science & Technology,. Print.

Gerbert, P., Castagnino, S., Rothballer, C. and Renz, A. (2016) 'Shaping the Future of Construction A Breakthrough in Mindset and Technology', *World Economic Forum (WEF),* 1–64

Papanikolaou, D., "Changing Forms, Changing Processes" in *Interdisciplinary Design: New Les sons from Architecture and Engineering*, ed. Hanif Kara et al. (ACTAR Press, 2012), 106-114.

Pedreschi, R. F. (2000) *Eladio Dieste* / Remo Pedreschi. London: Thomas Telford.

Pedreschi, R., Theodossopoulos, D., 2010a. Eladio Dieste; 'Resistance through form', in: *Structures and Architecture - Proceedings of the 1st International Conference on Structures and Architecture*, ICSA 2010.

Pedreschi, R. 'Form, Force and Structure', *AD Architectural Design*, 78.2 (2008), 12–19.

Ramage, M. H., Ochsendorf, J. A. and Rich, P. (2010) 'Sustainable shells: New African vaults built with soil-cement tiles', *Journal of the International Association for Shell and Spatial Structures*, 51(166), pp. 255–261.

Rogers, D. F. (2001) *An Introduction to NURBS With Historical Perspective*. San Francisco, CA: Morgan Kaufmann Publishers

Scheurer, F. (2010) 'Materialising Complexity', *Architectural Design*, 80(4), pp. 86–93

Tang, G. (2015) 'An Overview of Historical and Contemporary Concrete Shells, Their Construction and Factors in Their General Disappearance', *International Journal of Space Structures*, 30(1), pp. 1–12.