1 Synopsis

This paper describes the result of a travel scholarship undertaken in 2013 and generously funded by the Institution of Structural Engineers' Educational Trust Pai Lin Li Travel Award.

The principles of form active design can facilitate architecturally interesting, structurally optimised, materially efficient construction. The paper sets out to illustrate 1) how the concrete construction industry may be positively influenced by recent advances in flexible formwork technology, towards an aim of low carbon construction and 2) how the prestressed brickwork and construction techniques of Eladio Dieste might be utilised to influence the future direction of form active construction across the world. Links between these two objectives are made, before conclusions and ideas for future work are presented. Covering European and South American construction the travel award provided a unique perspective on the political, social, economic and technical demands of sustainable and materially efficient construction.

Relationships between these complex demands will be considered to demonstrate the important role that Structural Engineers can have in facilitating sustainable construction through their choices of form and material.

2 Introduction

Against a backdrop of carbon dioxide emissions reduction targets (Figure 1), recognition of the impact construction has on the environment and an increasing focus on sustainability, design philosophies centred on the need to put structural material only where it is required are increasingly desirable. In order to meet the aims of the Climate Change Act (2008), changes in the way we design and build will be required. In this paper two opportunities to achieve this are discussed.
3 Flexible formwork

Research at the University of Winnipeg (Hashemian, 2012, West, 2003), the University of Edinburgh (Lee, 2010) the University of Bath (Orr et al., 2011) has shown that by replacing conventional rigid concrete formwork systems with lightweight, high strength, low cost, sheets of fabric, significant embodied carbon savings in new concrete structures can be achieved. In addition, the use of a flexible, permeable fabric mould provides durability benefits by allowing air and water to escape during the curing process (Orr et al., 2013). Architecturally, the flexible mould provides opportunities for innovation in form (Figure 2).

Structural engineering research has covered both beams (where material reductions of up to 40% have been achieved when compared to equivalent strength prismatic sections) and shells, where processes for their design and construction have been the focus (Orr et al., 2011). In both, the principle of using a flexible mould to provide a means to create low-material use, efficient structures remains. This new construction process represents a step change in the way that concrete is used as a structural material. Further opportunities for flexible formwork include the use of low-carbon cement replacements, prestress, and non-metallic reinforcement, all of which are the focus of on-going research.

4 The Open City, Chile

Located 30km North of the city of Valparaíso, The Open City is a 300ha area of the Chilean coast dedicated to cultural discovery in America. The City is closely linked with the School of Architecture at the Pontificia Universidad Católica de Valparaíso (PUCV), which was founded in 1952 by a group of architects and poets, including Godofredo Iommi.

In 1970, at a time of social upheaval in Chile which led to an economic depression in 1972 and a military coup in 1973, the founding group at PUCV purchased an area of land to create a place with a particular way to live, work and study. The activity of both PUCV and The Open City continues to be influenced by Iommi’s poem ‘Amereida’ (1967), which discusses the origin and destiny of being an American, and acts of poetry continue to form a strong part
of the teaching ethos at PUCV. Today the Open City today is home to around 30 people, living and working together towards a common goal of cultural discovery.

4.1 Travesía

As part of their teaching, an annual ‘travesía’ (a voyage, literally crossing) is undertaken with students at the PUCV. Each of these travelling projects has the simple aim to provide a gift to a place in America. The travesía use poetic ‘acts’ to form the architecture they create; in this way the poets of the Open City take an integral part in teaching. A focus is placed on detail, or creating “the smallest space you can inhabit with your mind” (D Jolly, pers com. 16/01/13).

4.2 Flexible formwork

Professor Mark West (University of Manitoba) introduced flexible formwork to the Open City in 2002. Since then, it has formed a continual part of their travesía, teaching, and professional practice.

The first teaching experience with flexible formwork at the Open City was in 2003, on a travesía to Garupa, Argentina (Figure 3). Here, flexibly formed concrete elements were used to provide an area of play, calm, and shelter at a refuge for children. Working in Chile the students first formed their concepts in scaled-down plaster models. Once the design process was complete, these were translated into full-scale fabric moulds (using a locally sourced geotextile) that were proofed in Chile using sand. With the geometry confirmed, the formwork sent to the site in Argentina. The transportation of a fabric mould is simple - it can be rolled up and put in a box – a contrast to the bulk and weight of conventional concrete formwork systems. This ability to fabricate the formwork and then post it anywhere in the world offers a significant opportunity for introducing low carbon construction in both developed and developing countries.

Since 2003, flexible formwork has been utilised in multiple travesías. In 2006, to Sao Miguel des Misors, Brazil, in 2009 to Pan de Azucar, Chile, and in 2010 to Valle de Elqui, Chile (Figure 4). In each case the ability of the formwork to be designed, modelled, and tested in
Chile before being transported and cast in concrete at the chosen location was a key advantage.

4.3 Works

In addition to the travesía, flexible formwork is also used in the teaching of concrete technology and casting techniques. Across the Open City are examples of works in flexible formwork undertaken by teachers and visiting academics (Figure 5).

Flexible formwork has also been used to create structural elements. A concept for a new workshop space, designed in collaboration with engineers at PUCV, is shown in Figure 6. The proposed workshop will be supported on pairs of optimised flexibly formed beams hung from four-leaf columns. To date, only a test element has been created, as is shown in Figure 6, where the unique form and optimised beam shape is seen. The columns are created from four identical pieces cast in a flexible mould that are subsequently tied together with in-situ concrete.

The structural design of this beam and column system is unusual. Chile is a highly seismically active area, and the principle behind the hanging beam system design is similar to Bogue Babicki’s ‘hung buildings’, in which a single central core is compressed by the weight of the floors above. A similar hanging structural frame has already been used at the Open City. In the 2010 Chile Earthquake (magnitude 8.8, the sixth largest ever recorded globally), no structural or internal damage was recorded in this particular house, while in other residences internal effects such as overturned furniture were seen (D Jolly, pers com. 17/01/13).

Flexible formwork has also been used in works outside of the Open City. Victoria Jolly’s public seating in the nearby town of Loncura (Figure 7) was entirely cast using flexible formwork, one of few such projects that currently exist.
4.4 Conclusions

Working at the Open City has shown that flexible formwork has a huge potential for application to the construction industry. The simplicity of the formwork making, as has also been seen in research at the University of Bath, offers real benefits for construction. The ability of the formwork to be transported anywhere in the world (after fabrication at a central location) is another advantage.

At present the use of flexible formwork in ‘real’ projects is limited. However, industrial engagement is high, and new research in this field is providing an ever-growing body of knowledge. This research momentum is demonstrated by the wide-ranging and innovative work that was recently presented at the Second International Conference on Flexible Formwork (Orr et al., 2012).

The differing economic, demographic and social perspectives of America and Europe do not detract from the strong global need to balance new construction with environmental impact. It is clear that many of the perceived hurdles to adoption of flexible formwork that exist in the UK also exist in Chile. These hurdles, which include the simple fact that it is an unconventional and relatively untested construction technique, will require some forward thinking contractors and engineers to overcome. In the Open City, flexible formwork has been used with success to create beams, columns and sculptural elements. Its use as a tool for teaching is also important, as future innovations will be fostered by educating the next generation of architects in the advantages of moving away from rigid formwork systems.

Flexible formwork has at its heart the concept that by following the loads applied to a structure an optimised form can be generated. This optimal form is often non-prismatic and is therefore ideally suited to casting in a flexible mould. This approach combines the efficient use of materials with a simple and potentially cost effective construction method.
5 Brick shells

Eladio Dieste was born in 1917 in Artigas, Uruguay. At the age of 26 he graduated in Engineering from the University of the Republic in Montevideo and in 1946 he worked with architect Antoní Bonet to design the roof for the Berlingieri house in Maldonado, Uruguay, which became his first work in reinforced brick. Dieste went on to spend his career pushing the boundaries of design with his structures in reinforced and prestressed brickwork. In this section a small part of Dieste’s work is explored before links with flexible formwork and applications of Dieste’s designs in modern construction are considered.

5.1 Form

In the same way that flexibly formed elements are designed for structural efficiency by utilising the flexible mould to create an optimised shape, shells gain strength through the form that they take. Defining this form is crucial. A thin, flat plate without curvature must carry load through bending and shear stresses; the addition of curvature to the plate allows it to act as a membrane, carrying in-plane forces and providing greater load capacity. This requirement for form is wonderfully summarised by Dieste (cited by Pedreschi (2000)):

“The resistant virtues of the structure that we make depend on their form; it is through their form that they are stable and not because of an awkward accumulation of materials. There is nothing more noble and elegant from an intellectual viewpoint than this; resistance through form”

Early adopters of reinforced brick include Marc Isambard Brunel (Peters, 1996) and de Baudot (Frampton, 1995). At the Berlingieri house, Dieste’s own introduction to brick vaulting came by chance. His use of a catenary form for the roof demonstrates his approach of thinking first of structural, rather than purely architectural, forms. After this, his work in brick moved beyond the traditional timbrel vault (a precursor to thin reinforced concrete shells) to include both reinforcement and prestress. This allowed Dieste to greatly extend the architectural and structural possibilities of the brick vault.
Dieste’s use of brickwork, rather than the more fashionable concrete being used in Europe at the same time, is itself interesting. Brick offered Dieste many advantages, including:

1. A lower self weight of brick compared to concrete (resulting in lower stresses in the vaults) (Anderson, 2004);
2. Unitised brick construction using less cement than a concrete solution (Pedreschi and Theodossopoulos, 2007);
3. Control of the internal conditions beneath the shell by utilising the hygroscopic properties of bricks (Anderson, 2004).

5.2 Construction economy

Dieste’s shells were constructed not because clients were looking for a particular form, or because they wanted iconic projects and were willing to incur greater costs, but because Dieste (through his company, Dieste y Montañez) bid against more traditional construction methods, and won.

Dieste achieved economy through repetition, allowing his formwork to be reused throughout his projects. The majority of the building components used by Dieste were widely available - brick, steel reinforcement and cables for prestressing - and his systems for construction were made as simple as possible.

In contrast to the high cost of formwork for brick shells, flexible formwork for concrete has a relatively low cost. Flexible formwork therefore offers the intriguing potential for economy in construction, without requiring repetition of form. By optimising each unique flexibly cast element, the overall embodied carbon of a structure could potentially be reduced while retaining architectural interest and complex geometries. The economics of Dieste’s shells are also related by Anderson (2004) to the craftsmen working for Dieste y Montañez, as many of the masons who built Dieste’s shells worked with him for over thirty years. This long lasting relationship meant that the company could continually learn and innovate.
5.3 Works

Discovering the works of Eladio Dieste required considerable travel across Uruguay. A total of 29 locations in Uruguay were visited in the writing of this paper, each of which is documented online (http://goo.gl/maps/JBz6e). Allen (in Anderson (2004)) describes four general categories into which Dieste's work can be divided, and these typologies have been adopted for the following sections.

5.3.1 Self Supporting Shells

Dieste's 'self supporting shells' are intriguing, and often appear to be almost impossible, acting as both thin shells and cantilever beams.

This is elegantly expressed in the Hydro Agri SA warehouse, Figure 8. Here, a folded edge beam supported on a diagonally braced reinforced concrete column takes thrust from the brick vaults. The main building consists of five vaults, each 114.9m long and 12.8m wide (Anderson, 2004). In the longitudinal direction the vaults span 35m between columns, with a 16.5m cantilever at one end (Figure 8). The cantilevered section overlaps another shell; this one being balanced on just one set of columns and cantilevering from this central column in both directions by 13m. The long spans reduced the cost of construction by minimising piling requirements in difficult local ground conditions.

In order to span such distances with thin shells, prestress is used to place the entire section in compression, with tension due to bending from imposed loading relieving this compression. By careful control, very efficient forms can be achieved. To retain construction economy a method of prestressing was required that did not add considerable expense and maintained the desired thin structural form.

In the self-carrying vaults, prestress is applied to the brickwork during construction primarily through simple loops of steel cable. For the cantilevering vaults, running track shaped loops of steelwork are placed and clamped to the shell using steelwork embedded in the brick. By pulling the wires together in the middle to create a figure of eight, prestress is applied to the
surface. This pulling of the cables was achieved with a simple hand operated jack, also designed by Dieste. Multiple loops are laid in each shell, with progressively less prestress applied as the calculated bending stresses reduce.

Where tension is felt in the valley of the vaults Dieste used a similar method to prestress the shell. A loop of cable is placed along the length of the vault, its ends overlapping in the middle. The cable is tensioned by pulling the ends of the cable loop against each other until the required extension is reached, with the cables then locked together with a steel piece of a predetermined size. In this way Dieste was able to effectively prestress his entire brick vaults without complex end anchorage and prestressing equipment.

5.3.1.1 Turlit Bus Station

On a small site in the centre of the city of Salto the Turlit Bus Station (completed 1980, and now operated by Agencia Central) is Dieste’s second bus station in the town, completed six years after the Municipal Bus Station.

The Agencia Central station develops the theme of the Municipal Bus Station. The vaults, which project 13.7m to the rear and 14.3m to the front, span 5.8m laterally. Dieste uses an elegantly optimised folded surface at the edge of his vaults to carry horizontal thrust to concrete piers (Figure 9). Thrust from the vault is resolved one story below in the tie beams between columns (with the end column also being shaped to follow its bending moment diagram). Since the vault cantilevers are not balanced, a steel tie to ground level was added at the back of the shell.

5.3.2 Gaussian Shells

Barrel vaults tend to have low span:rise ratios, ensuring stresses in the bricks are low. Reducing the arch rise while retaining a thin shell increases compressive stresses in the brick, and introduces buckling as an increasingly likely failure mode (Pedreschi and Theodossopoulos, 2007). In the Gaussian Shell, Dieste resists buckling by taking a new form to the shell beyond that seen in his self-carrying vaults. From a horizontal junction with each
support, the Gaussian Shell rises to form an ‘S’ shape at the apex. This form provides buckling resistance as each point is now stiffened by two curvatures. The form also provides an easy connection to the surrounding walls and also allows for the addition of roof glazing.

Axial compression along the shell varies depending on the cross section, and the shear stresses resulting from these variations are carried by steel reinforcement laid in the brickwork. The repetitious nature of the Gaussian shell design allows for great economy in construction, with the formwork for one project reused on another. Many of Dieste’s Gaussian shell structures were built as storage sheds or warehouses - where construction economy is a key requirement. The largest of Dieste’s Gaussian Shells is found at Montevideo Port, with a span of 50m and a maximum rise of 6.4m.

Dieste’s structure for Álvaro Palenga SA, Montevideo, is possibly unique as it remains unenclosed (it is currently used to store machinery). The form of the structure and its estimated dimensions are shown in Figure 10. The structure is in an adequate condition, although the first steel tie at its South end is sagging considerably, and clearly does not provide restraint to the final shell.

5.3.3 Folded Structures

Hidden behind the surviving facade and outer wall of the original Church of St. Peter in Durazno is a wonder in folded brick plates. Here, Dieste has used three plates to enclose the church space. Two ‘Z’ shaped walls spanning 30.5m and a pitched folded plate roof above are all formed in brick tiles. The large wall span facilitates a column free interior between the nave and side aisles (Figure 11, Figure 12). A narrow gap between walls and roof lets in light, although short steel posts do connect the two. At the sanctuary, high walls lead to a clerestory window. Above the main entrance, Dieste’s brick rose window adds further delight.

The folded plate is particularly unusual as a form for brickwork. Here, stiffness is gained from the folds in the surfaces and the structure therefore works in bending both locally and globally, meaning that it is not just carrying membrane forces.
5.3.4 Ruled surfaces

The Church of Christ the Worker, Atlantida, is one of Dieste’s earliest works – and also one of his most impressive. The church is shown in plan and elevation in Figure 13. The walls of the Church begin at ground level as parallel lines, moving upwards (constructed without formwork) as ruled surfaces to become a series of parabolas at the top of the wall. This parabola then meets the continuous double curvature vault of the roof (constructed with formwork). In the valley of each vault, cables run transversely to tie the walls together.

In transverse section the geometry follows the bending moment diagram of the portal frame under self-weight, creating a materially efficient overall geometry by converting bending into axial forces in the wall. The junction between the complex geometry of the wall and the roof, both doubly curved surfaces, is described by Pedreschi and Larrambebere (2004) as the ‘most lucid expression of Dieste’s desire “to resist through form”’.

In addition to the Church building itself, which has recently been restored, the site at Atlantida also includes one of Dieste’s towers (Figure 14). Dieste’s towers show extraordinary efficiency, not just in material use but also in construction. By using perforations, each tower becomes a series of vertical brick piers interlinked by horizontal reinforced brick ribs, thereby reducing the number of brick cuts to be made. The perforations not only reduce wind load, but also provide a means to support work platforms for the masons. By tapering the perforations rather than the brick piers, construction is simplified and the tower’s verticality is emphasised (Figure 15).

6 Future developments

Hanging models, which define a form in tension, can be turned over to provide a form carrying only compression. Work at the University of Manitoba (West and Prakash, 2005) has taken inspiration from Dieste’s shells to use flexible formwork in the creation of brick shells (Figure 16).
Bricks are laid onto the hanging fabric formwork, with the joints between them then mortared in-situ. Once set, the entire construction is turned over to create an efficient, compression only, shell. The act of turning the shell over clearly introduces new difficulties, overcome by West and Prakash (2005) by post-tensioning the shell laterally with threaded rods and adding rotation points along the centre of gravity of the shell. This approach suggests new possibilities for larger scale construction, and the hanging fabric could also include a light steel or FRP mesh for reinforcement, providing a participating formwork system. Once in place, a thin topping might be used to seal the structure and provide additional deadweight.

As compressive stresses in even the longest span shells can be very low (Nervi, 1956; Chilton, 2000), alternative materials may be more appropriate, resisting buckling through an appropriate form. In complex designs such as those presented by Dieste, this might be combined with reinforcement or prestress to carry bending. Such an approach would therefore be considering both optimisation of form and optimisation of materials - putting the appropriate material in the right place.

In addition to possibilities of shells formed in flexible formwork, research at the University of Bath is also considering optimisation of prestressed fabric cast structures, the use of ultra-high performance concrete to achieve very slender structures, the use of permanent participating fabric formwork systems, and non-metallic reinforcement as further opportunities for achieving low carbon concrete construction.

7 Discussion

The Pai Lin Li Travel award provided the author with an opportunity to visit and investigate two innovative forms of construction, both of which facilitate form-active design and offer the potential for sustainable construction in both brick and concrete.

In Chile, the use of flexible formwork at the Open City was a great inspiration. The School’s pedagogy, with poetic acts and travesías, is unique and intriguing. In Uruguay, the work of Eladio Dieste illustrates how sustainable design should relate structural mechanics to
climate, local workers, and material availability. Sustainable construction should consider what is appropriate to every project and location, and this includes the use of local resources (people, materials, and technology). The introduction of new technologies (such as flexible moulds) will require clients and contractors who are willing to rethink approaches to construction. This will be made possible if research can show that flexible formwork is an economically advantageous alternative to conventional construction processes.

It is notable that Dieste and Nervi, along with John Roebling, Gustave Eiffel, and Robert Maillart, all created innovative structures through their own construction companies. This deep involvement and understanding of the construction process may be missing in linear design processes where information simply feeds from Architect to Engineer to Contractor, and such a linear approach is unlikely to achieve the best solution to a design problem. Nervi (1956) suggests that the presence of separate Schools of Architecture and Engineering simply serves to create divisions between the two professions, and that engineering and architecture should be taught as one, removing the barriers between the two types of designer who rely so much on one another. Nervi also expressed a desire for students who have an intuition of structural behaviour, separate from “abstract and impersonal mathematical formulas” (Nervi, 1956).

Just as the engineer should know the difference between mathematics and engineering, so the architectural student should be taught not to mistake drawing for architecture (Nervi, 1956).

8 Conclusion

This paper has shown how the principles of form active design can facilitate architecturally interesting, structurally optimised, materially efficient construction. Advances in flexible formwork technology have the potential to positively influence concrete construction. Work presented by Orr et al. (2012) illustrates considerable on-going research in this field that has potential applications for a wide range of construction processes.
The prestressed brickwork and timbrel vaulting techniques of Eladio Dieste demonstrate how resistance through form can be not only structurally, but also architecturally, inspiring. It is the collaborative nature of the relationship between architect, engineer, and contractor (as exemplified by Dieste) that is arguably the key to sustainable design. Achieving all of this while meeting each project’s economic conditions means that structural engineers must take a more significant role in facilitating globally sustainable construction through their influence on the choice of form and material.

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10 References


Figure 1: Emissions reductions targets to 2050
Figure 2: Flexibly formed beams.
Figure 3: The results of a *travesía* using flexible formwork in 2003. All photos courtesy D Jolly, PUCV.
Figure 4: Top: ‘T’ beams as outdoor tables in Sao Miguel das Missoes; Middle: Sculptural installations in flexibly formed concrete, placed in the Atacama desert near Pan de Azucar; Bottom: Seats in the desert, near an artificial lake in Valle de Elqui, Chile. Photos courtesy of D Jolly, PUCV.
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Figure 15: 1) TV Tower, Maldonado; 2) Water tower, Salto; 3) Church of Christ the Worker, Atlantida; 4) Refrescos del Norte, Salto; 5) Internal to (3); and 6) Internal to (2).
Figure 16: Fabric formed brick shell. Hung in the fabric mould and awaiting mortaring (left); Complete, turned over shell (right) (West and Prakash, 2005).