The Structural Behaviour and Design of Free-Standing Barrel Vaults of Eladio Dieste

Remo Pedreschi

INTRODUCTION

The period from the late nineteenth through to the twentieth century was a time of great innovation and experimentation in structural form and the expression of structural form in architecture. Engineers such as Gustav Eiffel (1832 – 1923), Eugene Freyssinet (1879 – 1962) and Robert Maillart (1872-1940) worked with new materials and techniques to produce structures and buildings that were elegant, economic and structurally efficient. More than this they showed a great care for the expressive qualities of structures. David Billington describes this combination of structural efficiency and expression as “structural art” (Billington 1985). Later on in the twentieth century the work of engineers and architects such as Nervi, Torroja and Candela became rightly recognised for their “structural art”. Common to most is the strong relationship that they had with the process of construction, learning and developing technique with successive projects. Many of them concentrated on one material. The engineer Eladio Dieste (1917-2000) without doubt deserves to be part of this company. Throughout a long career Dieste developed many new techniques and forms, almost entirely in brick that are only now becoming recognised as masterpieces of structure and architecture. His company Dieste y Montañez constructed over 1.5 million square metres of building in South America, The bulk of these were thin brick vaults in either single or double curvature used in buildings such as warehouses, factories, gymnasia and workshops. The paper considers in particular one form of vault, developed by Dieste, the Free-standing Barrel Vault.

These highly expressive vaults were developed as economic solutions for the construction of industrial buildings. The evolution and design of the vaults is explained including the innovative construction techniques, such as looped pre-stressing that Dieste developed to optimise both the expressive qualities and efficiency of the vaults. Examples are presented and finite element techniques are used to gain further insight into the behaviour of the vaults.

Background to the life and career of Eladio Dieste

Dieste was born in Artigas, a small town in the northern part of Uruguay. He studied engineering at the University of the Republic in the capital city, Montevideo, graduating in 1943. Montevideo at this time was growing culturally and economically. It was a period of great optimism. According to Lucio Cáceres a former student of Dieste and Minister of Public Works and Construction for Uruguay “He (Dieste) played an active role in a generation that exalted duty towards oneself and toward’s ones fellow man as a way to elevate the soul and to promote private and public virtues”

(Cáceres 2003). An aspect of this sense of duty is apparent in his attitude towards the use of technology. In an essay entitled "The Inevitable Invention" Dieste argued that the developing countries of South America should seek their own indigenous technology.

> An uncertainty that always arises when we talk about technology is the attempt to decide if our approach should be focussed on assimilating technology of the industrialised countries our if we should develop our own technology.
>
> (Dieste 1996(a))

Figure 1. Free –standing barrel vault Bus Station Salto, Uruguay (V. del Amo)

In the early part of his career Dieste worked for the Ministry of Public Works and various other firms. In 1955 the construction company Dieste Y Montañez S.A. was established in partnership with Eugenio Montañez, a friend from his student days. The activity of the company could be reasonably described as "design and build", undertaking complete projects from concept through to handover. In contemporary architectural circles " design and build" is often regarded somewhat pejoratively, implying a reduction of design or architectural quality in favour cost and construction time. The combination of Dieste's inventive and visionary genius and the management skills of Montañez, created an organisation noted for its project performance and the stunning architecture. It is interesting to note that the company was promoting the use of innovative brick structures against the prevailing trend of the period to use concrete in large span industrial or commercial projects. The scale of some of the projects is worth noting for example the CEASA Produce Market, Porto Alegre in Brazil over 53 thousand square metres of vaulted space and the Rio Metro Workshops, Rio de Janeiro over 52 thousand square metres. The success of the company in these highly competitive projects would not have been possible without strict control over cost and time. Dieste has also created individual works that are now considered as architectural masterpieces, most notably The churches of Jesus Christ the Worker, Atlantida (1960) and St Peter, Durazno (1971). Although both churches used innovative reinforced and pre-stressed brickwork techniques they are entirely different in character, see (Pedreschi 2000 and Anderson 2003). The former consists of undulating surfaces for both walls and roofs and the latter a series of pre-tensioned folded plates brick plates for both wall and roof. What is typical of both is Dieste's use of light to create almost mystical and spiritual spaces. Towards the end of his career Dieste worked in Europe in a series of projects around the city of Alcalá. The techniques that he had developed to suit the needs of South America were employed effectively in Europe (Pedreschi 2000).

DEVELOPMENT OF FREE-STANDING VAULTS

Dieste's first involvement with thin masonry vaults started with a project for the Berlinghieri House in Punta Ballena with the Spanish architect Antonio Bonet. The original proposal for a series of reinforced concrete shells roofs was superceded by brick vaults or perhaps more appropriately described as reinforced brick shells. Thus Dieste started a lifelong interest in the potential for contemporary brick structures. There is a Spanish tradition of thin masonry structures, the Catalan vault introduced to the United States in the mid nineteenth century by Rafael Guastavino (Collins, 1968). Essentially the technique involves the creation the thin vaulted structures without formwork by bonding thin clay tiles using rapid setting plasters. Guastvino used the method of graphic statics (Allen, 2003) to determine the correct funicular geometry and consequently was able to build large span thin vaults very efficiently and thus transformed a traditional vernacular technique into one that was used in many monumental building of the time. Dieste's use of the vault is quite different. He sought contemporary methods that were more effective than similar concrete structures and that were clearly the antithesis of the traditional heavy, grounded vaults. He discovered a language of lightness, separation of the vault from its supporting walls and buttresses, see for example **(fig.2)**

Figure 2. Double cantilever free-standing vault, Refresco del Norte, Uruguay (V del Amo)

Use of brick

Dieste used brick almost exclusively as the primary structural material for his projects. Bricks are indigenous and readily available in Uruguay, bricks also had advantages over concrete.

- Lighter hence less reinforcement and formwork structures
- In a vault 80-90 % of the material is already hardened and the hygroscopic nature of the brick draws water from the mortar causing the vault to stiffen rapidly and hence the formwork can be stripped earlier than comparably concrete structures
- Brickwork uses less cement than concrete
- Brickwork ages well

Dieste used a variety of different types of brick, from solid handmade to hollow clay pots, depending on the requirement of the structure.

Surface structures

Dieste had a strong sense of what structure should be.

> The resistant virtues of structures 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.
>
> (Dieste 1996b).

The use of the surface form can be seen throughout Dieste's work, either as undulating doubly curved walls or vaults or as folded curved and folded plate structures. He consciously avoided discontinuity. Dieste developed two forms of vaulted construction to take advantage of surface form, the Free-standing Vault and the Gaussian vault. In both systems the directrix is defined by the geometry of the catenary. The forces due to self weight are axial and the thickness of the vault is kept to a minimum, only one brick thick plus a thin layer of sand–cement topping. The Guassian vault uses a double curvature to stiffen the cross-section against buckling and tends to be used for long spans between the springing points of the directrix, up to 50 metres. Typical span to rise ratios of 8 to 10. For more information see Pedreschi 2000 or Anderson 2003.

The free-standing barrel is used in shorter transverse spans between the springings up to 10-12 metres with span to rise ratios no greater than 4, therefore deeper than the Guassian vault. The greater depth of the vault and the shorter spans greatly reduces the stresses in the brickwork due to self-weight and therefore the risk of buckling is not significant and the vault adopts a simple curvature between springs.

The depth of the cross section is utilised to create a self-supporting barrel vault capable of spanning long distances between supports. Dieste, counter to perceived thinking avoids the use of tympanums at the end of the vault, often considered necessary to provide restraint to the vault. Tie rods between the ends of the vault are omitted, the thrusts from the arching action of the vault taken by folded horizontal edge beams which transfer horizontal forces to buttressed columns. A typical example is illustrated in **(fig.3).** Indeed he makes a play of deliberately separating the vault from enclosing walls giving emphasis to the lightness and separation of the roof as it appears to float above and over the vertical structure. The depth of the vault provides the opportunity to create long spans up to 35 metres between vertical support and cantilevers of up to 15 metres. In some cases the vaults are used simple as canopies with no vertical enclosure and sit rather precariously as double cantilevers on a single row of columns, **(figs 1 and 2).**

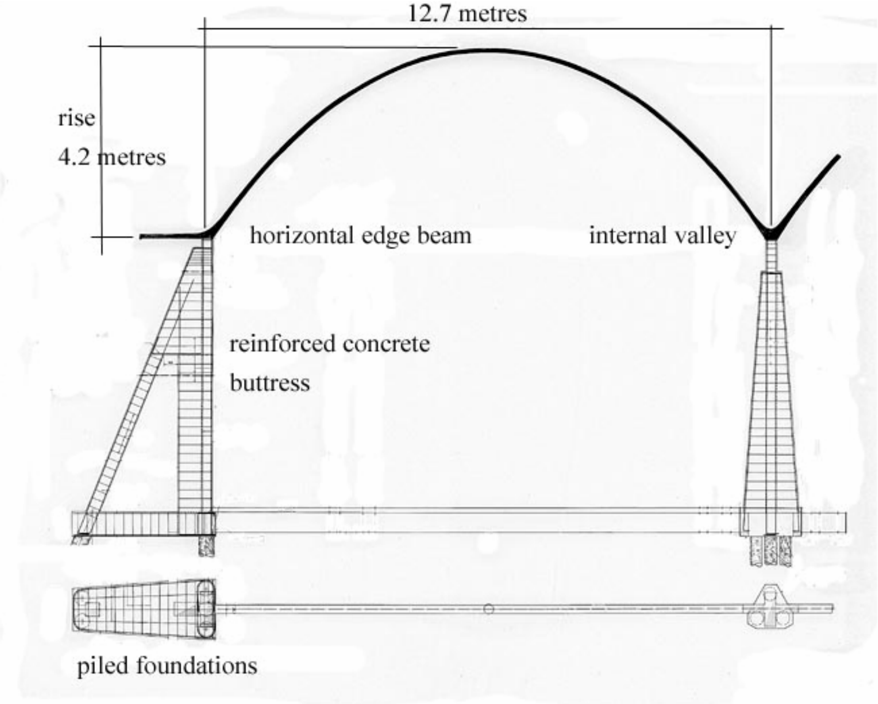
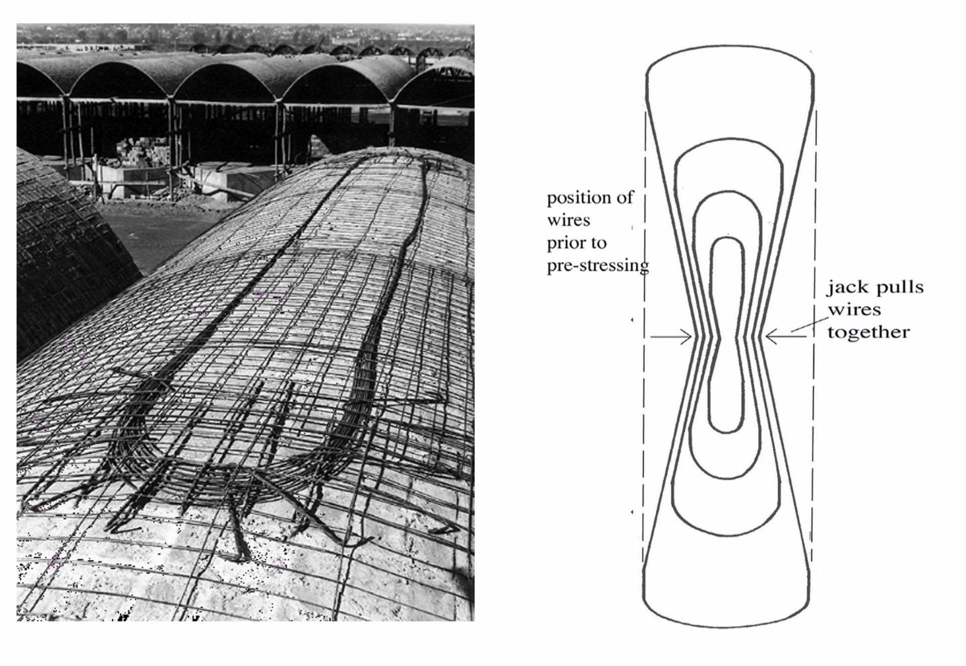


Figure 3. Part section through free-standing vault Agro-industry Massaro Uruguay, (Dieste archive)

Innovative construction techniques

The large spans of the vaults were achieved by the development of a number of innovative techniques for pre-stressing to resist the tensile stresses created by bending. In a double cantilever vault the primary bending action is a hogging moment over the central columns **(fig.4)**.

The vault is pre-stressed along the crown. Dieste developed a method of pre-stressing using welded loops of steel. These are placed on the crown of the vault and anchored using steel reinforcement bonded into the vault at each end of the vault.



Prior to stressing

After pre-stressing

Figure 4. Looped pre-stressing steel (Dieste Archive)

Between these ends the loops are free to move. Pre-stress in produced by pinching the wires together at the mid point of the loops and stretching them into a figure of eight. The tension in the wires pre-compresses the vault. The length of the loops and the distance between the long sides determine the level of pre-stress. Once the wires achieve the required extension they are held in position by metal clamps. The wires are then covered by a thin concrete screed. This very simple technique had a number of useful benefits:

- The prestress force is distributed over a large area at the anchorage avoiding high local stresses
- The prestress is held within the thickness of the topping of the vault
- The pre-stress is applied using a very simple jack, without hydraulics, which can tension a number of wires simultaneously

Dieste designed a simple screw jack used to pull the wires together, (**fig. 5).**

In vaults spanning between supports the tension occurs in the bottom. Pre-stress was applied either at the junction of the edge beam and the vault or in the valley between vaults. Clearly the same pre-stressing system used in the crown is not appropriate. A separate system was used. Over lapping loops of pre-stressing steel with their ends anchored firmly into the vaults were used. Again a specially developed jack was used. This was inserted into the overlap between the loops. The action of the jack pushed the two ends of the loops apart, stretching the steel. Once the required extension had been reached a steel block, pre-determined to maintain the distance between the loops, was inserted, this locking the pre-stress force.

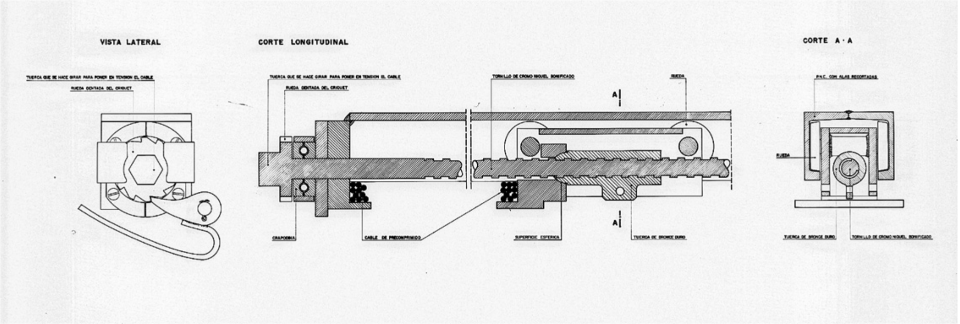


Figure 5. Pre-stressing jack designed by Eladio Dieste (Dieste Archive)

The jack was adapted from a truck jack. These pre-stressing techniques were very simple but effective systems developed to suit the available technology and the particular requirements of the vaults. In later projects more conventional pre-stressing methods using proprietary hydraulic pre-stressing jacks were used. Presumably, as they allowed more accurate and direct measurement of the pre-stress forces. It is worth noting that throughout the twentieth century there was an active research community interested in reinforced and pre-stressed masonry, much of the research was focussed on substituting brickwork for concrete rather than, as Dieste did, develop new and more appropriate uses for brickwork. For further discussion see Pedreschi and Sinha 2003.

Construction Sequence

The vaults are constructed on moveable formwork. The need for economic formwork dictate that the vaults are constructed in sections with the formwork moving along the axis of the vault. During the construction it is very important to ensure the structural behaviour of the vault is clearly understood at all stages. Pre-stress forces can only be applied once the vault is complete. The sequence starts with the construction of the supporting concrete columns. Projecting reinforcement is used to attach the vault to the column. The first segment of the formwork comprising the vault and edge beam is positioned. The bricks are laid in stack bonded manner joints typically 20 millimetres wide. Longitudinal and transverse reinforcement 5-6 millimetres in diameter is placed in the joints. The joints are then filled using a 1:2.5 cement /sand mix. A coarse sand rather than a finer bricklaying sand is used to give greater strength. The bricks absorb moisture from the mortar and its starts to stiffen almost immediately. The formwork is usually struck the following day depending on the weather conditions. The edge beam is propped both vertically and horizontally.

As the formwork is stripped the self-weight of the vault is transferred to the props by the action of the catenary arch. The formwork is then moved to the next section. Usually the formwork sits on steel rails and is raised and lowered on mechanically driven jacks. Great care is taken in aligning the formwork to the previous section of the vault to facilitate continuity of the reinforcement and the visual integrity of the soffit of the vault, usually left as exposed brickwork. The sequence continues until the vault is completed. The complete vault remains propped vertically along the valleys between vaults and vertically and horizontally along the edge beams. The pre-stressing steel is attached and the vault is pre-stresses. The vault is completed with a topping usually 30-40 millimetres of sand-cement incorporating a fine steel mesh.

STRUCTURAL BEHAVIOUR OF VAULTS

The thinness of the vaults, the long cantilever spans and the use of brick together create a series of significant structural challenges. The geometric proportions such as the transverse span to rise ratio in relation to the cantilever and the use of the stiffened edge are clearly important. The use of the catenary geometry in the cross section results in low axial compressive stress. For a span to rise ratio of 4 the maximum axial compressive stress is approximately 0.3 MPa. This increases quite rapidly as the span to rise ratio increases. Dieste tends to limit the transverse span to rise ratio to maximum of 4 for the free standing vaults. For greater transverse span to rise ratios he uses the double curved Guassian vault (Pedreschi 2000). A parametric study using finite element techniques was undertaken to examine the influence of the transverse span to rise ratio, the width of the edge beam and the use of pre-stressing on the behaviour of the vaults. To provide a perspective on this analysis it is useful first to consider a typical application in more detail.

The Free-Standing Vaults for Fagar Cola

The bottling plant for Fagar Cola (1992) was constructed in two phases, each one consisted of a pair of vaults over five spans. The building is illustrated below, **(fig. 6)**

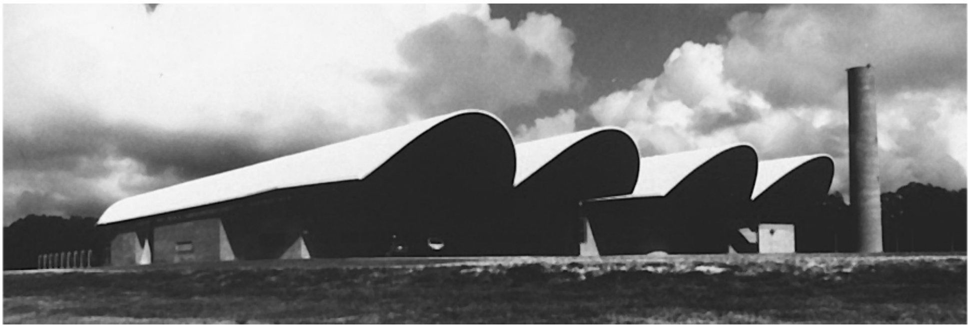


Figure 6. Fagar Cola, Colonia, Uruguay, (Dieste Archive)

The longest internal span is over 24 metres. The vault cantilevers over 12 metres at each end. The transverse span between springing points is 12.65 metres and the rise of the vault is 4.175 metres giving a span to rise ratio of 3. The vault is pre-stressed over the crown at the cantilever and 1st interior span with a pre-stress force of 840 kN and in the valley and edge with a pre-stress force of 480 kN. The general thickness of the vault is 100 millimetres comprising a rectangular extruded hollow clay unit 70 mm and a 30 millimetre sand-cement topping. The maximum width of the edge beam is two metres. Typical of many of Dieste's buildings there is a clear visual separation of the roof from the walls. The roof is supported on a series of concrete columns independent of the enclosing walls. The space between the underside of the walls and roof is enclosed using glazing, particularly noticeable at the gable to clearly show that the walls offer no support to the roof. The plan for the building is show below, **(fig.7)**.

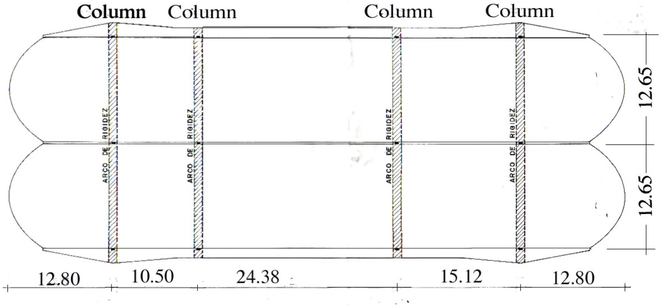


Figure 7. Plan of Fagar Cola, Colonia, Uruguay (Dieste Archive)

Parametric study of the vaults

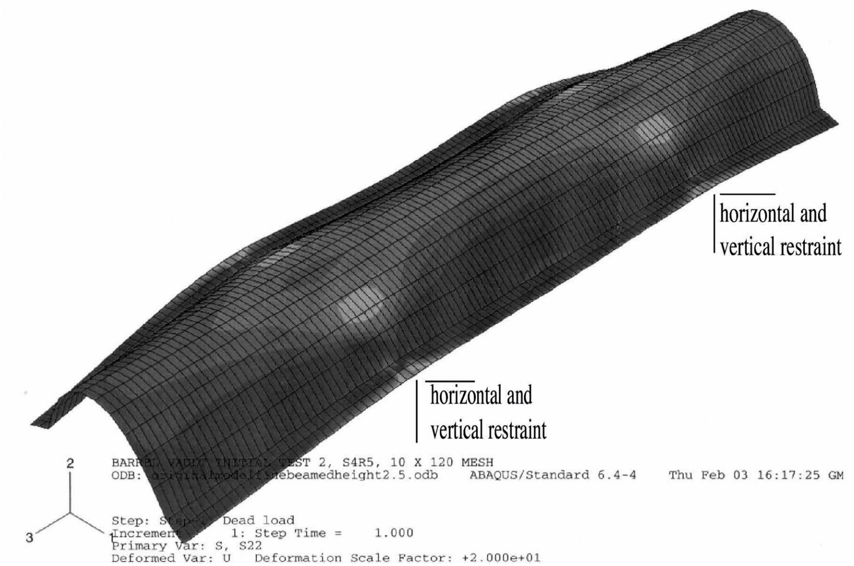
The vaults were modelled using a finite element suite Abaqus. The parameters are loosely based on the building for Fagar Cola but simplified for ease of interpretation. Earlier studies had indicated that a 4 node doubly curved shell element was most appropriate. The vaults were modelled using a 10 by 120 node mesh The elastic modulus of the brickwork was taken as 7000MPa, the value used by Dieste and the density of brick work was taken as 20kN/m3. The thickness of the vault was 130 millimetres. It is not possible within this paper to present the full results of the study but some key findings are presented.

A typical output from the analysis is presented in (**fig.8)**. The model used consisted of a single vault with equal cantilevers at each end. The model was restrained in both the horizontal and vertical positions where the vault would normally sit on columns. Pre-stress forces were not applied. The vault deforms downwards and inwards illustrating the dominance of beam action rather than arching.

Influence of span to rise ratio

The influence of span to rise ratio on deformation of the vaults was considered. The model consisted of a vault with a central span of 20 metres and two cantilever spans of 12.5 metres each. The transverse span is 10 metres and the span to rise ratio varied from 1.85 to 6.0.

The influence of span to rise ratio on the vertical displacement of the crown and at the end of the cantilever, is illustrated in **(fig.9),** positive displacement indicates upwards displacement.



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BARRELLED VAULT INITIAL TEST 2, S4R5, 10 X 120 MESH
ODB: originalmodelfinebeamedheight2.5.odb    ABAQUS/Standard 6.4-4    Thu Feb 03 16:17:25 GM


Step: Step-1   Dead load
Increment      1: Step Time =    1.000
Primary Var: S, S22
Deformed Var: U   Deformation Scale Factor: +2.000e+01
```

Figure 8. Typical deformation pattern of vault

The vertical displacements are presented at four sections, mid-span at both the crown the edge beam and at the same positions at the end of the cantilever. As would be expected the maximum displacements occur on the cantilever edge. At low span to rise ratios the mid-span deflection is downward whilst the deflection at the end of the cantilever is upward slightly. As the span to rise ratio increases magnitudes of the deflections increase considerably. The displacement at the mid-span crown is upwards whilst the displacement of the mid-span edge is downwards. At high span to rise ratios the deflections of the cantilever edge become very large.

(Fig.10) illustrates the influence of span to rise ratio on the horizontal deflections at the junction between the vault and the edge beam. Positive displacement indicates the edges of the vault move inwards and negative displacement indicates outward movement of the vault. As the span to rise ratio increases the lateral displacement of the vault at the cantilever end decreases whilst the lateral displacement of the vault at mid-span changes sense and moves outwards. The displacements in **(figs 9 and 10)** illustrate the general patterns of deformation of the vaults. The vaults tend to deform inwards, adopting a deeper but narrower profile.

However the magnitudes of deformation of the lower transverse span to rise ratios, typically used by Dieste, are relatively low in relation to the spans but increase rapidly as the rise to span ratio increases.

Influence of width of edge beam

The edge beam is an important element in the behaviour of the vaults: it fulfils the role of buttress during construction and provides stability to the geometry of the vault. A further study was undertake to consider the influence of the width of the edge beam has on the behaviour of the vaults. The results are presented in **(fig. 11).**

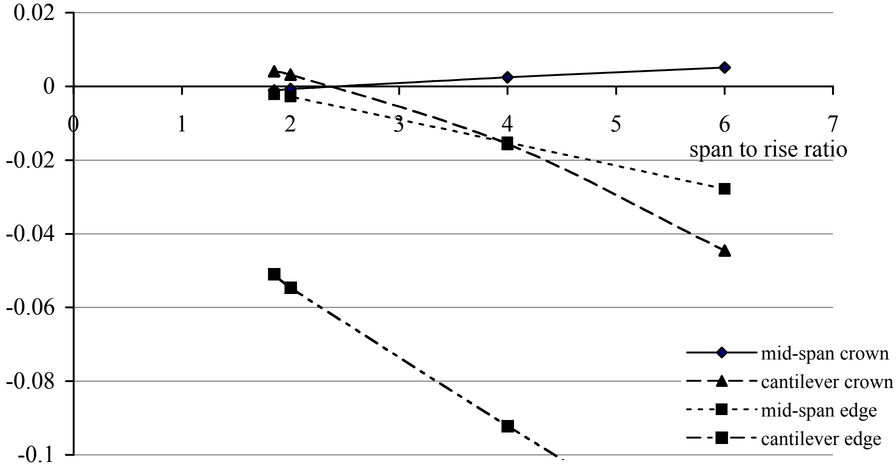


Figure 9. Influence of span to rise ratio on vertical displacement of vault

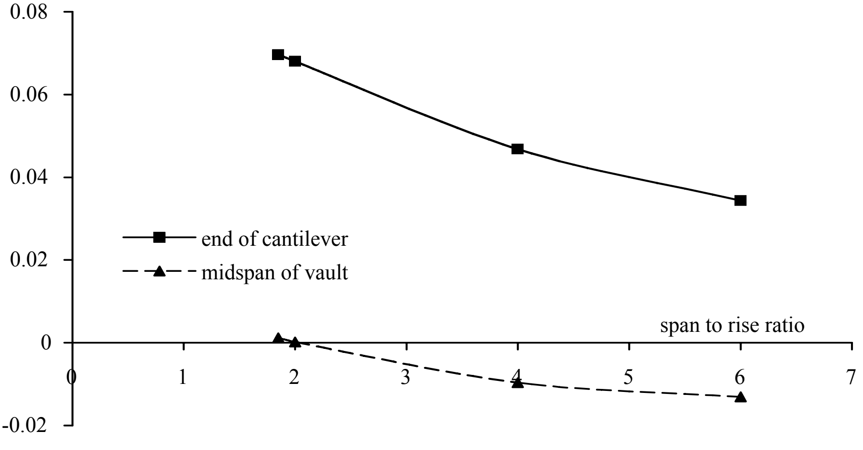


Figure 10. Influence of transverse span to rise ratio on horizontal displacement of vaults

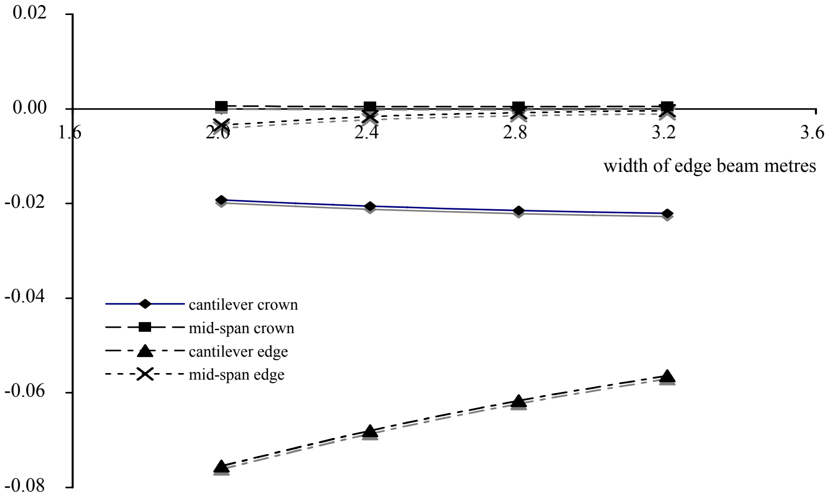


Figure 11. Influence of width of edge beam on vertical displacement of vaults

The overall geometry of the vault was constant, with a transverse span to rise ratio of 4, cantilever span of 12.5 metres, middle span of 20 metres and transverse span of 10 metres. The width of the edge beam varied from 2 to 3.2 metres.

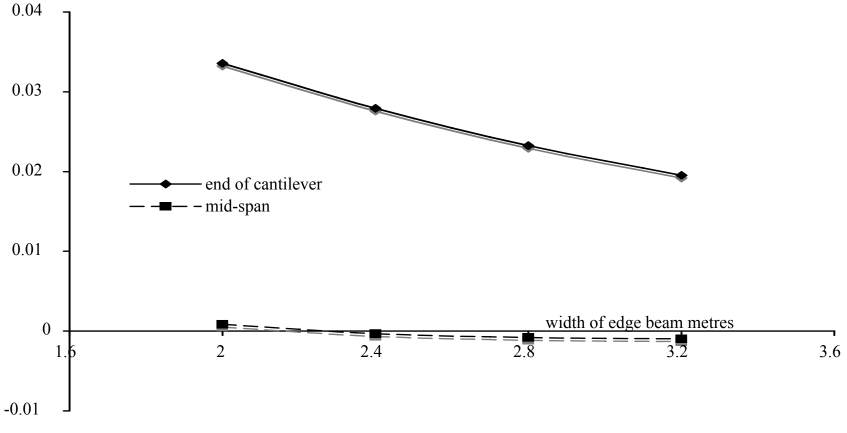
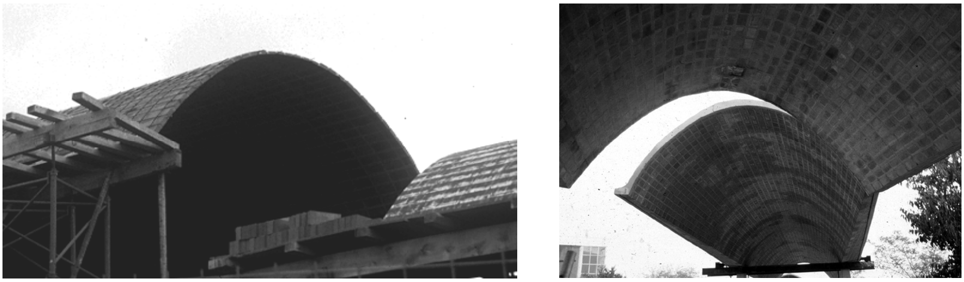


Figure 12. Influence of width of edge beam on the horizontal displacement of the vault

From **(fig.11)** the width of the edge beam has little influence on the displacements at the mid section and only a minor influence on the displacements at the end of the cantilever on the crown. However the vertical displacement of the cantilever edge reduces as the width increases **(Fig.12)** illustrates the influence of the width of the edge beam on the horizontal displacement of the vaults. The width of edge beam has relatively little impact on the displacement in the middle section of the vault however the displacements change from inwards to outwards as the width increases. This behaviour implies that there is sufficient stiffness allow arching action in the middle section. The displacement of the cantilever edge show considerable reductions with increasing edge beam width.

The influence of Pre-stress force

In the previous examples it was not practical to consider the influence of the pre-stressing forces on the behaviour of the vault. As the geometry of the vaults changes so also does the self-weight and hence the require pre-stress force. This section considers the effectiveness of the pre-stress force. In order to do so an FE model of an existing structure by Dieste was studied. The project is known as Camino de los Estudiantes and is located in the city of Alcalá in Spain, a rough translation of the title is the Student Walkway. During the last decade of the twentieth century Dieste was involved in a number of projects in Spain. There was considerable interest in his techniques both for their practical and economic value as well as the obvious architecture quality of his work. The project consists of a series of 52 double cantilever vaults, each supported on a single pair of columns, forming a covered walkway from the railway station to the Campus of the University of Alcalá **(fig.13)**. Each vault is identical but the height of the supporting columns varies from vault to vault, allowing an overlap and articulation of the adjacent vaults. Each vault is 30 metres long and cantilevers 15 metres either side of the central supporting columns. The transverse span is 4.2 metres and the rise is 1.6 metres, a span to rise ratio of 2.63. The edge beam varies from 0.86 metres at the column to 0.14 metres at each end.



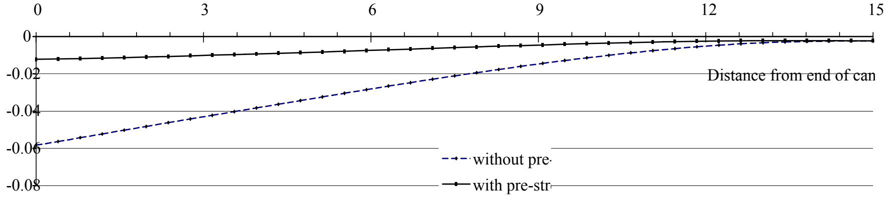
(a) Removal of formwork

(b) Overlapping vaults

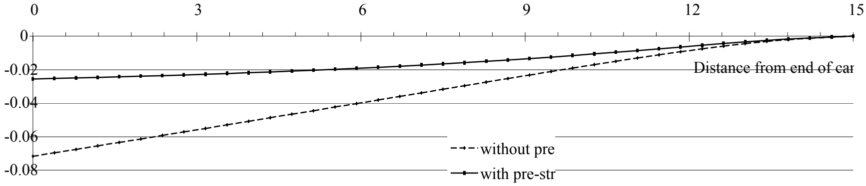
Figure 13. Camino de los Estudiantes Alcalá, Spain (R. Pedreschi)

The general thickness of the vaults is 80 millimetres comprising a 50 mm thick solid rectangular brick and 30 mm of sand-cement topping. The joints between the units are 20 millimetres and are reinforced with 6 millimetre diameter bars in every transverse joint and every second joint in the longitudinal direction. Additional transverse reinforcement is added in the sections adjacent to the columns. The formwork for the vault is a single element 15 metres long. The vault is constructed in two stages starting from either side of the column. The vault is pre-stressed using nine 16 millimetre diameter steel tendons. The pre-stress force in each tendon is 178 kN. The pre-stressing forces are curtailed in nine steps, decreasing the pre-stressing forces towards the cantilever end. The thickness of the topping increased to 50 millimetres around the tendons.

An FE model was constructed to represent the vault as described above. The reinforcement was not included and the edge beam was simplified to a average width of 0.5 metre for the full length of the vault. The pre-stress force was applied as a series of nodal forces at the same positions applied in the actual structure.



(a) Vertical displacements along crown of vault



(b) Vertical displacements along vault edge

Figure 14. Displacements in vault with and without pre-stressing

Figs 14 (a) and (b) clearly show the effect of the pre-stress forces on the displacement of the vault. The maximum displacement of the vault with the pre-stress applied is approximately 25 millimetres at the lower edge of the cantilever.

(Fig. 15) Illustrates the effect of the pre-stress force on the stresses along the crown. The FE model without pre-stress in effect represents a stress condition that could not exist in reality. The brickwork would fail in tension over the support at much lower stresses than illustrated, it does however help demonstrate the effectiveness of the pre-stress force in counteracting the flexural tensile stresses. The pre-compression induced by the pre-stress force results in a net compressive force along the crown. Steps in the graph indicate the progressive curtailment of the pre-stressing tendons along the crown providing a more even distribution of resultant compressive stress along the crown of the vaults thereby avoiding unnecessarily high levels of resultant compressive stress towards the end of the cantilever.

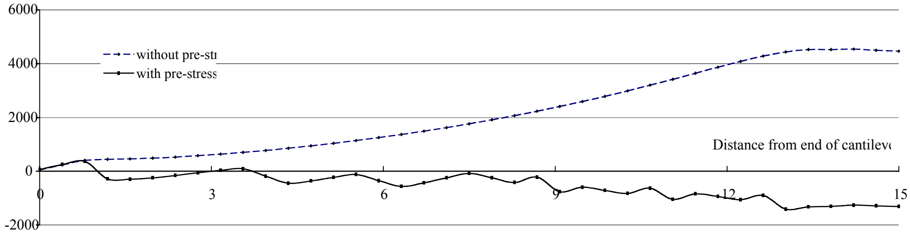


Figure 15. Variation of compressive stress along crown of vault

SUMMARY AND CONCLUDING REMARKS

This paper has described briefly one of the key structural typologies developed by Eladio Dieste. Dieste described these as Cascaras Autoportantes de Directiz Catenaria sin Timpanos, roughly this translates to Free-standing Vaults of Catenary Directrix without Gables, (Dieste 1994). In this book Dieste presents an account of his calculation methods. These remarkable structures are visually dramatic and highly innovative on a number of counts:

- The elimination of the support of the gable wall runs counter to perceived wisdom.
- Barrels (vaults) should be supported on end walls or stiff arches to avoid unnecessary and costly buttresses or interfering tie rods (Salvadori and Norton 1990)
- The innovative construction techniques in the use of pre-stressed and reinforced brick have created a form of construction that is more effective that other in reinforced concrete. The techniques are far more sophisticated and advanced than most research and practice in the middle to the end of the twentieth century, (See Pedreschi and Sinha 2003).
- The use of brick at the same time as some of the great concrete shell constructions. Dieste sought for a new contemporary expression for brick. He saw that accuracy in construction, rigour in analysis and design were possible, he also saw the practical and cultural significance of the use of a familiar and indigenous material.

The computer is not a substitute for experience, practice and intuition. Dieste constructed the first major free-standing vault in 1963, (Anderson 2003, p, 236), long before the wide spread use of computer aided design. Nevertheless computer modelling has provided some useful insights. It helps to demonstrate the structural challenges posed by the avoidance of the gable walls for support by illustrating the nature of the deformations that occur at the end of the cantilever. It also demonstrates both the effectiveness and the sophistication of the pre-stressing techniques. Dieste clearly operated a broad rule of thumb regarding the geometry of the vaults. The transverse span to rise ratio never exceeds 4. Dieste was known to carry out tests on vaults and to monitor the movement his structures during construction. The magnitudes of displacement obtained in the parametric study support this. Ratios larger than this result in significantly greater displacements, which in turn would require much greater levels of pre-stress force. For the range of vaults examined, increasing the width of the edge beam beyond 2.0 metres provided only marginal improvement to the behaviour. The width of the edge beam in the project for Fagar Cola was 2.0 metres. Ultimately the most important demonstration of the efficacy of his methods lies in the extensive catalogue of successful projects. He was truly a remarkable engineer.

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