ARCH 431/531: BLDG SHOP | **DIESTE WALL: RULED SURFACES & BRICK MASONRY** | SPRING 2017 | 2 CREDITS

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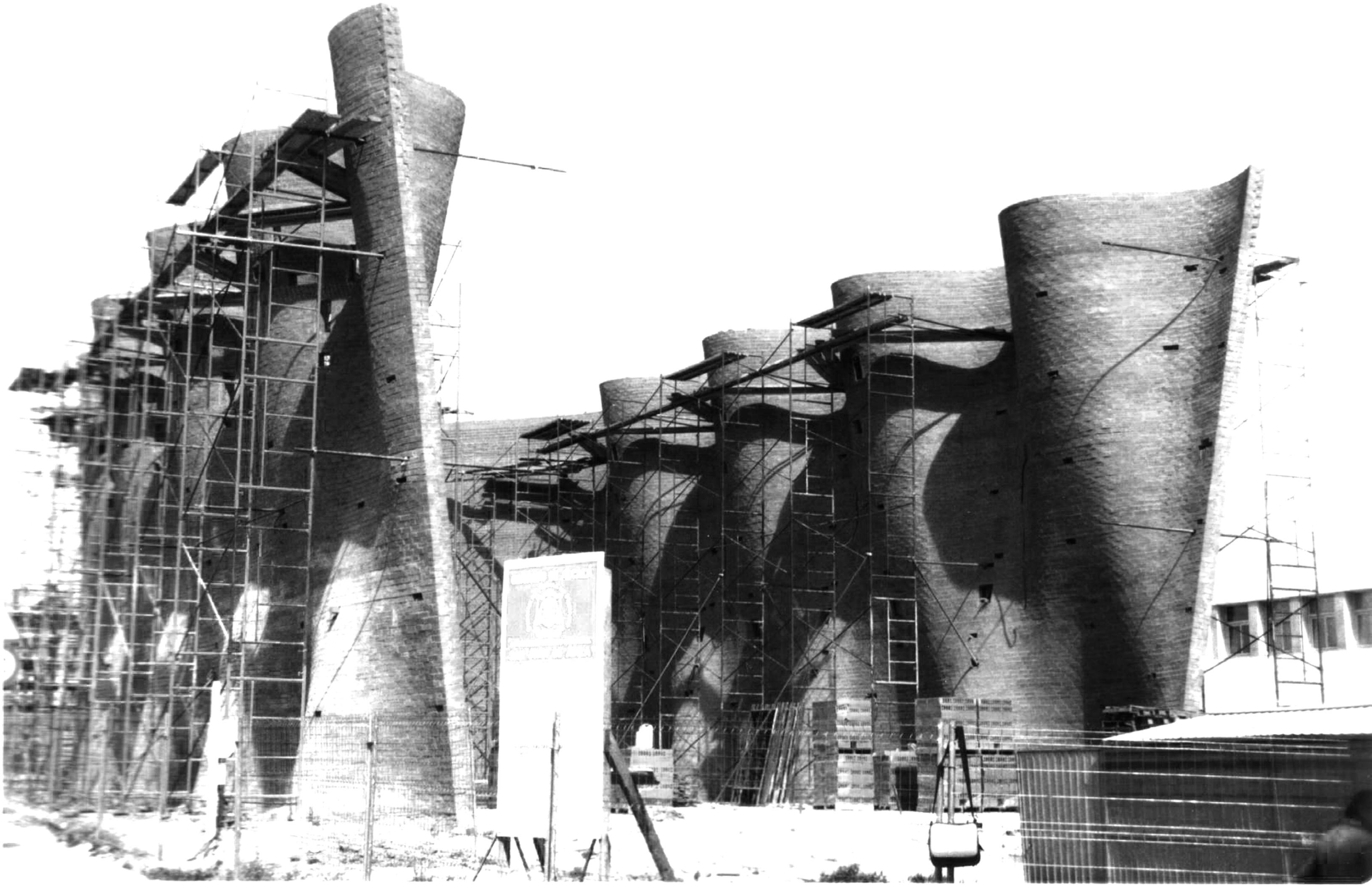
READINGS



Iglesia parroquial de San Juan de Ávila en Alcalá de Henares. Madrid, Spain. Eladio Dieste and Avila Arquitectos

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The following reading packet is comprised of essays originally translated and compiled in Sanford Anderson's Eladio Dieste: Innovations in Structural Art.

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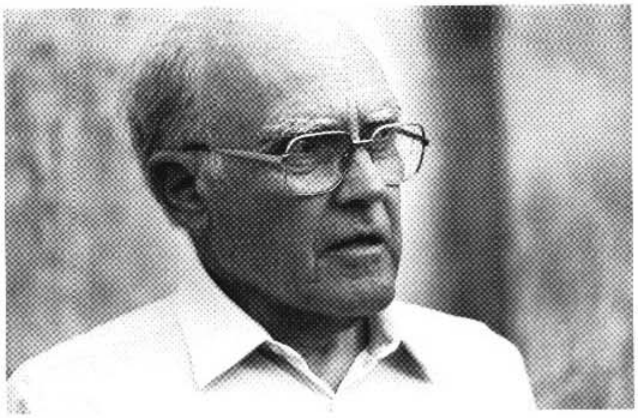
MONTEVIDEO



Julie Méndez Ezcurra

fig. 221

DIMENSIONS OF A CREATOR: A TRIBUTE TO ELADIO DIESTE

Lucio Cáceres

Eladio Dieste was a man of essence. His life and work left no room for the anecdotal or the adjectival. He played an active role in a generation that exalted duty toward oneself and toward one's fellow man as a way to elevate the soul and to promote private and public virtues.

Raised in the modest home of immigrants, Dieste was enriched with the intellectual and spiritual fertility of a family that made knowledge and poetry, charm and religious faith, their most cherished patrimony. Under such circumstances it was natural for him to emerge as an ascetic, a personality that was admired (and sometimes endured) by those who shared his life, work, or classroom.

Destiny endowed him with an extraordinary intelligence, a noble face, and fine looks, maybe as proof of the saying that a man's mouth reflects the heart's wealth. His professional training and his gifts combined to provide him with an analytical capacity to envisage the problems of his trade with clarity and simplicity. His intuition and creative spirit gave rise to a "mechanism" that the artist feels as he works; he sees it operate in the immobile movement of architecture.

We were still too young to understand the significance of Dieste's recommendation that we read *Razón y ser de los tipos estructurales* ("Reason and being of the structural types"), by Eduardo Torroja.[1] In his manual on the philosophy of structures, Torroja wrote:

> Every material has its own distinct and specific personality, and every shape imposes a different stress phenomenon. The optimum natural solution to a problem—art with no artifice—vis à vis the set of previous impositions that caused it, impresses us with its message, concomitantly meeting the technician's and the artist's requirements.
>
> The birth of a structural whole, resulting from a creative process, implies the merging of art and technique, ingenuity and study, imagination and sensitivity. It escapes from the pure domain of logic to enter the secret frontiers of inspiration.

> Before, and above all calculations, this is the idea, molding the material in a resistant manner in order to fulfill its mission.[2]

Creative work in architecture or engineering is the product of harmoniously considering the essence of functionality or utilitarian aims, a resistant function and a structural type, and economy and its constructive process, as well as the aesthetic qualities of the construction's shapes and dimensions. These basic considerations are present in the Gaussian shells of a warehouse or an industrial building, in the self-supporting shells of a bus terminal, in the ruled surfaces in Atlántida, in the folded plates of the aisles of Durazno.

The master's message becomes especially relevant in this technologically advanced era, when man, besieged by instruments, has available immediate solutions to his problems. Utilitarian concerns may be solved safely and inexpensively, but these solutions may occur at the expense of aesthetics. Dieste is a man prior to hypotheses. What I mean is that most men accept a series of hypotheses as truths that go beyond the basic axioms. One can accept Euclid or challenge him, put faith in the Ptolemaic system or discover Copernicus's, and open a new path of knowledge in each case. In twentieth-century architecture, structural typologies conditioned by the use of steel and concrete led builders to turn to flat surfaces. When Dieste conceived his solution of shells with double curvature and found brick to be the natural surrogate for concrete, he quit the accepted planar shapes and materials and placed himself prior to accepted hypotheses.

A wall is generally conceived as a vertical surface. However, for Dieste, as for Antoni Gaudí, it is possible for a wall to be a ruled surface, finding in its curves the inertia needed to prevent a thin structure from buckling. The paths exist; we only need pilgrims ready to take them to enhance knowledge.

Dieste rediscovered brick not out of nostalgia for the past but rather in light of its inherent virtues—it being resistant, elastic, inexpensive, and having acceptable thermal features. Its shapes give prestige to the material in its structural function. That function had been degraded since the introduction of steel, aluminum, and concrete—materials that, following the Industrial Revolution, seduced engineers and architects and led them to put aside the noblest materials in history, such as stone and wood. Rather than renounce technological developments, Dieste incorporated them in his work.

Dieste designed and built using materials and shapes of his own inspiration, making use of the old and the new, what was native to Uruguay and was taken from abroad. He mastered them all because he was a universal creator who achieved freedom through knowledge—sound, basic knowledge—through the rules of construction and physics, which he applied to the broadest range of aesthetic and structural problems.

The man, the master, the artist, Dieste was nourished by different sources that, when adequately combined, play that silent music that moves us when we contemplate or experience his work, enlightening our way when it is our time to design or construct, and bestowing upon us the personal freedom we need to face our future.

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1 Eduardo Torroja, *Razón y ser de los tipos estructurales* (Madrid: Artes Gráficas, 1956).

2 Ibid., i. This prefatory statement, "the idea to which this book is dedicated," does not appear in the first English edition, *Philosophy of Structures* (Berkeley and Los Angeles: University of California Press, 1958). Translation by the author.

The essays by Eladio Dieste published here were translated from the Spanish by Michael Maloy and Harold David Kornegay and published in *Eladio Dieste: 1943–1996*, ed. Antonio Jiménez Torrecillas (Seville: Consejería de Obras Públicas y Transportes, 1996). Mr. Maloy kindly gave the present editor permission both to use their translations and to revise them as he saw fit.

ARCHITECTURE AND CONSTRUCTION

Eladio Dieste

What follows is a somewhat vague meditation on the subjects that concern me. It is not a rigorous and comprehensive essay on the title's difficult subject. These are passing reflections that I have organized as best I could. They are reflections of an engineer who found in the process of building warehouses, he was creating architecture, even though that was not his object. He also found that he had an awareness of form and in confronting this awareness, he discovered that it helped him to solve problems that were strictly structural.

I began to work on designing and building structures in 1942. Since then, I have thought about why we build things the way we do. I have thought not only about the source of the technologies that we apply but also about the philosophy, not evident to me at the time, that is the foundation of our activities.

In order to recount these reflections, it is necessary to summarize the evolution of construction methods since the industrial revolution. In analyzing this summary, the evident break in a thousand-year-old tradition that was concurrent with the industrial revolution has to surprise us. Until the end of the eighteenth century, the construction methods employed were a natural extension or evolution of the methods used in the late Middle Ages and the Renaissance. The great expressive traditions of the earlier periods (Romanesque, Gothic, etcetera) used fundamentally the same construction tools and, even more importantly, had the same concept of how construction was related to architecture. In passing from the eighteenth to the nineteenth century, the use of iron as a construction material became possible (first cast iron and later the different types of steel). With great speed, this new material began to be supplied in prismatic components that had to be assembled to form the structure of the building. It is quite common to emphasize the importance for the evolution of architecture of the fact that the structure of a building began to be thought of as a skeleton, partially independent of the walls, through which the function and space of architecture became free from the limitations of resistance in a way that was unknown until then.

Iron invaded and revolutionized construction technology very quickly. This rapid change was not due to economic reasons, since a new technology can be more expensive to use at the beginning, as it was in this case. Instead, the change can be attributed to the fact that, fortunately, man has the altruism to undertake endeavors that he feels are worthwhile. Structures were possible with steel that could not have been built with the previous technologies. These new technologies were well suited to the necessities of building programs in the large population centers of the industrial era: warehouses, large workshops, stations. The most typical architecture of the nineteenth century is the architecture of large iron structures.

However, there is an aspect of this revolution that I have not seen made explicit. Perhaps this is because it is strictly a structural consideration, but it seems to me every bit as important to the evolution of architecture as the liberation of the ground plan that structural independence permits.

Iron: The Technological and Theoretical Predominance of the Plane

The assembly process for iron components made it possible to break down a building into planar framework sections in a natural way and without neglecting to consider anything essential. What is more, these planar framework sections were calculable. The great advances in the science of construction were concurrent with this technological revolution. Even without the subtleties of the theory of elasticity and of superior stability, using only the great principles of statics (which are easily applied to planar systems) and the rudiments of the resistance of materials, the thrusts and sections of all the parts of a structure could be determined. This is why there was such a great effort to reduce everything to planar schemes, since engineers could work with only the planar structures with ease.

The technological dominance of the plane must have been of great importance to the later evolution of construction and consequently of architecture. Having rational security over a problem creates a confidence in oneself and, at the beginning, an interior elation. The most perceptive and daring minds set out enthusiastically to explore the new possibilities of the use of iron. The traditional technologies did not use this kind of analysis. Instead, their achievements were of a very different nature, and the perfection that was achieved is sometimes disconcerting. I remember seeing the analysis of one of the arch buttresses of Notre-Dame de Paris, in which the stress lines corresponding to the loads and the effects of wind, snow, and temperature were studied. These stress lines are transferred to the inside of the central nucleus in all cases, touching the edges of the nucleus and always staying inside it. Therefore, the buttress is always stressed without any extra section.

Those medieval masters seemed to know theories and working methods that were only formulated seven or eight centuries later. In order to contend with the always present forces of irrationality, it is advisable to note that this precision and accuracy of dimensions is not universal. The vaults, for example, are much heavier than is statically necessary. However, this example allows us to see the points of refinement that this age-old process of adjustment achieved. As we said, all of a sudden engineers had at their disposal building methods that could be gauged with security, rather than by trial and error. These methods replaced long and imprecise processes with new forms of rapid analysis. Only the euphoria of such security can explain that an enormous amount of traditional wisdom of construction was abandoned.

This construction tradition had lost the vitality of its great creative movements, but as a sum of possibilities it was still intact. It was intact but resistant to the design methods of those who could have made use of it. This is the only way to understand how the minds that were capable of founding a whole new tradition were unable to make use of this older tradition—minds like Eiffel's, who was not only a brilliant engineer but also an artist, who built structures, and above all bridges, of great beauty.

The structures made from iron were planar. These are typical of the nineteenth century. Even today, the majority of buildings are designed with planar framework. These are the buildings that the science of construction analyzes, and they are almost the only ones that we have studied and continue to study in our engineering and architecture schools. The old structures, like Santa Sofia or a Gothic cathedral, are not planar. They are structural systems that have to be thought about in three dimensions and are much more difficult to conceive and analyze. In a Gothic cathedral, for example, the stresses of the ribbed vaults, which in the end are supported by each other, are concentrated on the central pillars. The thrusts are absorbed partially by the buttresses, and by the aisle vaults, and are finally transmitted to the ground by the walls and these same buttresses. It would be difficult even for an experienced engineer to imagine, much less calculate, the stresses of the different parts of such a building.

The rational clarity of planar framework must have had an enormous effect, even on the compositional aspects of architecture. Not only was it natural to build with the planes that construction technology provided, but its incipient rational clarity gave the plane a peculiar expressive force that one day would coincide with the formal investigations that were at the root of the Modern Movement. This plane that vibrates with a kind of religious fervor can be seen in the works of Le Corbusier, Gropius, and Mies van der Rohe.

Even today, architects are more at ease working with planes. Even though they may not always be the most appropriate forms, architects choose planes as a surface to limit a space in a natural way. We have all seen buildings in which the solution for the roof, for example, struggles structurally not to go beyond the plane. The fact that a building of this kind is much easier to express graphically has a great influence. I remember when I asked a friend about Gaudí's work, he told me that he wasn't at all interested. "His work has nothing to do with us," he told me. As a final argument, he added, "I wouldn't know how to draw one of Gaudí's buildings. How can we construct a building today without ground plans, facades and cross sections?" [1] This is something that was said without thinking. This friend was not interested in Gaudí as an artist. This is an example of a tacit mental outlook that thinks about the graphic means that we need to build structures, giving these means a disproportionate importance. The essential thing is the structure, not the plans. If the plans are not able to express something we have good reason to believe is valid, this is no reason to abandon the idea.

All of the great structures of the past were built with extremely simple plans. I am aware that the organization of work was very different. I also know by experience the difficulties involved in envisioning things that cannot be expressed well in drawings, but many times the results are worth this effort, worth it from the most utilitarian point of view. The double-curvature vaulted structures, for example, that cannot be easily represented in graphic documents, are very economical and easy to build. I believe it is evident (and serious because of how it impoverishes the process) that the first thing we do is draw plans. We think more about the plan than about the structure or, better said, we only think about the structure through the framework of the plans. Everything leads us to this; the way we build and even our training in which we learn (it is almost inevitable) to do projects, not build buildings. The natural tendency is to emphasize what we dominate. It is only with sustained effort that we can liberate ourselves from what José Luis Sert calls "the tyranny of the drawing board."

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[1] This was twenty-five years ago, when these brilliant works were still not appreciated. I did not know anything about Gaudí, but the great painter Torres Garcia had spoken enthusiastically about him to me.

Along with the new technologies, a new attitude toward the structure was formed. It was precisely the clarity, rationality, and speed of the design and construction process that did not allow the new technologies to gradually develop personalities of their own, as was the case in the past. It was very unlikely that we would suddenly be able to see in some corner something as alive as a human face (which happens so many times in older cities).[2]

One of the great advantages of planar framework is that it is so easy to analyze, but it also has great disadvantages from another point of view. The plane is structure's most elemental form. It produces structural solutions that are simplistic at times and does not make use of materials in any rational way. As in other cases, its primary clarity loses many of its most important elements along the way. The men who built the wooden roof trusses in the first basilica already knew its essence. All of the stone vaults and domes in medieval architecture came after this. Great technological refinement and penetrating analysis of the construction problem were necessary. There is a sensation of incompleteness that we still feel, at times, in front of good buildings that are structurally and compositionally created using linear structures. In the end, this sensation comes from the synthetic and intuitive perception that there is something incomplete in the analysis, something elemental that has been left unfinished.

Concrete: Vaulted Structures, Calculations, Models, and Imagination

The technological revolution continued, and in the second half of the nineteenth century reinforced concrete was discovered.[3] From its modest beginnings, it very quickly became one of today's most vital technologies. With its discovery came a revolution in which the use of materials yielded structural forms that exploited surfaces and were both more rational and expressive.

In the beginning, reinforced concrete was used by breaking it down into planar systems: slabs, beams, arches, and pillars. This was not only the case when its use seemed logical and rational, as in a mezzanine, but also in other evidently absurd cases, such as putting beams in the ridge of a double-pitch roof or arches at the intersection of two cylindrical vaults. It was slowly realized that this was not the most rational way to use it. The ridge beam did not make sense, since one slab gives rigidity to the other and the arches channel their stresses along the intersection. The awareness of this problem is sufficiently new so that we have just begun to see its results. I remember how difficult it was to free myself from the traditional way of conceptualizing structures which was the consequence of all my previous training. Besides, when I did come up with other solutions, the analysis of the building process was consumed in a sea of doubts. I was continually on the threshold of knowing how to calculate something, and for an engineer to conceive of something was equivalent to knowing how to calculate it.

Sometimes when I speak to young people and explain that there is still not enough time dedicated to the study of the surfaces of structures, I see in their eyes the obvious question, why? The honest answer is that it is difficult to talk about vaulted structures without falling back on the list of solutions that are already known. Today, it is true that there is not a structure that cannot be analyzed in finite terms, and discussion about structural problems with an intelligent specialist is not difficult. However, we always find that the most magnificent forms are resistant to simple analysis, and we will have to do quite a bit of simple analysis before we can achieve the most sensible and responsible way to calculate these structures.

Almost all that has been written about this kind of structure—and certainly the most interesting—is the work of builders. These men devised a solution first and then, after the process that we spoke of before, completed the process by testing their ideas with trials at the site. Their analytical and building experience was systematized in theories that are valid for the structure used. The problem is that we can devise many more solutions, some logical, economical, and clearly stable, than those that we know how to calculate easily. We find ourselves in a situation that is symmetrically different than the situation at the beginning of the nineteenth century. We have a material that we have every reason to use and that is naturally very suitable for the surface forms of our work: slabs, diaphragms, polyhedron systems, vaults, and domes. However, we have to use inadequate and awkward

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[2] In this as in all things, there is no advancement or enrichment that does not imply risk. Let us take a contemporary example. Few things in our world are as marvelous as computer science. Many of the calculation difficulties that I refer to later have almost disappeared. This is because there is no system of differential equations, as complex as it might be, that can resist the capacity of a good machine to solve. However, a computer cannot respond on its own. It will never give us essentially more than we put into it. This is to say that the creation of forms will continue to be the result of work done by the human mind, that marvel that produced computers and transcends them infinitely.

There is, of course, an interaction between man and machine. He that knows how to and is able to solve equations acquires a great power. However, there are dangers when we let ourselves get carried away by a fascination for the instrument. Of course, I am speaking as someone who has acquired technologies but has not completely absorbed their uses due analytical methods in our designs, and we have not succeeded in making them into efficient tools.

The study of models is possible, but in general it is necessary to understand that these models will give us a qualitative orientation. In order to make our efforts more quantitatively systematic, we will have to define and study the problem to achieve sufficient precision.

In addition, the model is slower and more expensive than computation. I see it as the final step in very complex structures. In my building experience, I have used the model very little. Whenever I thought about using it, I had, by that time, studied the problem so much that it wasn't necessary. What I can say is that I have proceeded bit by bit and that the smaller structures have been the models for the larger one.

Even with the help of all the modern methods, the design process for structures that are more rational and at the same time more expressive, will always be slow and require an enormous amount of work. I have come to think that the most rational thing to do would be to create a repertoire of forms—forms that have been thoroughly studied and in which we would perceive the interior solidity that is the fruit of an intense effort. Wouldn't the most sensible thing be to use these forms in the design process? Wouldn't this be a completely rational justification of what we could call by extension "style?" In ancient times, style was the creation of a repertory of studied forms and was part of a process that included building and the age-old perfection of proportions.

These richer and more complex forms cannot be made routinely. They require a love for the project and a taste for details—qualities that do not abound among businessmen. Anyone with experience knows that, in general, the construction engineer participates very little in the project (especially in the projects that are more typically architectural). He is limited to managing the efficiency or productivity and controlling the project financially and administratively. He does not participate actively in the construction process's daily routine. What I have described reaches, at times, scandalous extremes, and it is no exaggeration to say that in many cases it is the foreman that builds the project. I believe that this is the real cause of what is called low worker productivity. The worker feels that his superior does not contribute his share to the project, that he does not truly fulfill his duties and the part of the final benefits that he receives is not morally justified. This extremely immoral and all too common conduct is even more intolerable in the projects that we have discussed. We don't only have to design and calculate these structures, we also have to build them. This is not possible without a greater personal dedication on the part of the person that oversees the construction. This is why some building contractors are so resistant to these solutions. They say that they are expensive. This is not true. What is true is that these solutions require them to perform as they should, as builders, not just contractors or businessmen.

The builder is indispensable. In fact, the project for a building is not really complete if it does not consider how it will be built, and the ways in which a building can be built have a notable power of inspiration. All viable new structures are intimately related to construction methods, and these methods are visible in the finished building.

It is common that the legitimate and inspiring concern for the economic aspect of a project can be an obstacle. As soon as a new

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to a generational problem. I cannot help but remember the dangers I saw in the attitude of a young man (director of a work group at MIT a long time ago). He believed that there was some dubious merit in not thinking, in "letting the machine do it," as he put it. Of the ten solutions he presented me, nine could be discarded just thinking about them for five minutes or, I would almost say, just understanding the problem.

The great danger of computers is this, that laziness and the tremendous mechanical labor that is required to make anything work is distancing us from the substance of reality. We tend to simplify and impoverish our concepts and thoughts so that they will fit into the mold that will "run on its own." For example, it is easy to program the calculation for the classic skeleton of an important building with columns. However, it is not so simple if we move to the solution, which could be more suitable, if we substitute for it diaphragms.

What precedes does not defend the reactionary or simple-minded position that we should not use these amazing instruments that technological progress has put in our hands. No modern day Luddism here. I only want to call attention to the dangers implicit in an attitude that leads me to believe that we could use this technological advancement in a way that will sterilize its force and, as a result, the capacities of man will not grow but instead shrink. I fear that what we will do, instead of being more fruitful and truly rational, will in the end be an impoverished simplification of what we have already done with more primitive methods.

[3] What I say about reinforced concrete can be applied to reinforced brick.

solution is developed, cost calculations are made that are noticeably uncertain. The only costs that are known with any kind of certainty are those for structures that have been built many times. Cost estimates for really new solutions are not to be trusted. In this case, the only way to be certain is to break down the construction process into those parts in which the difficulty and price can be evaluated. In the last analysis, when the methods that are being considered are very new, it is the power of the imagination, the power to see the building process in its different stages, that will ensure its viability and efficiency. This ability to see the process using one's imagination is not something belonging to the highly gifted. I believe that human faculties are much more equally distributed than is imagined. This ability to imagine is learned. What we call difference of faculties or abilities is, more often than not, a difference in background or personal history. Lack of imagination is more likely an "ablation" of the mind that has turned its back on innovation and has chosen to remain with what is already known, like the boy that doesn't learn how to swim because he was frightened when he was a child.

We should note that when first we enter the process of thinking about structures, which is our everyday work and how we make our living, we do not do cost analysis. Analysis of the costs comes at a later stage and that permits adjustments and refinements in the details. We imagine the structures, sometimes all at the same time, with all their essential details: the tension patterns, the construction methods, the equipment. Later, reality almost always confirms what we have imagined. It is not appropriate for us to say that we have built these structures for crudely economic reasons, because they were less expensive. Even in the case of the more "artistic" projects, like the churches, the costs have been ridiculously low.

Rationality and Expressiveness

After this first attempt to deal with the problems that we have set forth, it seems natural that we should consider once again something that seems evident to me. In many cases, once these structures are spatially conceived, designed, and built, we are moved by them. They move us not only because of their dimensions or their boldness but because they are mysteriously expressive. If we think about the reason for this, we will see that, in the first place, our emotion is due to the fact that we perceive in them our spirit, in a synthetic and intuitive way, a more exact adaptation to the laws that govern matter in equilibrium.

Keep in mind that this adaptation is not only rational in the sense that we normally give this word because we do not have perfect knowledge of the materials or of the loads that our structure must support, nor do we have calculation methods that permit us to determine the stresses of its different parts. This is also true in many common cases, like the mezzanine of an apartment building. We have become accustomed to and reassured by the secure results that we obtain. However, we forget how primary and approximate our analytical methods are and how much their results differ from reality. In other words, to give form to a structure, whether consciously or unconsciously, there is always something of a leap into the void. However, if we give ourselves to the problem seriously, we later acquire a different kind of security from all the analysis. It is then that we begin to live the structure from inside, and the leap we take is to fly rather than to fall. This is why it is more appropriate to talk about the art of construction rather than the science of construction. It is only with enormous rational effort that we will acquire the ability to take that leap.

Financial Economy and Cosmic Economy

You might ask me if there is a reason for a line of inquiry that attempts to delve into the laws of equilibrium and into the many varied ways we can discover to adapt ourselves to them. Is it not enough if we try to build structures that are resistant, simple, and economical to construct? With what is normally understood as simplicity and economy, I do not hesitate in maintaining that this is not enough. What is called simplicity is usually unjustified simplification, and economy usually refers to money and its movements—economy in the financial sense. The things that we build must have something that we could call a cosmic economy, that is, to be in accord with the profound order of the world. Only then can our work have the authority that so surprises us in the great works of the past. This is what many of the practical gentlemen who control us have forgotten or do not want to hear. There are an enormous number of people in the world creating wealth, trying to adapt themselves to the world's profound order. It is this wealth that we later squander through carelessness, financial schemes, and speculation.

As an example of what I am trying to explain, I remember a passage from a novel by Knut Hamsun. The action takes place in a clinic for aristocrats in the north of Norway. Supplies arrive from the south every day by railroad. One day they run out of meat. The director of the establishment knows that a local peasant has a cow, and he wants to buy it. The peasant tells him that he cannot sell him the cow because it is not yet time for it to be butchered. The director says that he will pay him as if it were time for it to be butchered, but the peasant will not change his mind, which in the end shows that there is an order that is independent of money. The peasant asks the director to return in the month of May when he will sell him the cow at its fair price and concludes by saying that it would be different if they had nothing else to eat. This conversation is significant because it brings face to face two ways of seeing reality: the apparently practical and the profoundly practical, which takes into account the existence of an order that permits disorder but also a squandering by those who do not serve the world and mankind but instead make use of them.

There are profound moral reasons (and practical ones, that in the end are the same) for our search. To attempt the search is to give form to our work. In other words, the form of the things that we build will make us able to adapt ourselves to the laws of matter. There is in this endeavor and exploration all the nobility and reverence that a dialogue with reality and its mystery implies. This struggle shows us that the world is not alien to us but is, instead, in essential communion with us.

The resistant virtues of the structures that we are searching for depend on their form. It is because of their form that they are stable, not because of an awkward accumulation of matter. From an intellectual perspective, there is nothing more noble and elegant than resistance through form. When this is achieved, there will be nothing else that imposes aesthetic responsibility.

Architecture Is also Construction

The necessity to clarify other fundamental aspects of architecture has made it seem that we have forgotten something quite elemental—that architecture is also construction. It is not enough that we contemplate and resolve functional problems and their spatial expression. We should build architectural spaces, and their expression will be conditioned by how we build them. This is why the spatial conception and the form in which these spaces are built should be one and the same thing. They should be unified in the creative process only after they have actively and uncompromisingly interacted in the architect's head. Almost all of the buildings today seem assembled rather than built. We have the belief that we must enclose the spaces that we envision. The architecture that is a result of what we are talking about is like the very best of the construction process itself: if we proceed in this way we will find that the structures we build are rational and economical, much more so than if we had given more importance to primarily practical considerations.

This is why construction and its relationship with architecture are so important. There can be architecture without installations (electrical, plumbing, etcetera), but there cannot be architecture without construction.

Construction will always be indiscernible from architecture because it is like its flesh and bones. Furthermore, each art has its sphere, what we could call its limitations, if it were fitting to give this name to a process. This is why scenography is not architecture, or at least only a very special kind of architecture. There are great architectural works in which you sense this weakness. They are not constructed; they have something that makes them seem like scenography.

· For architecture to be truly constructed, the materials should not be used without a deep respect for their essence and consequently for their possibilities. This is the only way that what we build will have the cosmic economy that we spoke of, and this cosmic economy is what sustains the world. When we use materials with this profound respect, we must be modest and be careful of our own aesthetic refinement. It is not enough to use brick because we like its texture and the fact that it is a material full of historical references. It is not that this is bad in and of itself, but we can take much better advantage of its possibilities. In this sense the current risks are much greater than before because modern technology apparently gives us the possibility of doing anything, of realizing any fantasy. It seems as if we can use construction materials as the set designer uses cardboard. The economic risks that this infers are not necessarily immediately visible, especially in the richer developed countries.

Up to now we have been looking for what should guide us in our structural conceptualization. We have also answered to simplistic objections that have come to our attention. However, there are other things to be said, although I would not necessarily say other things as much as the same things, phrased in a different way.

Architecture Is an Art

Apart from its obvious functions, architecture is an art. Perhaps it is the most important art since it forms the spaces in which we move. It has in common with all the arts the ability to help us in the contemplation of the universe through its own infinite and therefore rationally incomprehensible definition.

If we could know the world in a perfect and infallible way, then we would not make art; we would simply contemplate the world. The moment of the final leap, like a lightning flash of vision, allows us to contemplate the harmony and intelligence of the world. This is the moment of art, but this does not mean that we can only contemplate through art. All of mankind's spiritual activity is the conscious or unconscious search for this contemplation. Once I told a friend, thinking about the ancient cities, cathedrals, and temples, that our era had not created anything similar.[4] It did not escape me that these works were the spatial expression of a culture, or rather, of a complete vision of the world, man, and his destiny. In this sense, our era does not have a culture that informs the social body. My friend responded by saying that this depended on what we understood to be architecture. In his opinion, the Dutch highway system was as much architecture as Chartres Cathedral. It is like saying that there is no difference between a piece of good legal prose and a good sonnet by Quevedo.

What my friend said is partly true, but as a response to what I had said it shows a strange blindness. The two works were created for a purpose. It is through the full achievement of this purpose that we experience the pleasure that is the principle component of the happiness that art gives us. However, the two works are very different. In the second work, the artist or artists did something more. As a result of their attempt to interact with the world, they gave us a glimpse of the superior order that, through our struggles, we strive to contemplate. Without these glimpses that show us that the world has meaning, we would succumb to despair.

A building cannot be profound as a work of art unless it has an earnest and subtle fidelity to the laws of matter. Only the reverence that this fidelity requires can make our buildings serious, lasting, and worthy partners in our contemplative journey.

Not all the architecture that we create can aspire to be art in this last sense. There should be prose and poetry, popular dances and Bach cantatas. I believe that this final result cannot, nor should it, be directly sought after. When the final result is the product of a project that is earnest and humble, it will achieve art, but without having sought after it. The building or buildings in which we achieve difficult goals will have an exemplary power over the city. In these buildings men will see the true expression of mankind. They will recognize one another and their weariness will be overcome. Architecture that is understood and felt in this way is poetry. We are not all able to create it, but we all need it.

Industrial Society and the Paths of Mankind

Once, I encountered the objection that the structures that we have been talking about would not be viable in the machine-driven society of the future, in which everything would be made by mass production in huge industrial complexes. Continuing to study forms that require skilled workers and an engineer's close supervision is a sentimental approach that is opposed to progress. First of all, we would have to define what we mean by progress, which would oblige us to define the goals of society or even the aspirations of man himself. If we do not specify these goals and principles, we cannot know if we are progressing toward them or if we are being consistent with them.

It is always the fundamentals that are left vague. Since this type of criticism is also levelled against things that are much more important than the ones we are talking about here and since it has the blind force of the imprecise, I think that it is important that we comment on it.

It is very probable that in the future we will have a civilization in which most, if not all, of what is produced will be produced by large organizations in which the use of the machine will be even greater than it is today. However, these organizations and machines will need to be built and maintained. Someone has to design the prototypes and processes. It seems to me that there is a great risk in taking for granted that the paths that dominate today will prevail in the future. If this were the case, the only reasonable thing to do would be to perfect what is already known. I do not believe this, because the failures of our admirable civilization are too evident for us not to believe that we find ourselves on the brink of changes as fundamental as those that brought us industrialized civilization. The kind of people that are captivated by a machine-driven society of the future and theorize about it are usually not people that *do* things. What they take as definitive and immutable is more like the past than the future. Their opinions are the result of a somewhat childish amazement when confronted with the power and efficiency of the world's powerful nations.

We are not confronted with a world in which the problems and solutions are clearly worked out. We are the eternal traveler who has or should have his compass and know his aims. I think that we would reach a wide consensus if we proposed as a common aim the fulfillment and happiness of mankind. This is an aim that would certainly produce different principles in accordance with each individual's philosophy of life and his religion.

From this sound point of view, focused on the aims of man, what we see around us is not acceptable. Today, the countries that are developed are those that initiated the revolution of the scientific interpretation of reality and later its application to technical knowledge. This is what we call the Industrial Revolution, and it had many positive aspects. It showed man part of his power to transform the world and truly make it his home. However, it took place with such great injustice that the repercussions from the fierce indignation that its inequities produced in mankind are the reason for the destructive madness that has spread throughout the world. In order to comprehend these injustices and inequities, I do not have to have read history books or novels by Dickens. It is enough for me to have worked one month in an industrial city in northeastern France. I cannot forget its miserable rows of squat houses, comfortable stables that housed the poor exploited wretches that are still not humanely treated even today.

These were, as I have said before, "houses with an animal comfort but without the slightest indication that they had been made for men who were destined to speak with the stars. The whole city was an insult to the destiny of man. I was there in spring and the only human things were the sky with swift clouds that cut across it and the lilies and cherry trees in bloom, which were not, of course, in the houses of the poor." I will pose the same question again and again. Is development desirable at the price of this sordidness and misery? Does it make any sense to continue to make this or similar mistakes? For example, for years a paper manufacturing company dumped chemicals into a river in Porto Alegre that made the air unbreathable. Can we justify that this company comes to this poor area of the world to do what it cannot do in Sweden? Is there anyone who will defend such a thing? Is there not another way? I know that through our determination and persistence we will find other ways.

One of the clearest examples of this, even for someone who has little knowledge of architecture, is the modern city. Is what we see being done acceptable? Do we not see an iniquitous brutality that is destroying incredibly beautiful things and mercilessly ravaging the heroic dignity of the poor? There are few things more disheartening than the construction explosion in Europe that has not been aimed at correcting the deficiencies of the previous civilization but instead at crudely making money. Once again, I will refer to things that I have said on another occasion: "I remember Tours. From the war, two sections of the medieval city were saved, two marvels of 'modern architecture.' Then there was the boring, mechanical, unimaginative, and ungainly monstrosity that was the reconstructed zone. This, at a moment when technology would have permitted the creation of a city with a spatial abundance, with a harmonious approach to the space and the people in it. The Middle Ages could not have even dreamed of this approach. The difference is that in Tours, when the city was built in the Middle Ages they thought about eternal man: child, youth, adult, elder. When the parts of the city that were destroyed in the war were rebuilt, they thought about circulation problems, structures that would be solid, with good light and ventilation, good bathrooms, but they forgot the great number of things that we all have in our heads and hearts in our journey through life on this earth. The result is a truly ugly sight. The new city is not a city at all. It is a place built for the rapid and efficient circulation of automobiles. The people sleep and bathe comfortably, but they feel uneasy because at no time do they feel that the space expresses the mystery that they carry inside themselves.

"In the old part of the city you feel an intense happiness. This is due to the fact that the space, the thing that is so inexpensive, has been handled with wisdom and humanity. The music of space, which is architecture, is in accord with the music of the world and the music that we carry inside us. They thought about children chasing each other around in the streets, evoking this dormant memory that we all have of heroic deeds from other times. They thought about the young couples that discover the mystery of love, the old people that sit in the sun to reminisce. They thought about something dense, complex, profound, incomprehensible—like man. They did not use schematic concepts that are formulated in a quarter of an hour and leave everything that is important out."

Let us return to the large organizations of which there is much more to be said and which we usually think of as if they were a means for us to sleep peacefully at night. In order for these organizations to serve mankind, they would have to be very different from the overwhelming majority of those with which I am familiar. They must not only be different in their aims and political and economic activity but also in their pure and brutal efficiency (true efficiency cannot be brutal.) Efficiency is the dark god to whom we sacrifice so many things. Its worshipers, in most cases, are ingenuous, irremediably sentimental, and dazzled by the prestige of the powerful. Having worked with them, I know what is behind many of these large organizations. I know about their scandalous inefficiency and stupidity and their very low technological level. I know about the unthinkable waste of human labor and the miserable, routine, and boring work. All of this is what they do. They do not deceive me. Their force is in the accumulation of capital that sustains them, not in their present level of efficiency.

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4 I haven't done it, but I could do it, and I'm sure I will do it, and with a plenitude about which artists from other times could not have even dreamed. Concerning the lack of unity in our societies, comparing it with other "unities," and summing everything up, pluralism is better. However, if this pluralism had a true fraternity, then nothing would impede the expression of man by spatial means.

The ingenuous South American (which we have all been) believes that behind this power there is always real efficiency. This is not true. What they do have is history. Surely there was efficiency, just as there was stealing, crime, and shameless exploitation (think about the slave trade and the opium war) and other equally iniquitous and sinister things. Today there is not even the barbarity that was at least audacious. The only thing left is an infernal machine that is manifestly senile yet always counts on our foolishness and complicity.

These large institutions that so many people admire do not deceive me. They do not deceive me because power for power's sake does not interest me. What interests me is the fulfillment and happiness of man. We have not found the way to make human fulfillment and happiness compatible with the great faceless monsters that dominate us (speaking of corporations, Chesterton called them "those institutions without souls to condemn and without bodies to kick senseless").[5] The great problem of industrial and post-industrial society is how to save mankind and even how to save this machine from self-destruction, the same machine that we have built and that has so many good and fascinating aspects.

Personally, what most terrifies me is not being able to find a way to prevent that the work of a large percentage of people will be boring and dangerous, even to a much greater extent than the strenuous work of other times. More than once, I have compared (during the same construction project) the workers from a highly developed country with our own countrymen. I have seen very well the poverty that they suffer and have felt the all-consuming desire to correct so much injustice. I would find myself in a serious predicament if I had to choose between the two destinies. In ninety-nine out of one hundred cases I would choose the destiny of the local laborer, even with his poverty. As a man, the worker in a developed society is much more alienated than the laborers from the River Plate area, and this is judging from men that I know from both groups. Another thing that I am sure of is that in a society in which such a large percentage of men live lives that are so unfulfilling, there will be a slow but general social disintegration.

In summary, I would like to say that I do not see "models" to imitate. I see something much more provocative: a task, a path, and I know that I have a compass.

It is obvious that what precedes is not intended to be an analysis or a judgement of industrialized society. These are things that I would not be able to do properly. I have a clear idea of the principle to which we should be faithful if we want to achieve the world that all of us, in some way, aspire to. I do not know very well what this world will be like. Who really knows that? What a great truth, the belief that "you find the path by walking!" What I would like is to try to destroy, using my years of experience as a builder, a false and paralyzing atmosphere (in our technology as well as our society) that seems to take for granted that all the paths are already inexorably plotted out. These already plotted paths are those that the powerful have marked out and those that have been marked out for us. It is not true that all the paths have already been inexorably plotted, nor is it true that the powerful are so powerful. They will not be powerful for very long if they ignore mankind, even if they can crush us momentarily.

The earliest version of this essay known to the editor is "Arquitectura y construcción," in "Eladio Dieste, el maestro del ladrillo," sp. no., *Summa: Colección Summarios* (Buenos Aires) 8, no. 45 (July 1980): 84–93. *Ed.*

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[5] With expert assistance, the source of this quotation has, nevertheless, not been found. On Chesterton, see Dieste's essay "The Awareness of Form," on page 192, n. 5 of this volume. *Ed.*

THE AWARENESS OF FORM

Eladio Dieste

When I have been asked to explain what has guided our projects, it is natural that I have always centered the explanation on what I had on my mind: the functional aspect. This is the most important consideration. Yet I understand this within the context of the richness of all aspects of human culture and its extremely complex necessities and desires, which are not easily put into words. When the function of something is schematized and simplified, the reality of what is being said or done is impoverished.[1]

I have explained, and supported with evidence, the concern for rationality in construction and economy understood in, I dared to say, a cosmic sense rather than a financial sense. However, this is not the only thing that has guided me. I have also been guided by a sharp, almost painful, awareness of form. Since I never had an academic education in architecture or in the visual arts, a certain modesty is natural (a modesty that I am trying to overcome with these words).[2] This modesty hinders me from talking about form since I have studied almost nothing of all that has been thought and written about the problems that it poses.

I believe that you can look at the different projects that are illustrated in this book[3] and compare the perception of the relationship between the form, the space that this form configures, and the functions that are realized in this space. At the Salto Municipal bus terminal, pedestrians pass along the west edge of the vaults, so it is natural that the space should accommodate and contain them.[4] For this reason, instead of cantilevering the horizontal slabs, which are necessary to resist the lateral thrust of the vault, the slabs were supported by the edge of the vault and a very slender pre-stressed beam. Using the beam as a structural strategy helped to define the space created by the vaults. I remember that I first resolved the structure by using slabs cantilevered from the edge of the vault, which is the simplest solution. After further reflection, the structure was built using a solution inspired by the visualization of the space. The roof is almost continuous, producing a sense of calm and stillness in accordance with being in the space. In contrast, at the main entries on each side of the terminal, one passes freely under cantilevered self-carrying vaults. No edge beam is required either structurally or for the definition of space.

At the Turlit bus station in Salto, the horizontal slabs are cantilevered from the edge of the vault, structurally the most economical solution. Taking another step, the best solution for these slabs that resist the thrust of the vault is to make them of variable width, growing narrower at the end of the cantilever. In the Turlit station, the vaults are twice as high as in the other Salto bus terminal, and what we might there call "spatial mending" is not necessary at Turlit. Here the edge beam is not required to define the space, and the roof can be dynamic without making us feel defenseless.

It is obvious that the form can either emphasize or betray a spatial sensation that one is trying to achieve. For the niche in the lateral chapel of the Atlántida church, the bricks were cut in such as way that they are thinner as they move away from the observer. This accentuates the sensation of depth that we were seeking. In reality, since the niche was filled with an effigy, the sensation of an indefinite depth is quite real. In the warehouse for the Port of Montevideo, the window openings and the pillars emphasize the form without disturbing the "Roman" solidity of the older masonry. Finally, in the Durazno church we attempted, with the architect Alberto Castro, to make the lateral and presbytery walls move away, ascending. With this we achieved a calm and at the same time dynamic space that has a visual dimension which is much greater than its real size. From inside, the church seems enormous, but its dimensions, "measured" from the exterior, are quite modest.

Coherence between the appearance of the form and the constructed reality is also important. Coherence makes the form intelligible to us. In the Maldonado television tower and the support structures for water tanks [at Las Vegas, for example], the horizontal elements were placed in a discontinuous manner. The alternative solution, which was the first that occurred to us, was much simpler. This solution would make a ring from each group of horizontal elements. I remember the first time we had to build a perforated tower

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[1] In another explanation, I used the example of the bell tower. Could one even compare what it can mean to climb the Chartres bell tower, the Strasbourg bell tower, or the towers of Gaudi's Sagrada Familia with what is expressed, since we cannot climb it, in the pole that supports the bells in the Brasília Cathedral?

[2] These lines are complemented by what I have said in other articles and essays, with examples that are more directly related to form.

[3] Dieste here refers to the book edited by Antonio Jiménez Torrecillas in which this essay appeared. The reference is also applicable, however, to the present volume. *Ed.*

[4] This paragraph and the next are effectively reconstructions by the editor. In the original, Dieste refers to specific features of his two bus terminals in Salto. Joining the sense of his argument with the features discussed allows for a formulation that is clearer and more compelling. I am also grateful for the consultation of John Ochsendorf. *Ed.*

of any importance, I was not convinced by the ring solution. I had come up with the idea shown in the finished works, but I could not find a conceptual justification that satisfied me. I shared my doubts with an architect friend for whom I had (and still have) the highest regard. After reviewing all the solutions he chose the rings because it seemed to him to be the simplest, the most "rational," as he often said. With much effort, I realized that the rings would divide the surface of the discontinuous shell that was the tower; they would not have been expressively appropriate to the structural unity of the surface.

The Turlit bus station provides an example of the serious expressive change that can occur because of elements that seem unimportant. Offices and a cafeteria were situated on the second floor of the station. The corresponding mezzanine was used as a tension tie in order to restrain, at the middle of the pillars, the thrust of the vaults. At the same time, these pillars could be used to support the mezzanine. This combination of uses could result in a lack of expressive clarity. This problem was to have been resolved by joining the mezzanine beam to the column with iron connections, which were made from two lengths of channel iron forming a box beam. These were the beginnings of the mezzanine's concrete beams, of which the outermost two were to support, in addition, the thrust of the vaults transmitted to them by the pillars. As a result, the concrete mezzanine appeared to be separated from the vaults' pillars. Due to negligence, the distance between the concrete facing of the mezzanine and the pillars was not respected and, in addition, the clear intention for formal precision was distorted when the mezzanine and pillars were covered with plaster (the concrete was to be left exposed). Furthermore, the pillars had a width of 25 centimeters where they joined the vaults, which was the result of the channel created by a band of two bricks. When the pillars were covered with plaster, this precision of form was lost. When the extreme pillar was covered with plaster, its expressive form was radically changed, and it became crude and heavy. The final result was a decrease in expressiveness and a quite distressing level of quality. I would like to point out that our contract was limited to the design for the structure and the construction of the vaults. The rest of the structure was built by a local businessman, and the errors that I have referred to are due to the fact the architect that oversaw the construction could not fulfill his obligations during the final phase of the project. To whoever thinks that the insistence on the precision of forms and dimensions is a kind of obsession and that these errors are not perceived by those who will use the structure, I would respond, as I did once a long time ago, that the difference between a long and short nose is only millimeters.

Form is a language, and this language should be intelligible to us. We are anxious for intelligibility and therefore for expressiveness. Part of modern anxiety is due to the absence of legitimate expressiveness. It is also due to the hermetic inexpressiveness of the things that surround us. This is the negation of the fraternity that we take for granted and should be naturally perceived in man's work in the space that surrounds him. The void of legitimate expressiveness is filled with refined or vulgar adornments that do not satisfy. In advertising, this void is filled with forms that fraudulently use studies in painting and sculpture from the last decades (someone with the necessary preparation will have to write about the use of cubism and surrealism in advertising). Furthermore, what we build will always be expressive. When our work does not communicate something to us because of inscrutability or carelessness, it expresses a deficiency that does not have the dignity of silence. Modern society is sick from the absence, savagery, and stupidity that occupy the place that our negligence has left empty.

There are many building projects that are important in themselves and because of what they will mean for the landscape. The only concern evident in these projects is what is technologically efficient. They do not show the slightest concern for how these structures might enrich our lives if they expressed the complex functions of what we do and if their principal function were legible.

For example, a microwave tower is something that is full of content. All of the richness of human life passes through it. Its membranes are like ears or mouths. Let us imagine that in our small cities, full of low houses and expressively neutral, we built, instead of the familiar metallic towers, brick towers similar to the Maldonado

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5 The aphorism is actually from the American author and physician Oliver Wendell Holmes (1809–1894), in chapter VI of his *The Autocrat of the Breakfast Table* (Boston: Phillips, Sampson & Co., 1858). Holmes does not ascribe the paradox to any particular people or class. G. K. Chesterton, in the chapter "Dickens and Christmas" of his *Charles Dickens* [(London: Methuen, 1906), 127], only credits a "Boston paradox monger" and provides the text as follows:"'Give us the luxuries of life and we will dispense with the necessities.'" He introduces the paradox with an observation that the poor do not neglect special festivities but then says it applies to the entire human race. In the chapter "An Approach to Thomism" in Chesterton's *St. Thomas Aquinas* [(London: Hodder & Stoughton, 1933), 172], the quotation is identical and specifically ascribed to Holmes but now adduced simply as a good example of a paradox. The Spanish translations of these books render the saying differently; congruencies with Dieste's formulation suggest that Dieste's source was Chesterton's

television tower. The receiving (or "ear") membrane and the transmission (or "mouth") membrane could express their functions so that, with the same efficiency, the meaning of something that is so important in our lives could be perceived in space. I do not believe that the tower that I am proposing would be more expensive than the towers that are usually built. Perhaps with good guidance, the local bricklayer could build the tower, which would be another advantage. If the expressiveness of the density of human existence were embodied in everything that we see, our lives would be greatly enriched, and our quality of life would be incomparably better.

In order for expressiveness to be authentic, it cannot be gratuitous. The first principle is the consistency of what we build with the laws that govern matter in equilibrium. That is why it is logical that we build a structure to accommodate the stresses that it must resist. This is what nature does in its age-old and extremely subtle process of adapting the form to suit the function. However, when this process of adaptation is attempted by man, it does not always produce economies, at least not economies that are in line with a primal analysis.

In the pre-stressing equipment I designed and built, the lateral sides of the two U sections were reduced to adapt its form to the moments. Here, the intention was more instinctively expressive than a simple rational response to the need for resistance. I can affirm that when the equipment is assembled and in use, it has the quality of an abstract sculpture. Does this have any meaning or importance? I believe it does. I also believe that the person using this equipment unconsciously feels this just as I did when I built it.

When I speak of costs I am referring to the immediate costs, the construction costs. A more precise evaluation would measure the value of a structure in thirty or forty years. This evaluation would measure the benefits of seeing something that is elegant and expressive instead of something that can be equally efficient but less elegant, more mundane and less a source of inner strength, because it is less intelligible. When faced with incompetence and a false realism that believes that the only thing that matters is remorseless efficiency, we should remember the biting irony in the statement by G. K. Chesterton (1874–1936), "The people have always said, give us the superfluous and we will do without the necessities."[5] The superfluous, in this case, would be expressiveness and elegance, which respond to profound human aspirations that are full of meaning. In this sense, the superfluous will always find its way into our lives, even if it does so in a sordid or furtive manner.

Formal coherence and essential expressive adaptation are not valid in themselves, since they only comprise the ethical response to the problems that our work in space tries to resolve. They are like a preparatory school, and only with this school as a basis will a dynamic art be able to flourish. Without the revelation of the world's mystery, which gives us art, we will never be able to make anything really humane out of our lives.

The earliest version of this essay known to the editor is "La conciencia de la forma," in Galaor Carbonell, ed., *Eladio Dieste: La estructura cerámica*, Colección Somosur (Bogotá, Colombia: Escala, 1987), 185–92. *Ed.*

Dickens, as one might also expect from Dieste's ascription of the saying to "The people." Dieste also quoted Chesterton in his essay "Architecture and Construction" (see page 190, n. 5 of this volume).

G. K. Chesterton was a British poet, artist, playwright, essayist, and Catholic apologist in the first half of the twentieth century. At midcentury, Chesterton was very popular in Argentina, notably through the defense of his writings by Jorge Luis Borges. Ten of Chesterton's works were translated in a popular paperback series published in Buenos Aires. Chesterton was a friend and collaborator of the French-born, British Catholic poet and essayist Hilaire Belloc (1870–1953), whom Dieste references in his essay "Art, People, Technocracy" (see page 196 of this volume).

In personal communications, Antonio Dieste, a son of Eladio, confirms that numerous works of Chesterton and Belloc were in the Dieste library. Chesterton and Belloc invented a political philosophy they termed "Distributism," an anti-monopolist position that entertained various methods for the diffusion of capital. That Dieste, in these essays, cites only these two authors strongly suggests that he was sympathetic with their simultaneously Catholic and anti-capitalist position, which honored workers and those of limited means. (Dale Ahlquist, president of the American Chesterton Society, identified the possible sources for this quotation by Dieste. Arturo Villarrubia, a Chesterton expert in Madrid, provided information on the Hispanic appreciation of Chesterton. I am indebted to Carroll William Westfall and Ricardo Arosemena of the University of Notre Dame for checking the Spanish translations.) *Ed.*

ART, PEOPLE, TECHNOCRACY

Eladio Dieste

Some friends, whose opinions on the most important issues I share, differ with me when it comes to art. They talk as if art were just another luxury in a society sick with injustice and disorder. This is a misconception, but it is a congenial misconception. It is a reaction against the people who talk about art—people who believe art to be a less vulgar substitute for expensive perfumes and pedigree dogs.

Although art and good taste are very different things, for these people, art is the last and least important component of good taste. It is not easy, nor is it important, to define good taste. Nevertheless, permit me a definition that is valid for my particular limitations. I would say that it is the taste of that part of the upper class, sufficiently old and much better if it is already poor, that has done many different things in the course of its family history—the majority of which have been futile—and has developed a certain indifference toward almost all of these things. Certainly, this kind of good taste does not abound in the most familiar and visible aristocracy. Its formula in architecture could be Mies van der Rohe's creed, "Less is more." The definition that I have just given applies to one of the current styles of good taste, not to all styles nor to all time periods (remember the style at the end of the eighteenth century). At this point in time, this idea encourages a search for principles that have real value. One of these is the awareness of beauty in elemental and everyday things. Our world has acquired this awareness, I would hope definitively, through the influence of the modern architecture movement. For a tapestry to be more beautiful than a wool palliasse, the tapestry has to be very good. Many people prefer, and with good reason, a rough hospital cloth over almost all the elaborate fabric that is produced. It is difficult to make anything more surprisingly beautiful than a hammer, an axe, or a grafting knife. Their forms express with precision a given relationship with reality that is direct and decanted by time.

> Let us not make more out of good taste than it is. What really characterizes good taste is refinement combined with the desire to distinguish oneself, and for this purpose it often makes use of the human grace that gives life to the craftsman's hands.

Art is a different thing. It is the expression of man's awareness of his being and of the world. It is an awareness that, when it is intense, is always fleeting and is an expression that is mysterious even in the arbitrariness of the ways in which it manifests itself.[1] Bad taste can coexist with art. Quite often, the formidable artistic genius Gaudí did not have good taste. In his best works and in the essential moments of the others, a certain motley and cumulative heaviness disappears, and the light shines bright without shadows to obstruct it. The modest people that created the hammer and the grafting knife had good taste that transcended itself; they also had other qualities that are much more valuable, like innocence and a fresh appetite for the flavors of the world. From these qualities comes their baroque style, in the common sense of the word, not the architectural meaning. These qualities also foster their taste for adornment and decoration and the ease with which they are deceived by those that make commerce with their innocence and their respect for culture, using the prestige of long words to overwhelm them. For those of us who think it is important that good things reach everyone, it is important to know if modest people are indifferent to art. If this were irreparably the case, then it would not concern us so much anymore. I believe that they are indifferent to good taste that is nothing more than a passing fashion because they are not concerned about the game of those who want to distinguish themselves. They are concerned about tradition, a true and vivid tradition, rather than the one that the traditionalists talk about, which is an empty shell. What about art? If art were absent, would modest people be aware of its absence? Are they aware of its presence when so many signs seem to indicate the contrary?

In another place, I explain the conscious story, which is quite complex, of the things that guided me in the Atlántida church project. On the canvas that is this story, the soul embroiders obscure things for itself that almost always emerge painfully in the space, and because of this pain, have remained etched in the spirit. I also tell the story of how I was reassured by the comprehension shown by a very humble woman with her coarse shoes covered in mud. The itinerary that she followed, the places where she paused, the things that she said with complete simplicity and without accolades: these things made me realize that she really was seeing it. She did not see the complex, conscious intentions but rather the shape in which these had taken form. This was not, however, an isolated case.

I remember having attended, with very humble rural people, the moment when the scaffolding was removed from a very complex and audacious structure, audacious but serene. The structure was not important because of its size or cost but because you felt the tension of the effort that had made it possible. This is exactly what one of the men said, that it was not easy to build something like that. The audacity did not produce disbelief or surprise but rather happiness. This man distinguished very well the difference between what is important because of its size and cost and something that touches us in the most profound way because it expresses to us the force that produced it but without feeling that force.

I saw clearly, once again, that in order for something to truly reach modest people it must have a lightness, a mysterious ease, a concise simplicity, something like dance without effort or fatigue. It does not satisfy them, and they are right not to be satisfied, when a difficulty is resolved using blind force or money. They want the problem to be solved with the same effortlessness with which the sparrow hawk stays aloft and each flower in the field, when we really see them, is the center of a mysterious landscape and "not even Solomon, in all his glory, was dressed like one of them."[2] To perceive something in this way shows a penetration that is as delicate as the sweetness that the coarsest hands acquire when they caress the head of a child.

For those who are suspicious of anything that has an emotional charge, I want to clarify something. Like all human deeds that are dense with emotional force, what I have depicted above comes at the end of a rationally well-anchored chain of events. Behind the resolution of a problem that employs blind force and money, there is always the negligence, and behind the negligence there is the disdain or thoughtlessness and superficiality (which are other forms of disdain) of he who does not examine himself. This disdain is definitely contempt for human effort or for mankind itself; here, I think we have touched a common basis, something that we all agree on—the value of mankind. The grace that we demand from art is the flower of effort and energy, which is the opposite of negligence.

I use this example, as I do with those that follow, in an effort to investigate within my own experience whether or not art is important to modest people. For me, this is synonymous with whether or not art is important at all.

One of my childhood friends, Teófilo Ribeiro, was a good musician. He used to play the fugues of the *Well-Tempered Clavier* quite well on the guitar. We went together once to my father's small farm, and I remember how beautiful Bach's limpid music sounded beside the bonfire on those cold July nights. Within a week the farm workers had left their huts and were whistling very well these new songs that we had brought from the town. They whistled them because they liked them. They felt something of themselves expressed in them.

The most conclusive example of the creative capacity of modest people is the marvelous small villages that are something so perfect that there is almost no work of elite architecture that can be compared to them. It is conceivable that one or several geniuses could create something as beautiful as Chartres or the Parthenon again, but it is impossible that someone who is not a whole village of people could create something as marvelous as these villages. They are marvelous but at the same time fragile, precisely because of their innocence, so defenseless against the insolence of money or simply because that same innocence can be corrupted. Of these villages, I remember one in particular that was very close to my father's village and only a little bigger.[3]

The first time that I was there it was the end of summer, but because of the cool and misty climate, the vines that covered the path that lead into the village were still a transparent and tender green, as if it were springtime. The road came out onto a space that was a square and courtyard at the same time; or, in other words, the private space was public. It was surrounded by very old stone houses with windows that seemed as if they had been built from the inside, as we would make our eyes, if we could make them. (Haven't we really made them in the course of many thousands of years in which we attained, until the ages of stone and fire, an ever-increasing reverence for the mysterious center that spiritualizes the world?) From this square-courtyard with its flagstone surface, another street, which was lined with the same kind of houses, connected to another square-patio with a stone cross and a small tavern. In these squares there were several old women, as old as time, spinning wool as they did a thousand years ago. There was not even one tree; only stone, sky, and clouds. It was a landscape totally recreated by architecture with an unforgettable beauty and extremely modern. Everything that modern architecture was searching for was realized there. I thought with horror about the fact that the desire to correct the deficiencies, such as the sanitary system, of a village like this one would ruin this amazing masterpiece of architecture.[4]

Here, I would like to bring up another idea. Modest people have historically placed more importance on beauty than on the primary

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[1] I believe that this is what Aristotle wanted to express when he said that "the form is the soul of things."

[2] Matthew 6:28, 29. *Ed.*

[3] Antonio Dieste explains that Eladio Dieste's father was born in Uruguay but lived several years in Rianko, a small village near Santiago de Compostela in northwestern Spain. *Ed.*

[4] Years after writing this, I visited the town again and found that this marvelous place had been destroyed "by the defenseless innocence of the people against the power of money" and by the very human aspiration to liberate oneself from "corporal servitude."

[5] For more information on Belloc, see page 192, n. 5 of this volume. *Ed.*

[6] Matthew 6:33. *Ed.*

commodities that so obsess the modern world. The sanitary deficiencies that are referred to are obvious. I am not opposed to overcoming them. On the contrary, I believe that the modern aspiration to liberate man from corporal servitude is very noble and humane. I would simply like to point out that the focus of popular concern has always been directed at the most noble things. They are more concerned with proportions than bathrooms. In a way, this does make good sense. We always have proportions present in our lives, but we only spend a few short minutes in the bathroom.

We also have unexpected examples of this in the city, among us. Many years ago, during a project I directed, there was the risk that some old and poorly constructed houses would be adversely affected by the work that we were doing. The houses were rented by the room—one of our old tenement houses. I went to speak with the tenants to propose that they go to a hotel for a few days until the dangerous part of the work was finished and we had repaired the damages that had already been caused. Many of the rooms were quite cozy, but there was one in particular in which an extremely gracious little old lady lived. It was a marvel of spatial organization or, we could say, architecture. The shelves, the tables, the rocking chair, all seemed to extend her already trembling arms and knotted and wrinkled hands. She had the touching beauty that a life of work gives human beings. The room and everything in it had taken shape around and through her. As a consequence, the space was ordered in a very humane and beautiful way.

Knowing how to look beyond deceptive appearances, I would say that all of my experience tells me that people make art if you let them. They are sensitive to art and would surely be much happier if our cities, villages, and even our countryside were more humane, more like the little old lady's room. When we say "countryside" or "nature," we should know that it is man that permits us to see, contemplate, and understand these spaces. In the almost lunar plains between Cuzco and La Paz (as a whole, this is probably the most spectacularly beautiful thing that I have seen on earth), there is the vibrant presence of the Indians. On the train, from far away, they look like little ants. Then suddenly, they straighten up and look at the train that is carrying us and passes by. The Indians are like a flash of lightning that illuminates your soul. Only then, the vision, like an arrow, penetrates into the abyss of contemplation, and we see as never before. We see the yellow plain, the mountain peaks covered with snow, and the motherly affection that pulsates for us in the earth.

Let us leave the modest people and move on to those that control the world. It has been an unexpressed but vaguely felt desire of all aristocrats that there should be human archetypes of behavior and lifestyle, and they designate themselves to embody them (except for great men like Ortega in deplorable moments of weakness that it is better to forget). The payment for this is to eat better and to receive better treatment. In great moments of innocence or of great tension, like revolutions, these archetypes are produced. They are archetypes because they are created by the weight of the community, encouraging them and making them into their voice and their expression. When complexity and the lack of essential well-being in human relations cause these archetypes to become weak and nebulous, it is more difficult for them to be exemplary virtues and those that really have some force. It is most likely—we see this all the time—that a base shrewdness will take its place. Now, it is almost exclusively among the poor that magnificent, noble, and exemplary expressions take refuge. These are expressions of an aristocracy but in the etymological meaning of the word—more authentic than the aristocracy of sauces and perfumes. It is not, however, in the hands of the people but rather in the hands of the bourgeois elite that is spawned what we usually call aristocracy (Belloc said that the aristocracy is old wealth[5]) and the manipulation of art that we find among us. The result is as radically miserable and inhumane as the society that adopts it. It is these pseudo-aristocrats of today that have made our cities so ugly with museums full of beautiful paintings, our jarring streets, and our concert halls. This concern for art would be more logical and humane if it had a more general, less specialized character. Our societies are less and less popular and democratic. They are more and more controlled by technocrats, those gentlemen who think about everything except what is important. They make big decisions that have nothing to do with the final objectives of mankind. They do not consider these objectives because, in most cases, they are extremely cynical or politically pessimistic and, in general, are being paid by those who have no interest in considering these issues. The worst kind of aristocracy is the elite that believes that its preeminence is justified and is based on something serious like science rather than on trifles like sauces and perfumes. I have found among them a curious aberration: a certain horror at the idea that beauty is present in our lives. For them, the only option is for the world to be ugly and sordid because that is what is efficient, that is what works, and from this sordidness we can make a lot of money to buy paintings for the museums and music for the concert halls. What I am saying could seem a bit exaggerated, but, unfortunately, I have examples. Two years ago, I had an argument with a colleague who had decision-making power in the choice between two alternative proposals for a bridge. The project that he insisted on defending was more expensive without being any safer, but since it was uglier and unwieldy he supposed that it had to be more efficient. On another occasion, I proposed a structure for a steelworks. It took all the patience I had to counter the objections that were made until we reached the heart of the antagonism. In some way, they thought that it was immoral to build something that they felt was "not ugly" for a steelworks. They were suspicious of a concern for beauty. They felt something that was inexpressive, cold, and, as a consequence, ugly would be the safest. Without meaning to, they had created a new Moloch, which was no less sinister than the original. This new Moloch was meant to efficiently crush the people for their own good, and later they would receive good dividends.

Another time, when I was finishing a factory building with sawtooth vaults, I tried to convince the decisionmakers to put clear glass in the skylights. It was beautiful to watch the clouds go by and even a few seagulls, as we were not far away from the ocean. I was not successful. There were various objections, but the essence of them all was a dark fear that the beauty and grace of the world would become part of our lives. Even though they were shocked by this idea and complained that this was not at all what they were suggesting, everything that they had said suggested that life's grace and beauty should be isolated and stratified into levels of quality that become lower and lower as we get closer to the poorest classes. Does this have any justification, or for that matter, is it even efficient (although this kind of efficiency, if it existed, could not be justified)? Of course it does not. The worker who lifts his head from what he is doing and sees the clouds pass by or the marvelous security and grace of a bird in the air will not be as tired and will acquire in this contemplation new energy. In the end, he will produce more. In a hierarchy with appropriate intentions, all of this should be a reality, not intention. ("Seek first the kingdom of God and his justice and all these things shall be added unto you."[6]) They should make sure that everything is noble, appropriate, and elegant because this is what sustains man, what makes him. However, since their hierarchy of values is erroneous, they never seem to get it right.

In summary, the experience that I have had in my contact with modest people has shown me that they have a desire for contemplation (as all men do, because they are men). This desire is satisfied and nourished by the works of society and its individuals in the space that surrounds us. In the same way, my experience with the elite that governs us has shown me, in general, a mitigation of this noble desire, a lack of understanding for the importance of art for human happiness and, as a consequence, for its practical value. I have given examples that might be a bit extreme, but in order to see that what I am saying is essentially true, all we have to do is to look at our city or any other city. The spirit only rests in old things, in things that have been abandoned by "living forces," that seem to have become more human with the passing of time. However, this is not the vital and abundant expression of the mystery of the world in space, which is so important to a really humane existence.

> Nobody denies a kind of beauty to today's big cities. New York is beautiful; Buenos Aires is also beautiful. Everything human has an indestructible beauty. Mankind is expressed in these enormous urban areas. Nevertheless, what a difference there is between what they are and what they could be! What a contrast between their broken and frustrated appearance (redeemed only by the evening's sweetness, the sky's limitless depth, the tree's strength, the dove's grace) and what they should be—the home of mankind!

These lines do not suggest mistrust in the future of our civilization. On the contrary, there is nothing essentially inhuman. There is humanity in large urban centers and even in industrialization. These are paths that we have to follow to the end, but we should not take a single step that we can avoid, that is not guided by the principle that we all say we believe and yet betray all too often. We should be guided by an awareness of the dignity and value of mankind and its mission to make the earth a more humane place, to make the earth man's true home.

It is not easy to have a clear image of the goal. On the other hand, it is much easier to have a clear image of the foundations and principles that will shape that goal. This is why the idea that "the ends justify the means" is a drastic mistake. We do not know what the end will be. We have an image of our goals, but these will never be realized if in our actions we betray the principles that will shape and form these goals. We cannot postpone for the future city the beauty and dignity that we need so badly to endure the severities of life. We cannot postpone them as principles even though we might have to compromise in practice. When we have no other choice, we will have to compromise, but we should always continue to try to achieve the principles that will shape the goal, our future.

In this battle, as in all battles, we are sure that, through errors and ignorance that are certainly no greater than the mistakes and ignorance of the ruling elite, modest people will always come out on the winning side.

The earliest version of this essay known to the editor is "Arte, pueblo, tecnocracía," in Galaor Carbonell, ed., *Eladio Dieste: La estructura cerámica*, Colección Somosur (Bogotá, Colombia: Escala, 1987), 195–200. *Ed.*

RESEARCH AND PRACTICE IN REINFORCED AND PRE-STRESSED BRICKWORK AND THE PLACE OF DIESTE WITHIN IT

Remo Pedreschi and Braj Sinha

Eladio Dieste's work suggests a new paradigm for the use of traditional materials, a change in perception, and an expansion of possibilities. His work is exceptional in the history of structural brickwork. Overlapping with the period when Dieste was building, between 1943 and 1996, there was a general re-examination of the potential applications of structural masonry, mostly in Europe and the United States but ultimately worldwide. A sizable community of academics and engineers conducted research and developed many aspects of structural masonry. By and large, this community was unaware of the remarkable accomplishments of Dieste in South America. A review of the research and practice in reinforced and pre-stressed brickwork during the twentieth century may provide a further perspective on the work of Dieste and the nature of his innovations.

Although research on reinforced brickwork was in evidence for most of the twentieth century, various publications suggest that the major resurgence of interest in brickwork as a contemporary structural material started in the late 1950s in Switzerland.[1] Innovative tall load-bearing unreinforced brick structures were constructed using thin, engineered brick walls. Apartment buildings up to eighteen stories were being constructed with walls between 5 and 10 inches in thickness. The thinness of the walls was determined by rational structural analysis and substantive material tests. (Prior to this, load-bearing walls were designed largely by empirical methods; brickwork buildings taller than four or five stories were uneconomical and, by this time, had been superseded by steel or concrete frames.) A research community was stimulated. Many programs were initiated to develop the use of masonry in multi-story applications and to provide the necessary input into national building codes. These structures used the high compressive strength of masonry in an appropriate manner.

As the structural properties of brickwork became quantifiable, further applications were considered. Brickwork shares characteristics with concrete: it is brittle, but strong in compression. Could brickwork be used in beams, where tension occurs? Concrete deals with tension by either reinforcing or pre-stressing. Thus there was a progression in the interest of researchers and engineers toward the use of these techniques in brickwork. This appendix concentrates on the application of reinforcing and pre-stressing to primary structural elements rather than the use of reinforcement to improve earthquake resistance of masonry buildings or in secondary elements such as lintels. Developments in reinforced and pre-stressed brickwork are considered separately.

The Development of Reinforced Brickwork

The earliest recorded application of reinforced brickwork is attributed to Marc Isambard Brunel (1769–1849) (Beamish 1862). In 1825, during the construction of the Thames Tunnel, Brunel used wrought iron rods and hoops to strengthen two large brick shafts. The shafts, 49 feet in diameter and 43 feet in height, were sunk into the ground by excavating from inside the shaft. The reinforcement proved effective. Despite uneven settlement there was no cracking in the shaft during the lowering operation.

In 1837, Pasley (Marchant 1965) carried out experiments on unreinforced and reinforced brickwork beams. His results showed that the flexural strength of brickwork was increased many times in beams with reinforcement. Pasley used his results to develop an empirical procedure for structural design.

In the early part of the twentieth century, there were a few notable and substantial experimental studies in reinforced brickwork, by Brebner in 1919 in India and later Fillipi in the U.S. and Kanamouri in Japan. In 1923 the Public Works Department of India published the results of 282 tests on beams and slabs carried out by Brebner (1923). The tests confirmed that the behavior of reinforced brickwork was similar to that of reinforced concrete. He also tested brick columns with lateral and longitudinal reinforcement—columns with square, circular, and fluted cross sections, with longitudinal reinforcement varying from 0 to 1 percent of the cross-sectional area of the column and up to 6 percent lateral reinforcement. The longitudinal reinforcement did not significantly increase the strength of the column but the confining effect of the lateral reinforcement increased the strength by up to 36 percent and 62 percent for the circular and square columns, respectively. The results of the research were applied in a large building program in the state of Bihar in India: 279,000 square meters of building were constructed.

In Japan, Kanamouri's researches into the structural behavior of reinforced brickwork led him also to conclude that reinforced brickwork behaved in a manner similar to reinforced concrete. However, he also found differences: the modular ratio[2] was higher: 25 for reinforced brickwork compared with 15 for concrete. His work also demonstrated the increase in strength that the addition of steel reinforcement provided. The strength of a reinforced brick structure could be increased fourfold by incorporating up to 0.3 percent by volume steel reinforcement. This work supported the use of reinforced brickwork in retaining walls.

In the U.S., Fillipi (1933) published the results of tests on reinforced brick slabs and beams. He compared the results with the requirements of the Chicago building codes of the time, demonstrating that the deflections of reinforced brick structures were less than the maximum allowable, and further, that even when loaded to 1.5 times the design load, the recovery of deflection was around 80 percent.

During the period 1922 to 1935, a number of academic institutes in the U.S. became interested in reinforced brickwork. Whittemore and Dear (1932 and 1933), of Virginia Polytechnic, reported tests on thirty reinforced brick slabs, each 95 mm thick and using a 1:1:6 (cement, lime, sand) mortar. They compared the results with tests on similar reinforced concrete slabs. The reinforced brick slabs exhibited considerable ductility, had an adequate reserve of strength over the working load, and could be designed using principles similar to those for reinforced concrete.

Parsons, Stang, and McBurney (1932) studied the shear strength of reinforced brickwork, an area that a number of researchers would consider later. They tested eighteen beams, using two different formats of brick with steel reinforcement equivalent to 1 percent of the cross-sectional area. The shear strength obtained from these tests varied from 65 to 159 lb/in^2. They also studied more detailed aspects of behavior of reinforced brick beams, such as the strength of the brick/mortar interface and the bond strength between brickwork and steel reinforcement.

Withey (1933) presented the results of tests on twenty-five beams, with percentages of steel reinforcement varying between 0.5 and 2.5 percent. Shear reinforcement was incorporated in all of the beams. The research identified different modes of failure in the beams depending on the quantity of reinforcement, both over-reinforced and under-reinforced.[3] Three beams with a high percentage of steel were over-reinforced and failed by crushing of the brickwork rather than yielding of the steel. As with earlier researchers, Withey's results showed that calculation methods similar to those for reinforced concrete could be applied to reinforced brickwork.

Lyse (1933) tested thirty-three reinforced brick columns. The reinforcement was incorporated into a central core filled with concrete grout. The percentage of steel used varied from 0 to 2 percent for columns with mild steel and 0 to 0.675 percent for columns with high-yield steel reinforcement. Varying percentages of lateral steel reinforcement were placed in the bedding courses of the columns. Withey (1935) carried out a similar program of tests on thirty-two reinforced brick columns, varying the percentage of longitudinal and lateral reinforcement. The results of both researchers showed that reinforced brick columns behaved quite differently from unreinforced columns. Unreinforced columns failed in a brittle manner, while the failure of reinforced columns was initiated by vertical cracking followed by spalling[4] of the brickwork. The incorporation of lateral reinforcement helped to confine the longitudinal reinforcement, improving the structural behavior.

These early investigations demonstrated the ductility of reinforced brickwork. In the area around San Francisco, many buildings built in the 1930s used reinforced brickwork to improve resistance to earthquakes.

Hamman and Burridge (1939) conducted experiments on over-reinforced brickwork beams with substantial amounts of shear reinforcement. However, even with high levels of shear reinforcement most beams failed in shear rather than flexure.

In the United Kingdom, Thomas and Simms (1939) of the Building Research Station U.K. conducted a series of comparative tests on reinforced brickwork and reinforced concrete beams. Both sets of beams had the same cross-sectional areas and the same percentage of steel reinforcement. Tests were also conducted on beams with higher percentages of steel, with and without shear reinforcement. Both brick and concrete beams with low percentages of reinforcement demonstrated almost identical behavior with similar deformations and strengths. This was not surprising, as failure was determined by the steel yielding rather than by the strength of the brickwork or concrete. In more heavily reinforced beams, the failure mode changed from steel yielding to shear, indicating the weaker shear strength of brickwork.

To economize in the use of steel during World War II, reinforced brick columns were used in the construction of single-story

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1 See A. W. Hendry, *Structural Masonry* (Basingstoke, England: Macmillan Education, Ltd., 1990); Brick Industry Association, *The Contemporary Bearing Wall*, technical note no. 24 (Reston, Va.: The Brick Industry Association, 2002); and H. W. H. West, "The Development of Masonry," opening address to the Eleventh International Brick Masonry Conference, Shanghai, 1997, published in *Masonry International* 11, no. 3 (1998): 65–67.

2 The modular ratio is the ratio of the elastic modulus of steel to the elastic modulus of concrete or brickwork. It is a measure of the relative compressibility of the material. The greater the modular ratio, the more easily compressed the material compared with steel.

3 Under-reinforced beams fail by yielding of the steel and are characterized by large deflections and cracking. Over-reinforced beams fail by crushing of the brickwork or concrete *prior* to yielding of the steel. This type of failure is sudden, sometimes explosive, and thus considered undesirable.

sheds. Davey and Thomas (1950) reported on tests of eccentrically loaded columns. The columns were subject to both axial compression and bending. High stresses in both steel and concrete were reported.

Chambers and Schneider (1951) considered the effect of workmanship and other factors on the strength and behavior of reinforced brickwork. The research showed that the strength and behavior of reinforced brick structures are considerably influenced by workmanship in construction. Beams with careful construction, even with weaker mortar, were stiffer and stronger than comparable beams with stronger mortars but less care in construction. The strength reduced on average by 30 percent due to the effects of workmanship. Their research also demonstrated that the incorporation of shear reinforcement increased the shear strength of reinforced brick beams.

In the U.K., Bradshaw (1963) constructed a series of demonstration structures. Simply supported beams and slabs, cantilever beams, and stair treads were designed in accordance with the relatively limited guidance of the then current British Standard (BSI, 1948). Some of these structures sustained loads twenty times greater than the calculated working load. The research demonstrated very clearly that reinforced brick structures could be designed safely; however, it also showed the inadequacy of the simple elastic methods used in the British code to predict the load-carrying capacity.

Johnson and Thomson (1969) studied the effect of beam shape and the use of high-bond-strength mortars on the shear strength of reinforced brickwork. A total of twenty-two beams were tested. The high-bond-strength mortar produced much better results, with higher shear strengths than beams using normal type M mortar.[5] The tests also demonstrated the influence of the ratio of shear span to effective depth on the shear strength of the beams.[6] As the shear span to effective depth ratio increases, the shear strength decreases.

Anderson and Hoffman (1969) considered whether the method of calculating the ultimate load of reinforced concrete columns proposed by the American Concrete Institute (ACI) could be applied to reinforced brick columns. A series of load tests were conducted on rectangular brick columns 12 by 16 inches in cross section. The reinforcement was placed within a central cavity filled with concrete grout. Horizontal stirrups were incorporated in every third course of brickwork. The columns were subjected to axial and eccentric loads. The project confirmed that the ACI method of design is applicable to reinforced brickwork. They also suggested that further research was needed to take more accurate account of the stress-strain characteristics of brickwork and the effect of varying percentages of steel on strength.

In summary, most of these early studies were concerned with three issues:

> To demonstrate that reinforced brickwork was similar in behavior to reinforced concrete; namely, that the reinforcement adds ductility to brickwork
>
> To develop empirical design procedures
>
> To develop design procedures based on elastic methods of analysis

From the 1970s onward, research was directed toward a more detailed study of shear strength and the development of ultimate load analysis techniques, mirroring the shift in design philosophy taking place in reinforced concrete from an allowable stress approach to ultimate load methods.

Suter and Hendry (1975 a and b) studied shear strength by testing twelve reinforced brick beams. The shear span to effective depth ratio varied from 1 to 7. Two different percentages of steel reinforcement were used: 0.24 and 1.46 percent. Based on their results and the work of other researchers, Suter and Hendry proposed that the characteristic design shear strength of brickwork should be 0.35 N/mm^2 ($51 lb/in^2$), applicable for beams with a shear span to effective depth ratio of 2 and greater. In contrast to the design of reinforced concrete, they further proposed that there should be no increase in characteristic shear strength for increased areas of primary tensile steel.

Suter and Keller (1976) compared the shear strength of reinforced brick beams using different methods of construction. Beams were constructed using grouted cavity construction; reinforcement was placed in a cavity created between two skins of brick that was subsequently filled with concrete. These beams are in effect a hybrid brick-concrete construction. The other form of beam incorporated the reinforcement within thickened bed joints. Their results showed that the shear strength of the grouted cavity beams was greater than beams with bed-joint reinforcement but less than similar reinforced concrete beams. They compared the results with tests on reinforced concrete beams (Kani 1966) and suggested that the shear strength of grouted cavity beams could be calculated by adding the separate shear strength components of the brickwork and concrete core, taking due account of the relative thickness of each section.

In addition to a concern for shear, researchers were interested in the prediction of the ultimate flexural strength of reinforced brick structures and, consequently, the correct assessment of the compressive strength of brickwork in flexural compression. It was known that the compressive strength of brickwork is quite different from the compressive strength of either the brick or the mortar that constitute the brickwork (Hendry 1990). Brickwork is anisotropic in nature—the strength is influenced by the direction of the applied force in relation to the bed joint. Therefore, in flexural applications the compressive strength within the beam is different from the compressive strength in a conventional axially loaded wall.

Maurenbrecher et al. (1976) conducted tests on a series of reinforced brick retaining walls. The walls were constructed in both grouted cavity and Quetta bond formats. These tests were used to study different methods of calculating the ultimate load. The percentage of steel reinforcement varied between 0.33 and 1.78 percent. With low percentages of steel, failure of the walls occurred by steel yielding. Increasing the percentage of steel (from 0.33 to 1.78 percent) increased the strength fourfold. The experimental results were compared with the recommendations of the then current British building code for structural masonry, CP111: 1970, based on elastic methods. On this basis, using the recommended allowable stresses indicated that the factors of safety varied from 3.4 to 8.4. Replacing the allowable stresses of the code with allowable stresses obtained directly from small-scale tests on the actual brickwork used in the construction of the walls resulted in more uniform and acceptable factors of safety, from 2.8 to 3.2.

Research by Sinha (1979a) confirmed the inadequacy of the British structural brickwork code CP111. He tested a series of twelve grouted cavity brick slabs. Various methods of analysis were used to predict the ultimate strength. The current code was again found to considerably underestimate the ultimate strength of reinforced brickwork. A method following Zegler (1970) was proposed, which predicted the shear strength of the slabs accurately.

Sinha (1981) later proposed a method of predicting the flexural strength of brickwork, based on the stress-strain characteristics obtained directly from tests on brickwork prisms. A mathematical model was developed, assuming either a cubic polynomial or a curvilinear shape for the stress-strain relationship. Both models accurately predicted the strengths obtained from tests on brickwork beams.

Sinha (1982) presented the results of a further series of tests on the shear strength of grouted cavity beams and slabs. A comprehensive program was reported that considered the following variables: shear span–effective depth ratio; percentage of reinforcing steel; brick strength; mortar grade; and the effect of shear reinforcement. The results showed that thin wall sections have greater shear strengths than beams, that increasing the percentage of tensile steel increased the shear strength, and that shear strength is unaffected by brick strength and affected only to a minor degree by mortar grade.

Edgell et al. (1982) reported tests on four reinforced pocket-type retaining walls.[7] The percentage area of steel varied from 0.28 to 0.92 percent. Failure of the walls was due to steel yielding. The results were compared with the recommendations of the draft code of practice (BSI 1985).

In the same year, Appleton and Southcombe (1982) and Garwood and Tomlinson (1982) reported on separate experimental projects on reinforced grouted cavity beams. The aim of both studies appears to be a comparison of the provisions of the draft code of practice for reinforced and pre-stressed brickwork (BSI 1985). Both groups of researchers reported anomalies with the draft code. The working load and ultimate moments were underestimated by the draft. Appleton and Southcombe also found differences in the actual measurements of compressive zones and those suggested by the code. Garwood and Tomlinson suggested the use of lower partial safety factors to obtain more realistic design moments for the test results. Such calibrations with draft codes are inevitable, however; the most accurate predictions could have been obtained using the actual physical properties of the brickwork from small-scale tests on brick prisms, a procedure also allowed in the draft code.

Tests by Tellet and Edgell (1983) on a series of reinforced pocket type retaining walls showed that these types of wall conform to the same effect of increasing shear strength with decreasing shear span-to-depth ratio.

Hendry (1984) reviewed the research on shear in reinforced brickwork beams and found differences in behavior between beams where the reinforcement was surrounded with mortar—in the bed joints, for example—and where the reinforcement was surrounded by concrete, in grouted cavity construction. His analysis helped to explain the differences in the results from different researchers. In

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[4] Spalling happens when the outer surfaces of the column break away from the core of the column.

[5] Type M mortar has the following mix proportions: 1 part cement, 1/4 part lime and 3 parts sand, with a minimum compressive strength of 2,500 lb/in^2 at twenty-eight days.

[6] The shear span is the section of a beam span where shear dominates over bending stress. For a uniformly distributed load on a simply supported beam, the shear span is the first quarter of the span measured from each end. The effective depth is measured from the uppermost compression fiber to the center of the primary steel reinforcement. The section of the beam below the reinforcement is not considered to contribute to the flexural strength of the structure.

[7] In pocket-type walls, the reinforcement is placed in a "pocket" in an otherwise solid brick wall. Once the reinforcement is in place, the pocket is filled with a concrete grout.

fig. 253: Examples of reinforced brick beams:
a) grouted cavity construction,
b) pocket-type construction
c) pocket type, Quetta bond, and
d) bed-joint reinforcement
fig. 254: A typical post-tensioned wall
fig. 255: Examples of pre-stressed brickwork beams (in cross section):
a) unbonded tendon, and
b) bonded tendon

grouted cavity beams, the shear strength is greater due to the additional contribution of the concrete and the more effective contribution of the primary tensile steel. Examples of reinforced brickwork beams are illustrated in figure 253.

Schneider and Dickey (1980) published a comprehensive text on reinforced masonry design covering most aspects of structural behavior and construction. The design of flexural elements is based on elastic methods. The text concludes with a chapter reviewing research on reinforced masonry.

Davies and El Traify (1982 and 1984) studied behavior of reinforced brick columns subjected to bi-axial bending. They produced design charts to determine the ultimate load, taking account of the interaction between bi-axial bending moment and axial force.

Some studies have been carried out on the long-term behavior of reinforced brickwork. Sinha (1979b) and Maurenbrecher et al. (1976) monitored the movements of reinforced brick retaining walls. These tests tended to confirm an earlier study by Disch (1949) that the long-term movements of reinforced brickwork beams were generally less than those of comparable concrete beams. In both the U.S. (BIA 1988) and the U.K. (Curtin 1982), there were some notable applications of reinforced brickwork. In 1957, two 65-foot beams were used to support the roof of St. Hedwig's Church in St. Louis. At just over 10 feet deep and 17 inches wide, the beams were quite conservative in design. Compared to alternative constructions, the reinforced brick beam was considered to be cheaper when the cost of cladding either a concrete beam or steel truss was taken into account. Bradshaw and Drinkwater (1982) described the application of reinforced brickwork in the corporate offices of a major U.K. brick manufacturer, George Armitage and Sons, Ltd. A two-story-high reinforced brickwork frame comprising columns and cantilever beams was built. The frame supported a reinforced concrete roof and floor slabs. The project was intended to demonstrate the application of reinforced brickwork.

This latter period of research concentrated on a rational and comprehensive understanding of the structural behavior of reinforced brickwork, but was nevertheless still concerned with the comparison between and substitution of brickwork for reinforced concrete frames, beams, and columns. The development of brickwork building codes tended to follow concrete building codes. The strength of reinforced brickwork is very similar to that of reinforced concrete when ultimate failure is due to either steel yielding or brick crushing in flexure. However, the shear strength of reinforced brick is less than that of reinforced concrete and is influenced by factors not apparent in concrete, such as the position of the reinforcement in either a cavity or bed joint. The nature of construction makes it more difficult to incorporate shear reinforcement in brickwork.

Development of Pre-stressed Brickwork

The most comfortable stress condition for a brittle material such as brickwork or concrete is compression, where it is strongest. Reinforcing is essentially a repair that allows a brittle material to crack without collapsing. Reinforcement does not become effective until the brickwork (or concrete) cracks. Pre-stressing induces a more agreeable state of stress, a vaccination that prevents cracking. Although engineers like Eugène Freyssinet developed pre-stressing techniques for concrete early in the twentieth century, the techniques were not applied to brickwork until the second half of the century.

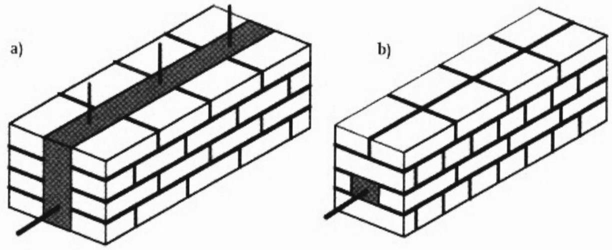
In 1952, Samuely used pre-stressing to stabilize 33-foot-high slender brick piers (Sutherland 1982). There seems to have been little further work until 1963, when Thomas (1969) described tests on two pre-stressed brickwork beams. High pre-stress forces of up to 1,600 lb/in^2 were applied. Plowman (Thomas 1963) followed this work with a program of tests on thirteen beams. In both programs, pre-stressing wires were threaded through small cavities formed by aligning the perforations in extruded bricks. Although there were construction difficulties, the results demonstrated a considerable reserve of strength past the decompression moment, and that the failure mode was flexure rather than shear, which occurred more typically in reinforced beams.

Around this time there was some research (Thomas 1963; Wass and Turner 1969) on the development of pre-stressed masonry floor systems. These systems used extruded clay units. Although these systems were patented, they appear to have had limited commercial application.

During this period there were some interesting applications of pre-stressed brickwork. In 1966 (Sutherland 1982), a 23-foot-high brick wall was stabilized using pre-stressing to increase its resistance to wind loads. The wall was only 10.9 inches in thickness. Pre-stressing avoided the need for piers or buttresses. Foster (1971) designed a 39-foot-diameter, 16.4-foot-high circular water tank. Both vertical and hoop pre-stressing were used. Pre-stressing was also used in the construction of a one-story-high box beam that used concrete floor slabs as flanges and brick walls as webs. The walls were pre-stressed to increase their resistance to diagonal cracking.

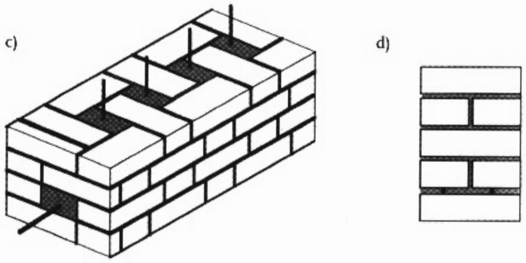
From 1979 onward there was a marked rise in both the research and application of reinforced brickwork. Two different areas can be identified: pre-stressed walls, and pre-stressed beams.

The most common application of pre-stressing to brickwork is in conjunction with diaphragm walls. Vertical pre-stressing is used to



grouted cavity construction

pocket-type construction



Quetta bond:
horizontal and vertical pockets

reinforcement in bed joints

fig. 253

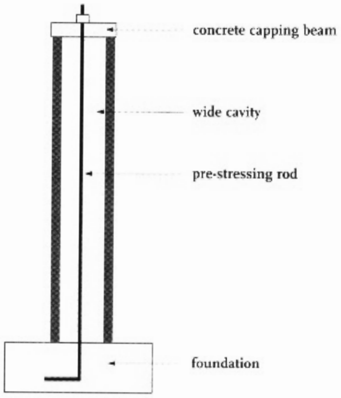


fig. 254

Unbounded tendon
(after Williams and Phipps, 1982)

Bounded tendon
(after Pedreschi and Sinha, 1982)

fig. 255

stabilize tall, single-story walls used in shed-type buildings or as retaining walls. Typically, such walls consist of two wythes of brickwork separated by brick diaphragms (fig. 254). The walls are usually between 17 to 28 inches in overall thickness. Pre-stressing tendons are attached to the foundations and run through the cavity in the walls to a concrete capping beam at the top of the wall. The wall is pre-stressed by tensioning the tendon against the capping beam, using either hydraulic rams or calibrated torque wrenches.

Williams and Phipps (1982) tested a series of six post-tensioned diaphragm walls. The tendons passed through the center of the walls and were unbonded and therefore free to move within the cavity as the walls deflect. By incorporating cross ribs within the walls to restrict the relative movement of the tendon, the strength of the wall was increased.

Curtin and Phipps (1982) tested two full-scale diaphragm walls 24 feet high. They studied the influence of pre-stress on the load to cause cracking in the wall. The pre-stress applied varied from 0–261lb/in^2. Not surprisingly, increasing the pre-stress increased the lateral load that the walls could sustain.

Roumani and Phipps (1985) tested fifteen beams, modeling typical sections of a diaphragm wall. They studied the influence of shear span-to-depth ratio and degree of pre-stress on the strength of the walls. They proposed a relationship between shear span-to-depth ratio and shear strength.

Montague and Phipps (1984) extended the earlier study of Williams and Phipps with a series of tests on twelve concrete block walls. Their study considered the influence of construction details such as the incorporation of a vertical damp-proof course between the diaphragm and outer leaf.[8] The damp-proof course was found to reduce the strength by between 20 and 30 percent. Thus, incorporation of practical construction details necessary for environmental performance can compromise structural efficiency.

An appropriate application of diaphragm walls is in retaining structures for soil or bulk solids. The loads from retained materials are applied in one direction only.[9] A series of research projects by Hobbs and Dahou (1988), Curtin and Howard (1988), Ambrose et al. (1988), and Sinha (1990) reflected this application. All of these projects studied the behavior of walls with eccentric pre-stress force. In most cases the pre-stressing cable was left unbonded. Filling the cavity with concrete grout—bonding the steel to the wall—increases the strength of the walls (Sinha 1990).

Generally speaking, the post-tensioned wall has been shown to be a practical form of construction. Quite a number have been built, either as retaining walls (Shaw 1980; Bradshaw et al. 1982;

Drinkwater and Bradshaw 1982), as tall walls of single-story buildings subject to wind-loading (Curtin et al. 1982; Shaw 1982), or to brace tall walls from the thrust from roofs (Allen 1986).[10] In most cases the level of skill required by the bricklayers was not much different from that needed for conventional building. Indeed, in some of the reported projects, the builders had not used post-tensioning before. Bradshaw et al. (1982) demonstrated that even farmers using agricultural laborers as builders could apply the techniques successfully. Other practical applications include:

> The use of post-tensioned diaphragm walls to support foundations in areas subject to mining subsidence to minimize subsequent damage as the building settled (Shaw 1982)
> The construction of channel-shaped walls (Othick and Priestley 1986)
> The stabilization of tall brick piers (Shaw 1980)

Some studies have been undertaken to consider the potential use of the technology in developing countries (Pedreschi 1994) and in Brazil (Parsekian and Franco 2000).

Pre-stressed Brickwork Beams

The use of pre-stressing in brickwork beams evolved largely from the experience of reinforced brickwork in an effort to improve the shear resistance and reduce or eliminate flexural cracking under working loads. A major difference between pre-stressed beams and post-tensioned diaphragm walls is the level of pre-stress applied to the brickwork. In walls the stresses are generally low, used to counter the effects of wind or retained materials. Pre-stressed beams, on the other hand, are much closer in concept to concrete beams acting as primarily flexural elements with consequently much higher levels of pre-stress. What distinguishes this latter period of research is the depth and scope of the investigations. In a series of publications, Pedreschi and Sinha reported the results of an extensive study of pre-stressed brickwork beams (Pedreschi 1983; Pedreschi and Sinha 1982, 1985, 1992). A total of sixty full-scale tests were carried out dealing with level of pre-stress force, brick and mortar strength, percentage of steel, type of brick, and shear span-to-depth ratio **(fig.255)**.

Beams spanning up to 21 feet and pre-stressed up to 1,087 lb/in^2 were tested. A detailed study of the load/deformation behavior of brickwork using a large number of small-scale tests was carried out (Sinha and Pedreschi 1983) and used to develop a theoretical model of post-tensioned brickwork beams. The model took into account the non-linear material behavior of brickwork and cracking once the initial pre-stress had been neutralized. The model was shown to provide excellent agreement with the experimental results (Pedreschi and Sinha 1985).

In a subsequent study, Walker and Sinha (Walker 1987; Walker and Sinha 1985, 1986) considered the use of partially pre-stressed brickwork beams. These beams included both pre-stressed and conventional non-stressed steel reinforcement. The study recognized that partial pre-stressing may offer a useful intermediate alternative to fully pre-stressed brickwork, retaining the improvements in shear and flexural behavior of pre-stressed beams while reducing the camber and anchorage stresses. A program similar to the earlier project of experimental tests on full-scale beams, with beams using various combinations of stressed and non-stressed steel, was conducted. The analysis techniques were refined further, and a computer program for the design and analysis of reinforced and pre-stressed brickwork beams was developed. It was found that the use of partial pre-stressing improved the post-cracking behavior of the beams, thereby allowing limited and controlled cracking at working loads.

These two projects demonstrate clearly that pre-stressed brickwork, if properly designed and constructed, has repeatable and predictable structural behavior and can be modeled accurately, provided the appropriate physical characteristics are obtained from suitable small-scale tests.

Robson et al. (1983) reported on a series of tests on eighteen pre-stressed beams, all with unbonded tendons. The results were compared with the recommendations of the British Standard, which was found to underestimate the strength of the beams substantially, and to overestimate the deflections.

Garwood (1986) reported on the results of nine tests on pre-stressed beams having varying degrees of pre-stress. The beams with lower pre-stress forces tended to fail in shear while those with higher pre-stress failed in flexure.

Uduehi (1989) compared the behavior of pre-stressed brickwork beams with pre-stressed concrete beams. The beams had the same cross-sectional dimensions, pre-stress forces, and compressive strengths. The results showed that the cracking moment was slightly higher for the concrete beams, but the moment-curvature relationship, load-deflection response, and strengths were similar.

Lenczner (1983; and Lenczner and Davies 1984) studied the long-term behavior of pre-stressed walls and developed a method to predict the long-term loss of pre-stress. Since brickwork does not undergo the same shrinkage as concrete, the long-term loss of pre-stress is generally less than in pre-stressed concrete structures.

Shaw and Baldwin (1995) claimed to "progress the application of structural masonry into a new era" with the construction of two post-tensioned brickwork footbridges, one using Parafil[11] pre-stressing cables and the other using steel rods. The span of the footbridges was just under 20 feet. The bridges were constructed vertically, in the same manner as a diaphragm wall. The pre-stressing cable passed through the central cavity of the section. The sections were cambered to allow for rainwater drainage. The sections were pre-stressed in their vertical position and then lowered onto abutments. The sections were similar in principle to those tested previously by Roumani and Phipps (1985). The major benefit claimed by this construction method was the construction of horizontally spanning brick elements without the use of formwork.

Baqi et al. (1999) carried out tests on twenty pre-stressed, rectangular brickwork beams. Their conclusions verified the work of earlier researchers.

Capozucca and Minnetti (1999) studied the behavior of pre-stressed brickwork beams subjected to cyclic loads. They used beams similar to those tested by Pedreschi and Sinha. A load of 60 percent of the ultimate strength of the beams was applied cyclically 180 times. Following the cyclic loading, the beams were tested to destruction. The effect of the cyclic load had only a minor influence on the strength of the beams.

Research and Practice in Relation to the Work of Eladio Dieste

As the previous sections have shown, during the twentieth century there has been a substantial body of research into the structural behavior of reinforced and pre-stressed brickwork, and there are now relevant building codes in many countries. Yet it is true to say that the use of reinforced or pre-stressed structural masonry is not extensive, certainly not in comparison with the other primary structural materials, steel and concrete. A great deal of the research was predicated on comparing reinforced and pre-stressed brickwork with reinforced concrete structures. The research has demonstrated that reinforced pre-stressed brickwork does behave in a manner similar to reinforced concrete structures, provided the physical properties of the brickwork are properly determined and used in the analysis. Being comparable, however, is not enough; there are inherent difficulties in the substitution of reinforced brickwork for concrete in framed structures:

> Brickwork is more difficult to reinforce using conventional brickwork bonding.
>
> Brickwork is weaker in shear and more complex in behavior.
>
> The physical properties of brickwork are anisotropic in nature.
>
> The specimens used to determine the physical properties of brickwork are dependent on the size, shape, and orientation of the bed joints, whereas standard, universal test specimens, such as the cube or the cylinder, have long been established for concrete.
>
> Relative to concrete, brickwork is more sensitive to workmanship, which may become critical in highly stressed reinforced brick structures or in conditions where shear is significant.

Some of these weaknesses can be overcome by pre-stressing. Pre-stressing increases the shear strength of beams, and the behavior is perhaps more predictable than that of reinforced brickwork, as the compression characteristics of brickwork are more reliable than its limited tensile properties. Again, direct substitution for pre-stressed concrete is possible, but the same conditions apply. The use of post-tensioning in diaphragm walls is, however, an advance that at a construction level succeeds over alternatives in concrete. Vertical walls are simpler to construct in brickwork than in in-situ concrete and, coupled with a simple method of pre-stressing, prove to be a practical system. The wall is both structure and enclosure in the same way that the multi-story load-bearing–wall building combined structure and enclosure, eliminating the steel or concrete frame. The post-tensioned diaphragm wall can save the cost of a portal frame in the construction of large single-story buildings. Thus, there is direct and tangible benefit that has a positive impact on the building as a whole.

Research has tended to focus on structure rather than construction. The nature of academic research is too often to focus inward, to refine analytical techniques, to dissect existing practice, or to probe weaknesses in building codes and develop new ones. Thus, the research tends to follow work on reinforced and pre-stressed concrete. The research community tends to be inward looking, with praise or success being measured by the esteem of peers within the community. West (1994), in his address to the Tenth International Brick Masonry Conference, spoke of an International Masonry Community. On this occasion he analyzed the proceedings of the ten

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8 The damp-proof course was a continuous bituminous vertical layer that separated the outer leaf from the internal diaphragm, separating the two layers.

9 In the use of diaphragm walls in buildings where the predominant lateral load is wind, it must be assumed that the load can be applied in either direction perpendicular to the surface of the wall.

10 Eladio Dieste used vertical pre-stressing to brace the walls of the Montevideo Shopping Center in order to carry the thrust from the roof vault. Remo Pedreschi, *Eladio Dieste*, The Engineer's Contribution to Contemporary Architecture (London: Thomas Telford, 2000).

11 Parafil is the trade name of a high-strength rope, made from high-strength synthetic fibers, enclosed in a polymeric sheath.

conferences, starting with the first in Austin, Texas, twenty-seven years earlier. Over the ten events, a total of 1,299 technical papers were presented. He broke these down according to countries. It is not surprising that the bulk of the papers came from North America and Europe.[12]

Out of this total, only two papers originated in Uruguay, one of which was written by Eladio Dieste (1991) and presented at the Ninth International Brick Masonry Conference in Berlin. The other was about Dieste and brick structures in South America (Diehl 1991). At the same time as the 1991 conference, the first exhibition of Dieste's work in Europe took place at the Hochschule der Künste in Berlin.[13] As far as the authors can determine, few of the delegates at the conference visited the exhibition. From the perspective of this community, Dieste was evidently on the margin. Although Dieste's paper presented some of his innovations in reinforced and pre-stressed brickwork that were altogether more ambitious than many of the technical papers presented at the conference, it was placed in the "architectural" section of the conference. The recognition that his work received tended to be by the architectural press, for its obvious architectural qualities.

Dieste's work was not reported in the scientific or engineering press. (Most papers in this area are actually written by researchers describing their own research rather than the work of others.) There is not the same tradition of journalistic review in engineering journals as compared to architectural journals. Dieste's work provided the most extensive and consistent application of reinforced and pre-stressed brickwork to date, yet it was largely unknown within the research community.

What then can be learned about the work of Eladio Dieste in relation to this considerable research field? The research certainly validates and supports Dieste's innovations in terms of his interpretation of structural behavior. It has shown that brickwork is a material that is capable of development and refinement and can be understood, predicted, and designed with the same level of accuracy as concrete. It does not, however, anticipate the spectacular forms shown to be possible by Dieste's work.

The difference between Dieste and the others is that Dieste sought to create new forms that were appropriate to the character and nature of brick, rather than replace concrete in linear, framed structures. Dieste saw these new forms and adopted them partly out of necessity and partly from a vision of the forms themselves. A comparison with St. Hedwig's Church is informative. Here, reinforced brickwork was used to create large rectangular beams to carry flat concrete roof slabs—a direct substitution for concrete with brick. Dieste, on the other hand, combined both roof and structure in one element, producing a surface form that acted both as cladding and structure. The most successful applications of contemporary structural masonry are those in which synergistic combinations of structure and enclosure were developed, such as in the diaphragm wall and the multi-story load-bearing brick building. Much of the research of others concerned the exploration of the structural—rather than the constructive—potential of the material. Academic rigor is often held to be synonymous with accuracy in prediction and analysis. Research and innovation are often used together, although success in one area does not always lead to success in the other. The research community itself has noted the lack of innovation in masonry by the construction industry. The British engineer James Sutherland (1981) considered this problem to be due to a lack of codes of practice, which engineers come to rely on and without which they are reluctant to innovate.

The Brick Institute of America, now called the Brick Industry Association (BIA 1988), is also reticent in its promotion of reinforced brick and suggests that its use is most appropriate when the structural medium is brick, the surrounding area is brick, or the appearance of brick is required. In an article entitled "Research and Innovation," the U.S. consultant Clayford Grimm (1997) considered the constraints on innovation in brickwork, among which were the fragmentation of both the research and construction sectors, and the lengthy and bureaucratic procedures for the introduction of building codes and standards.

The root of the problem lies, then, in two areas: the lack of codes, which in itself says much about the education and practice of engineers; and, perhaps more fundamentally, a perception that reinforced brickwork is not an entirely practical alternative to reinforced concrete beams and columns. West (1998), in a later address, reflected on innovation in structural brickwork. He concluded that reinforced masonry would not replace concrete in framed structure and that innovation in reinforced brickwork would be limited to a few selected applications. In other words, the developed economies, with relatively efficient and well-established construction methods and an engineering profession well-versed in their use and codes, do not really need a slightly more complicated and less understood alternative.

What then can the masonry community learn from Dieste? He was a designer, theoretical analyst, and builder. All of his innovations were driven by a need to find an effective and contemporary structural material that responded to the resources and skills of Uruguay. He had a clear vision that his material was not a substitute for concrete: "It is possible to find rational uses for bricks when combined with an adequate structure and suitable techniques which are not an imitation of what is done in concrete."[14] The construction methods he developed respected contemporary concerns for speed, prefabrication, and repetition: he pushed the technology to maximum advantage. His use of surface forms based on catenary shapes (especially the Gaussian vault) meant that the predominant stresses were in compression, and reinforcement was needed only to deal with secondary effects. In barrel vaults the surface form allowed the simple placement of reinforcement and pre-stressing steel. The pre-stressing techniques he invented distributed the pre-stress forces over the large cross section of the vault, avoiding highly stressed areas. The problem of shear was also minimized by similarly spreading the shear force over the large cross section of the vault and by using pre-stressing to eliminate tensile stresses. The additional payback was the reduction in the vertical structure and foundations, due to the relatively low self-weight and the large spans of the vaults.

Clearly, Dieste needed neither the output nor the support of the international research community to make progress through his innovations. He had a profound sense of, and confidence in, the application of the laws of physics, rather than codes, and used these to develop structural forms. He combined this with a social and artistic sensitivity that justified his endeavors across a much broader platform of ideas, thereby providing the backbone to support and sustain his work throughout his long and highly productive career.

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[12] Two hundred and thirty papers originated from the U.K.; 221, from Germany; 202, from the U.S.; 172, from Italy; 84, from Australia; 66, from Canada; and 6, from South America (including 2 from Uruguay). It should be noted that contributors from the developing countries often cannot afford to attend international conferences: the fees are high, and papers are generally not accepted without payment of the fee.

[13] Dieste was a special delegate to the conference, his attendance paid for by German sponsors.

[14] Damián Bayón and Paolo Gasparini, *The Changing Shape of Latin American Architecture: Conversations with Ten Leading Architects* (New York: John Wiley and Sons, 1979), 205.

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A GRAPHIC PRIMER ON DIESTE'S CONSTRUCTION METHODS

Gonzalo Larrambebere

Self-carrying vaults (also called freestanding vaults)
A series of photographs illustrate the construction of small, simple vaults at the CEASA markets in Porto Alegre, Brazil, 1969–72.

fig. 222: Small self-carrying vaults. In the foreground, the reinforced masonry "valleys" of what will be the laterally adjoining vaults can be seen; beyond, the wooden formwork for a series of barrel vaults.

fig. 223: Timber trusses for the formwork in figure 222. The formwork moves on rails set on the timber platform.

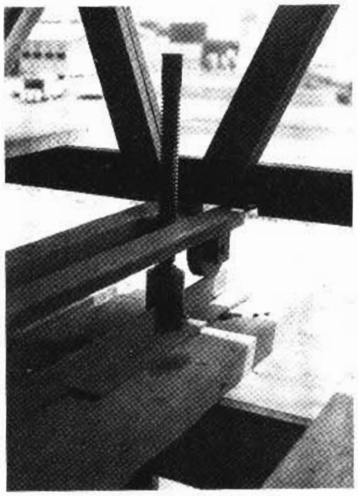

fig. 224: Detail of the simple displacement devices. Metal wheels and rails are used for horizontal movement; metal screws, for vertical displacement.

fig. 225: Small wood strips, nailed to the formwork to position the bricks. This stage is followed by the placement of reinforcing bars between the bricks and filling the joints with mortar.

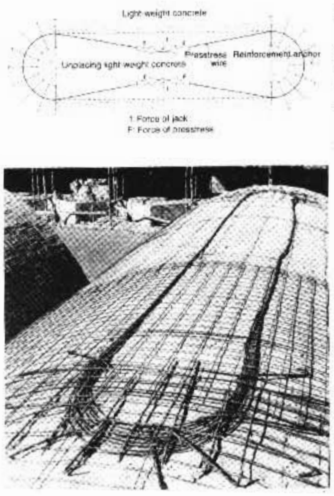

fig. 226: Looped pre-stressing steel, which absorbs negative bending moments. The brick vault, still supported by formwork, is shown prior to spreading the mortar that will cover most of the vault, including the fixed ends of the steel loops.

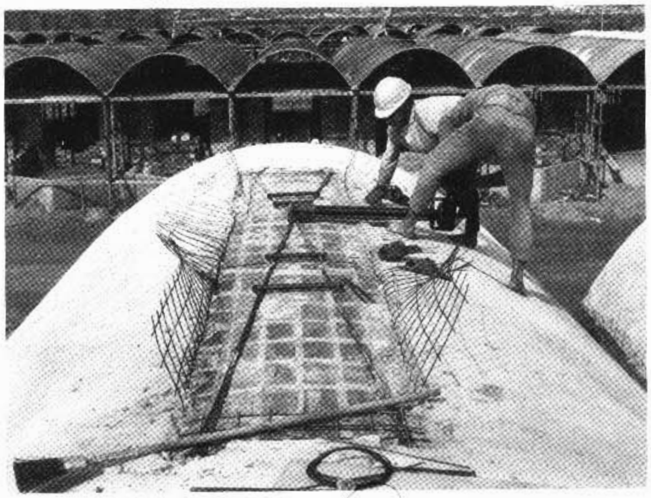

fig. 227: Pre-stressing the looped steel rods with a mechanical jack. The light steel welded mesh will be bent back and cemented to complete the roof.

Double-curvature vaults (also called Gaussian vaults)
A second series of photographs, illustrating a variety of projects, shows the construction sequence for moderately large, discontinuous double-curvature vaults.

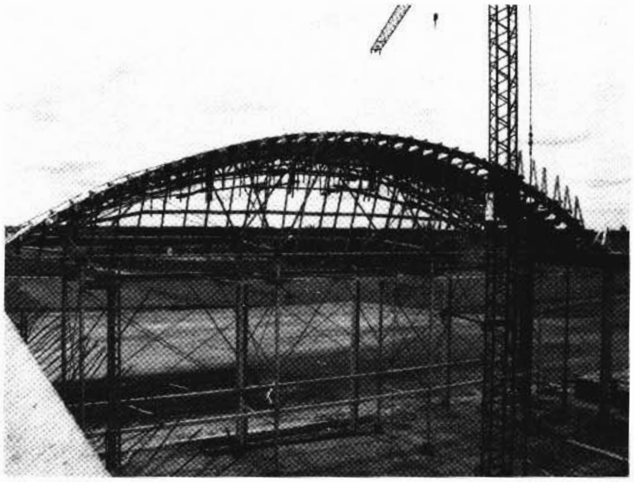

fig. 228: Metal framework and timber superstructure (ribs and planking) of formwork for a vault of 98.5-foot (30-meter) span. Rails are placed just under the outermost steel pipe columns. During horizontal displacement of the form, the central columns do not play a structural role. (Lanas Trinidad wool warehouse, Durazno, ca. 1988)

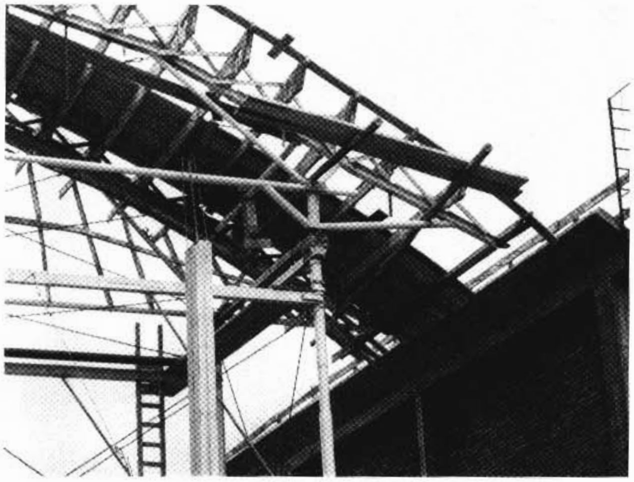

fig. 229: Detail of a device to allow movement of the formwork past the tie-rods. Two parallel metal beams, separated by wood blocks, are placed in the direction of the horizontal movement, between the pipe column and the upper lattice truss.

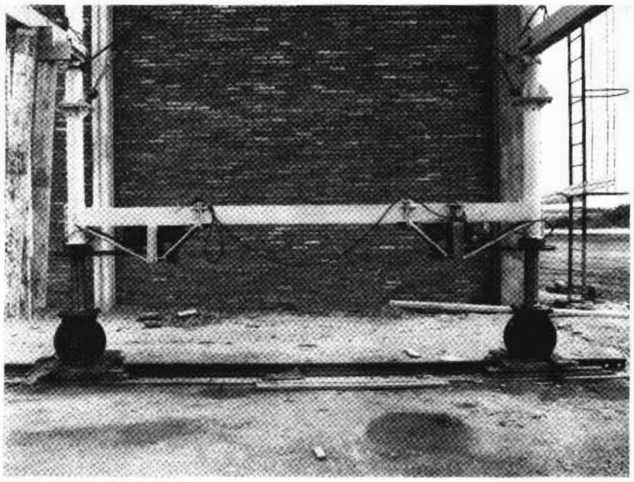

fig. 230: Wheels on rails, used for horizontal movement, and electromechanical jacks, used for vertical displacement

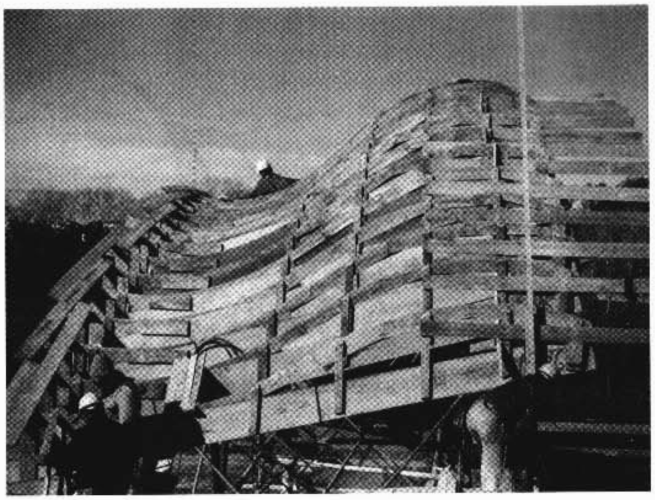

fig. 231: Timber ribs of the formwork, just before laying the surface planking

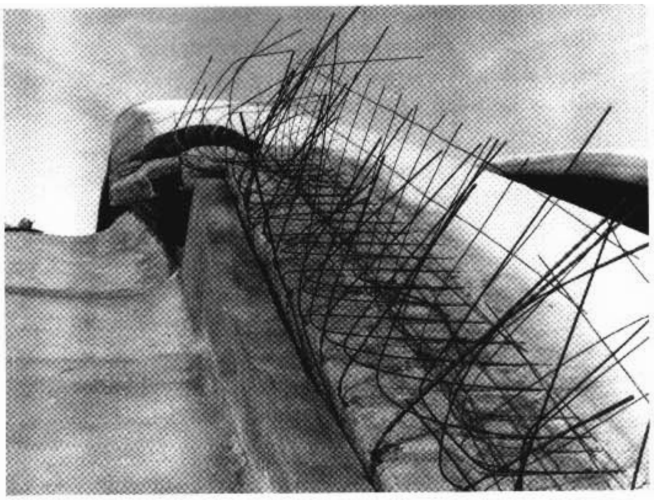

fig. 233: Detail of an expansion joint between two Gaussian vaults. To the left is the beginning of the groove to lodge the upper edge of the skylight. (CEASA markets)

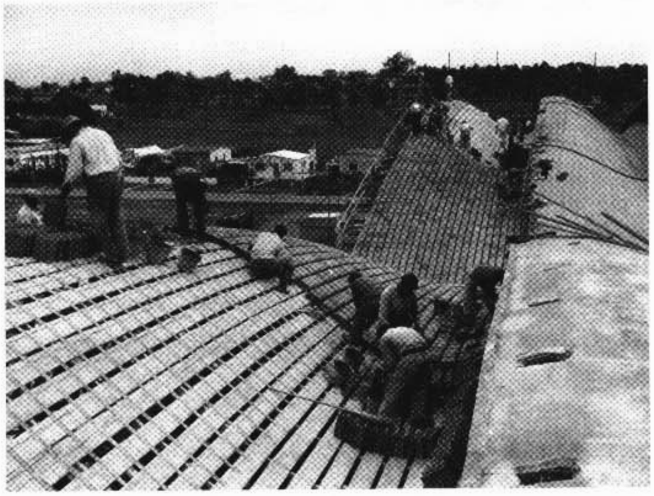

fig. 232: Discontinuous vaults with skylights. In the left foreground, wood strips on the planking control the location of the bricks. Reading into the center distance and back on the right side of the photograph, successive stages of the placement of brick, reinforcing, filling joints with mortar, and covering the bricks with a thin coating of cement are visible. The holes at the upper edge of the vault at the right allow the fixing of the vertical frames of the skylight. (TEM factory, Montevideo, 1960)

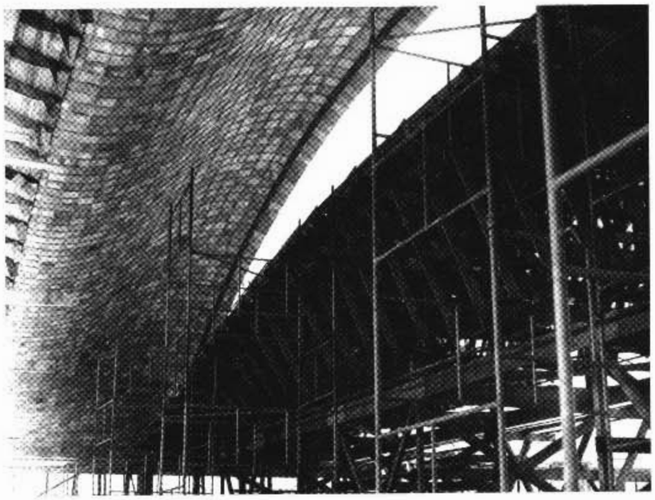

fig. 234: Interior view of discontinuous vaults. The vault at the left is newly finished; the formwork is positioned for the next vault. (CEASA markets)

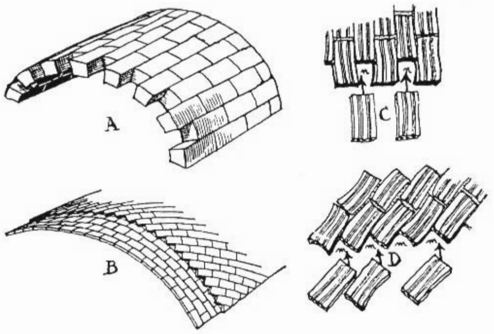

fig. 235

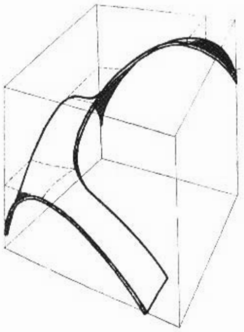

fig. 236

BUILDING CATALAN THIN-TILE VAULTS IN SPAIN: A FIELD JOURNAL

Timothy P. Becker and Kent Anderson

The origins of thin-tile vaulting are ancient, but the building method used to produce these elegant and expressive structures was not perfected until the early nineteenth century, in Spanish Catalonia. "Catalan vaulting," as it is called in Spain, is a system for constructing thin masonry vaults of broad, thin, terra-cotta tiles laid flat, usually in two or more layers, to form a pure masonry structure requiring no steel reinforcement. In contrast to standard stone or masonry vaults, Catalan vaults achieve a remarkable strength through the use of a highly cohesive mortar and the sandwiching of tiles to form a thin laminated surface. This sandwich construction, combined with the funicular shape of the vault, enables masons to build these vaults without falsework or supports **(fig. 235)**.[1] This vaulting method allows experienced builders to create with ease, using a series of straight lines, the curved or warped surfaces known as "quadric ruled surfaces."

In 1981 and 1982, the primary author of this essay, Tim Becker, initiated his research on Catalan vaulting. In 1988, he returned to Spain to study Antoni Gaudí's use of Catalan vaults and to document their construction procedures.[2] At this time, Becker met coauthor Kent Anderson, a Canadian sculptor interested in ceramic sculpture, who was in Spain to explore the sculptural potential of Catalan vaulting. Both were invited to conduct research at the Catedra Gaudí (Gaudí archives) in Barcelona. Between 1988 and 1989, the authors constructed six Catalan thin-tile vaults, documenting the process of construction. In this essay, we demonstrate how three of those vaults are laid out and built.

Bóveda de escalera (stair vault)

Tournabous, Llerida, Spain, March 1989
Supervising builder: Pere Camats
Head mason: Demetri Camats
Builders: Demetri Camats and Tim Becker

Becker began his investigation of traditional vaulting in consultation with the architect Puig Boada, a former student of Gaudí. Boada was director of the Sagrada Familia project during a period of growth in the 1950s and 1960s and was the designer of several churches in Catalonia. For instruction in classic Catalan building techniques, Boada recommended study with Pere Camats, a highly regarded builder in the Llerida region west of Barcelona. In the spring of 1982, the Camats family showed Becker how to build a thin-tile stair vault called an *arco de caballo* (horse arch). Upon his return to Spain in 1988, the author reestablished contact with Camats and arranged to build and document a *bóveda de escalera* (stair vault).[3]

The *bóveda de escalera* is commonly found in square or rectangular stairwells of older buildings. It is comprised of a series of horse arches built against each wall face, with each successive vault springing from the top of the preceding one **(fig. 236)**. A landing is formed at each corner.

Work began by clearing a space in a corner of a high-walled yard. Pere Camats emphasized the importance of accurately laying out the stairs before starting to build. Treads and risers were marked on the walls. After their locations were established, the center point of the stair was located, and a vertical guide pole was driven into the ground at that point. From the wall, the point at the bottom of each riser was transferred over to the guide pole using a straightedge and level **(fig. 237)**.

The actual vault layout began with marking the line of the arc of the stair vault using a strip of thin, flexible wood veneer **(fig. 238)**. Determining the proper shape is very important: if it is too sharp, the vault will be too steep; if it is too shallow, the vault will buckle and fail. The correct shape will transfer the loads down to the ground within its thin structure. Although there is a formula given in some masonry manuals, Pere Camats, like most experienced Catalan masons, formed the shape by eye.[4]

The veneer strip was bent to the proper shape against the wall and pinned with concrete nails. Pere Camats did the initial layout, with his son Demetri assisting. They mixed small batches of *hueso para lucir paretes* (a quick-setting plaster) used to glue the edges of the tiles together temporarily. Had this been a permanent exterior stair, *cemento rapido* (a rapid-setting, water-resistant mortar) would have been used instead of the plaster.

The first batches were slapped up against the underside of the guide strip and allowed to set. The strip was then removed, leaving a thin ledge of plaster that would serve as a guide for the tile assembly and as a temporary structural support to attach the tiles to the wall.

In the next phase of layout, a string was stretched between the lower riser points on the wall and level with the riser marks on the guide pole **(fig. 239)**. Strings forming a series of straight lines generated a curved surface—technically, a ruled surface. These strings served as building guides and took the place of wood centering. This was one of Gaudí's principal methods for generating complex forms.

After the line of the arc was bent, a foundation, or "kicker block," was built to deflect and transfer lateral forces down into the ground **(fig. 240)**. The location of the base of the arc was slightly below the first tread. The masons used *jeros*—light, extruded terra-cotta bricks with air cavities—for this part of the construction. The *jeros* fig. 235: Illustration comparing a) a traditional brick or stone vault, which relies solely on compressive forces to transfer gravity loads, and b) a thin-tile vault, which allows for some tensile forces to be resisted by the "cohesive" laminar construction where joints do not align one on top of the other. Two methods of assembly are also shown: c) tiles laid orthogonally, with joints parallel and perpendicular to the axis of the vault, as at the lower course in b); and d) an alternative assembly of tiles laid diagonally, with joints at 45° to the axis, as at the upper course in b).

Bóveda de escalera (stair vault).

fig. 236: Illustration showing parabolic arcs of vaults as they climb each wall. This version incorporates pendentive corners.

fig. 237: Masons lay out the center of the stair and transfer of the stair riser points with a straightedge and level.

fig. 238: The parabolic arc that will be used by the masons as a guide to form the vault is constructed using a strip of thin, flexible wood veneer.

fig. 239: Stair center guide pole and strings are set up to guide masons in the formation of the helicoid shape of the inside edge of the vault. The strings generate a quadric ruled surface.

fig. 240: Construction of the foundation, or "kicker block," of the stair vault involves a quick-setting plaster, used to "glue" the tiles together edge to edge.

fig. 241: Tiles are assembled along the interior edge of the vault.

fig. 242: The completed vault was able to support a concentrated load about four hours after the last tile was set in place.


fig. 237

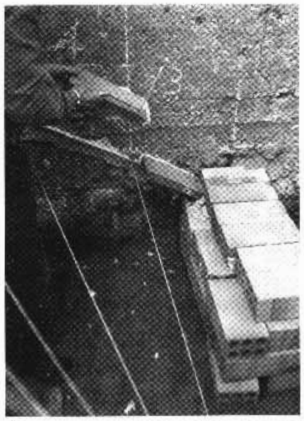
fig. 240


fig. 238


fig. 241


fig. 239


fig. 242

were approximately 11 inches long, 5 inches wide, and 4 inches thick. To this point, the layout was similar to that of a standard masonry or stone vault except for the curve of the arc.

The Camats demonstrated how to cut the tiles and mix plaster with the traditional Catalan masonry trowel called a *paleta*. *Mahones* —extruded terra-cotta tiles with air cavities that measure roughly 11 inches long, 5 inches wide, and 1 inch thick—were used for the vault construction.

During the construction of the first course, compression of the plaster between each tile is key. After the mason knifed a generous portion of plaster onto the tile's edge, he set it in place with a few taps of his trowel handle. This produced a slight suction that locked the tile firmly in place and created a compressed joint.

The Camats began laying the tiles using a quick-setting plaster. They cut and glued the tiles together at the edges, starting at the wall and following the line of the arc. After the first line was partially built, the second, third, and fourth lines were started, the mason making sure to stagger or break the joints. The bottom of the tiles just grazed the top of the string lines.

At this point, the building of the vault entered fully into the world of cohesive construction. The masons mixed up a small amount of plaster—enough for one or two tiles—and tiles were cut, plastered, and fitted quickly. The mason held the tile in place until he felt the plaster set up—usually about 45 seconds—then let go and set the next tile. The end tiles, in a line, appeared to float or be suspended in air (**fig. 241**).

As the vault turned the corner at the first landing, the interior edge, which curved around to begin the second arc, contrasted with

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1 Luis Moya Blanco, *Bóvedas tabicadas* (Madrid: Dirección General de Arquitectura, 1947).

2 This study was funded by a Fulbright/Hays Spanish Government grant.

3 This type of stair is also referred to in some masonry manuals as a *zanca a montacaballo* (horseneck vault).

4 A formula determining the proper shape of the parabolic arc can be found in an interesting Spanish masonry manual that features two chapters on thin-tile vaults: Fernando Cassinello, *Bóvedas y cúpulas de ladrillo* (Madrid: CIDE, 1969), 122.

the wall edge that followed the line of the scribed arc and dead-ended into the opposing wall. All tiles followed the guide strings to form a warped surface (fig. 241). Making a smooth transition on the interior edge was difficult work, requiring a good eye and proper cutting and placing of tiles. If the underside of the stair is visible, masons will often use a higher quality glazed polychrome tile and fit the pieces tightly with a very thin grout line.

Once the first layer had advanced a little more than half way up the wall, a second layer was started. A high-strength mortar was spread over the top surface of the first layer, and tiles were set into the wet bed of mortar with edges snug and all seams staggered. The mortar consisted of Portland cement and sand, mixed in a ratio of 1:3.[5]

Once the mortar or plaster has cured, the entire vault behaves as a single piece of material with remarkable tensile resistance for a masonry product. This is what gives thin-tile vaults their strength. When cured, the vault is so taut that it resounds like a drum when tapped; for this reason the vaults are sometimes referred to as *timbrel* (tambourine) vaults.[6] This single layer test vault was able to support a concentrated load about four hours after the last tile was placed **(fig. 242)**.

Bóveda de quatro puntos (four-pointed vault)

Montmelo, Spain, May 1989
Supervising builder: Sr. Castells
Head mason: Francesc Marin
Builders: Francesc Marin and assistant

To begin the *bóvedas de quatro puntos*, barrels and boards were set up to simulate walls. The masons used *jeros* and built above each wall with *cemento rapido* to form four arcs **(fig. 243)**. Construction of the vault started in the corners with thin-tiles—in this case, extruded solid *rasilla* tiles about 8 inches long, 4 inches wide, and 1/2 inch thick. The tiles were cut and fitted in a zigzag pattern. The first line of tiles ran up along the edge of the arc **(fig. 244)**.

The masons worked carefully in the beginning because the placement of the early tiles determines the final shape of the vault. All corners were worked up together, and subtle adjustments were made to each new tile as it was held in place and the *cemento rapido* was setting up. The masons added bit by bit to the whole vault, making repeated passes as they built **(fig. 245)**.

Had this been a permanent vault, a second layer of tiles would have been started when three full lengths of tile sprang from each corner. A thicker layer of high-strength mortar was used at each corner to add ballast and to strengthen those points (fig. 246). The arched ends of the vault are not structurally necessary; they are often left open or filled in with a thin-tile lattice to screen out the sun. All the weight of the vault is transferred through the four points at the wall corners (fig. 247). These vaults were commonly used in storage buildings in the Catalan countryside. When viewed from a passing car or train, they look like inflatable membranes, billowing and tent-like.

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[5] The ratio of Portland cement to sand varies between 1:3 and 1:4, depending on the amount of moisture in the building materials. This formula was identified by Pere Camats as a common recipe used by local masons.

[6] See George R. Collins, "The Transfer of Thin Masonry Vaulting from Spain to America," *Journal of the Society of Architectural Historians* 27, no. 3 (October 1968): 179, fig. 6, for a description of timbrel vaults.

Bóveda de quatro puntos (four-pointed vault)

fig. 243: Masons mock up walls with arched tops in preparation for building a vault.

fig. 244: Tile assembly begins at each corner and the masons gradually work up each portion.

fig. 245: The vault is constructed purely by eye, with no formwork or guidelines apart from the four arched wall tops.

fig. 246: A final touch-up using quick-setting plaster. Note that the vault corners are built up with a cement-based mortar to help transfer the load to the walls.

fig. 247: An interior view of the completed vault shows the oculus

fig. 243

fig. 244

fig. 245

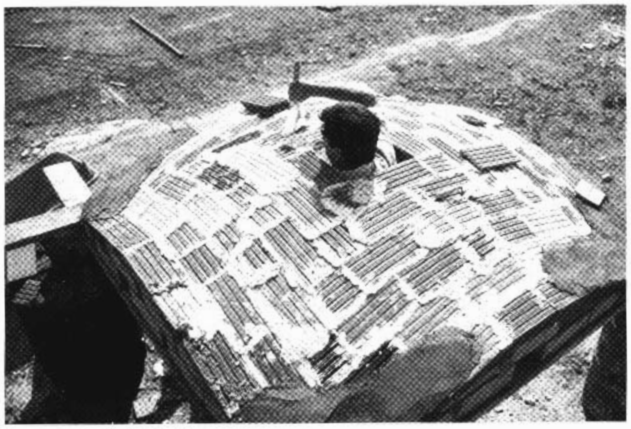

fig. 246

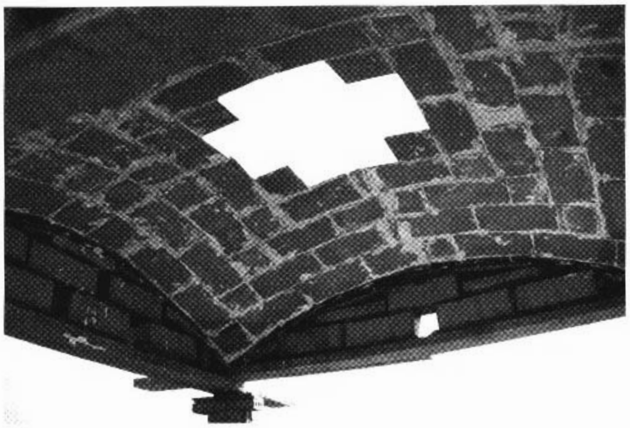

fig. 247

Bóveda de caracol (snail vault)

La Bisbal d'Emporda, Gerona, Spain, June 1989
Supervising builder and mason: Joan Rasos
Builders: Tim Becker and Francesc Font

Joan Rasos, a traditional builder from the Gerona region, provided instruction on constructing a *bóveda de caracol* while working on a country house north of Barcelona. The vault took six days to build and document.

Rasos began by laying out the wheel and spoke plan of a circular stair, marking risers and treads directly on the concrete floor **(fig. 248)**. Next he began an exterior supporting wall using *mahones*. Tiles were joined with quick-setting plaster, and the wall was built to a height of 7 risers. (In a permanent stair, the builder would start with a cylindrical stairwell.) Tread and riser lines were then transferred vertically from a central point on the floor plan and horizontally from a central column to the supporting wall with the aid of a level. Using straightforward building techniques, Rasos began transforming the plan into the three-dimensional stair.

He scribed construction lines onto thin beds of wet mortar to guide the mason in forming the helicoid vault **(fig. 249)**. A temporary central column was built to form the inside curl of the stair, and the mason translated the riser lines from the floor plan to the column **(fig. 250)**. The shape of the spiral stair vault was generated by a series of straight lines that were rotated in an ascending pattern. The vault was built following the lines brought up from the original floor plan. Lengths of bamboo provided the three-dimensional representations of the riser spokes in the floor plan and served as guides in the construction of the vault **(fig. 251)**.

When the vault was completed, the column support was removed. The riser and tread lines scribed on the inside of the supporting wall represented the profile of the future stair, which would be built on top of the vault. The structural load was carried through the vault and the supporting wall to the floor **(fig. 252)**.

The authors' investigation into traditional Catalan construction techniques provided special insight into the originality of this fluid style of vaulting. While the mechanics of each vaulting type varied, all shared a common reliance on a remarkably simple construction process. The lack of formwork allows masons to proceed without a rigid *a priori* shape for determining form. With faceted or tessellated assembly, the small bricks are joined together quickly, mosaic fashion, allowing for subtle alterations by the builder and designer during the process of construction. Gaudí in particular understood that, in the hands of a talented mason, this system could provide an unlimited vocabulary of form. In our opinion, such extreme economy and direct exposition gave architects like Gaudí greater freedom to experiment.

The compelling qualities of Catalan vaulting are both practical and poetic. On the practical side, the lack of formwork means that a construction company requires one less layer of skilled workers (i.e., formworkers); the transportation and storage of the formwork material are also eliminated. To this day, modern Catalan masons use small trucks, which carry only the bricks and mortar needed for the job at hand. The independence of the process from a more elaborate infrastructure encouraged a true vernacular building tradition, resulting in subtle variations from village to village. Another important implication of the lack of formwork is that masons must employ ruled surfaces; this not only imbues the vaults with grace but also creates forms on demand and with ease, with sound structural properties like those found in nature.

The poetic analogies are numerous. All masonry structures have a cave-like permanence that resounds deep in our past, but these thin-tile vaults go further to become a kind of miraculous hybrid of caves and tents. Upon finishing a vault, one has the feeling of a rightness of form, like a sail filled with air or a freshly thrown pot on the potter's wheel. The vaults, whether part of Gaudí's Colonia Güell crypt or a lowly carpenter's shop in a small village, have a magical quality that cannot be captured in words. When you are in these curved, textured spaces and you rap your knuckle on the taut surface, you truly appreciate the beauty of a Catalan vault.

The authors wish to thank Edward Allen of the School of Architecture, MIT; Juan Bassegoda i Nonell of the Gaudí Archives, Barcelona; and Dolores Ros of La Escuela de Cerámica de La Bisbal. We would also like to acknowledge the assistance of our editors and friends Carrie Allen; Bruce Hevly of the Department of History, University of Washington; Arnie Katz; James Thomas; and especially, Mary Lane. Special thanks go to the late George Collins of Columbia University for his early help and encouragement in 1981.

Bóveda de caracol (snail vault)

- **fig. 248:** Lines of risers and treads of the spiral stair are laid out in plan on the floor.
- **fig. 249:** A thin wall of hollow core tiles is built up to simulate part of a cylindrical stairwell, and the working lines are scribed into a bed of wet mortar.
- **fig. 250:** A temporary central column is built out of a plastic pipe sheathed with cut tiles and coated with plaster.
- **fig. 251:** The helicoid vault is built over a minimal ruled surface guide formed with bamboo sticks.
- **fig. 252:** When the partial vault is complete, center column is removed.


fig. 248

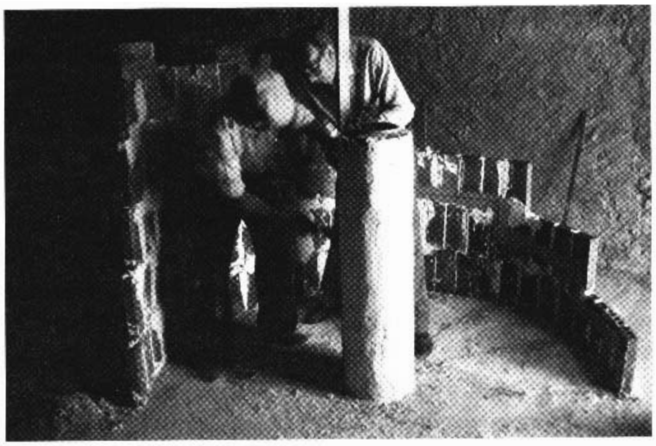
fig. 250


fig. 249

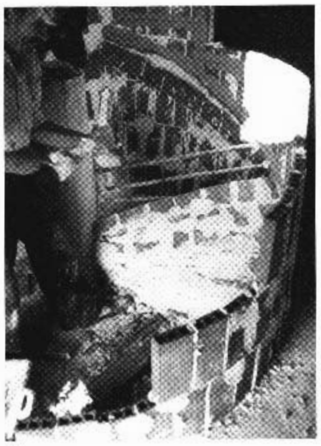
fig. 251


fig. 252

UNREINFORCED SHELL STRUCTURES IN TRADITIONAL MASONRY: A CONTEMPORARY APPROACH TO DESIGN AND CONSTRUCTION

Martin Speth

Is it possible to build shell structures in traditional masonry? What effect does the material have on design and construction? Are there morphological groups that are particularly suitable for this choice of material?

Inspired by the buildings of Eladio Dieste, a team of scientists and architectural students formed at the Institute for Structural Design and Research at the University of Hannover in 1996 with the intention of building shell structures.[1] Dieste developed his technique of reinforced masonry construction under particular circumstances determined by the availability of raw materials, economic conditions, climate, the manual skills of his workmen, labor costs, and structural considerations.[2] Discussion about the transferability of Dieste's technique soon revealed that simple copying and adaptation would be fruitless. Under the local circumstances of northern Europe in the 1990s—circumstances different from those of Uruguay in the mid-twentieth century—the idea of Dieste's work would need to evolve into a new technique for constructing shell structures in brick masonry. Questions about climate and appropriate corrosion protection of the reinforcement would have to be addressed. The increasing ratio of labor costs to material costs would also need to be adjusted. But encouraging further investigation was the fact that, to avoid frost damage, brick building material for external use in Germany is usually fired at high temperatures; the resulting high strength of the material was seen as a valuable byproduct that was not being exploited by existing masonry construction techniques. Furthermore, although curved forms could be easily produced in hand-worked masonry just by varying the dimensions of the joints, this morphology had not been widely explored. So the question arose as to whether it was possible to build shell structures out of plain masonry, making use of the full structural and formal potential intrinsic to this traditional material. Could the use of both reinforcement and surface formwork be avoided?

Positioning Traditional Masonry

The form of Dieste's shells seems magically to suggest an inseparable unity of construction and architecture. In contrast to the concrete of conventional modern shells, the material of Dieste's shells—brick, which has been layed on curved surface formwork, its joints filled with steel reinforcement and concrete—lends scale to the surface. The structure appears comprehensible and engaging when viewed from both near and far **(fig. 257)**. The square grid of joints traces how the structure works. A square net of reinforced steel together with the concrete and hat-like bricks form a powerful construction. A basic rule in structural design dictates that "force follows stiffness"; the grid of reinforced steel and concrete concentrates forces within the cross section of the shell as a result of its increased stiffness, as compared with bricks. Yet it would be wrong to understand Dieste's shells as grid structures of reinforced concrete. The efficiency of his technique results from the combined use of steel, concrete, and brick, where the brick not only constitutes shear bracing but also provides a load-bearing medium for an economical level of self-weight. According to the model of stiffness, there is a structural analogy to the steel-grid shells of the noted German engineer Jörg Schlaich. In his filigreed steel grid structures, the shell forces act in discrete straight members **(fig. 258)**.[3] The bracing of the quadrilateral grid is achieved by way of diagonal cables. Dieste's and Schlaich's structures exhibit basically the same behavior but are made of different materials. Developed under different requirements, they produce different types of architecture.

Considering unreinforced solutions, Catalan vaulting is a unique technique for building in plain masonry that has produced a rich variety of shell structures.[4] The Vapor Aymerich Textile Factory outside of Barcelona (now the Museum of Technical Sciences of Catalonia) was built in 1908 by Lluís Muncunill i Parellada (1868–1931) **(fig. 259)**.[5] Constructed with Catalan vaults, it provides a remarkable example of the efficiency of unreinforced structural solutions. The shape of this building recognizes to a great degree the characteristics of both brick and steel. The inclined shell arch is principally under compressive stress acting parallel to its span. The placement of

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[1] The work of Eladio Dieste, known through an exhibition in 1991 at the Hochschule für Künste in Berlin, led to the research activity presented here.

[2] Eladio Dieste, in *Eladio Dieste: La estructura cerámica*, Galaor Carbonell, ed., Colección Somosur (Bogotá, Colombia: Escala, 1987), 31–145.

[3] Jörg Schlaich and Hans Schober, "Verglaste Netzkuppeln," *Bautechnik* 69 (1992): 3–10.

[4] Luis Moya Blanco, *Bóvedas tabicadas* (Madrid: Ministerio de la Gobernacion, Dirección General de Arquitectura, 1947). See also Edward Allen's essay on pages 66–75 and Timothy P. Becker and Kent Anderson's essay on pages 202–07 of this volume.

[5] Mireia Freixa and Teresa Llordés, *Lluís Muncunill* (Barcelona: Lunwerg, 1996).

the curvature perpendicular to the span, which from an aesthetic point of view allows the surface to appear smooth, is, from a structural point of view, an effective means of increasing stiffness and thus avoiding buckling. The logic of the structure follows the conditions of its materials: the vertical support of the shell is shared equally by a row of brick arches that are fixed to slender steel columns. All horizontal thrust is taken up by steel tension members. Steel, more than one hundred times stronger (and also more expensive) than ceramics, needs just a very small cross section to maintain the shell's equilibrium.

In the Catalan technique, the shell consists of a number of layers of ceramic tile. The first layer is built with a quick-setting mortar or gypsum, sometimes cantilevering outward. This layer becomes formwork for the next layer of tile. Subsequent layers are laid with an overlap, resulting in a geometrically interlinked composite material of brick and mortar that is structurally efficient **(fig. 260)**. In addition to good resistance to compressive stress, tensile stress may also be accommodated due to the bond between the bricks and the high-adhesion mortar. Thus, the laminated tile section approximates the compressive and tensile strength of a laminated timber beam in its principal structural behavior.

This brilliant technique was transferred by Rafael Guastavino (1842–1908) to America by 1900.[6] His work can be found in more than one thousand buildings in the northeastern United States, particularly in New York City and Boston. Contemporary architecture, however, no longer makes use of this construction method. One of the reasons for this is a lack of skilled workmen. (This is a general predicament regarding vault construction in industrialized countries, which is true irrespective of economic conditions.) Consequently, a contemporary approach to building shells of masonry would need to employ current standard techniques that are within the capabilities of the local workforce.

Traditional masonry vaulting has an important advantage over Catalan vaulting—the advantage of reliable knowledge, most of which is laid down in local codes, thus simplifying the necessary procedures with building authorities. As with the Catalan technique, traditional masonry uses the principle of overlap **(fig. 261)**: the masonry bond can be seen as a typical detail, from the point of view of both design and structural behavior.

Owing to this important principle, concentrated loads at the top of a wall are distributed over the whole area. Also, shear stress and even tensile stress parallel to the bed joints are easily absorbed. Similar to the interlinked composite that characterizes the Catalan technique, the bond brings mortar and brick together to make a


fig. 257


fig. 258


fig. 259

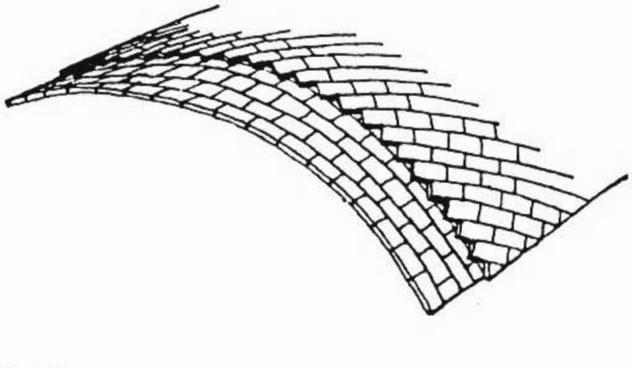
fig. 260

fig. 257: Eladio Dieste, Port Warehouse, Montevideo, 1977–79
fig. 258: Jörg Schlaich, double-curved steel grid structure, 1998. Shell structures of reinforced masonry and filigreed steel grid structures share structural principles.
fig. 259: Lluís Muncunill i Parellada, Vapor Aymerich Textile Factory, Terrassa, Spain, 1908 (now the Museum of Technical Sciences of Catalonia)
fig. 260: Principle of overlap in Catalan vaulting
fig. 261: Principle of overlap in masonry bond
fig. 262: Principle of overlap in friction grip of two steel plates
fig. 263: Principle of overlap in lap joint of reinforcing bars
fig. 264: Funicular curves of the arch and varying changing loads:
g=evenly distributed dead load, and
s=snow load in varying distributions

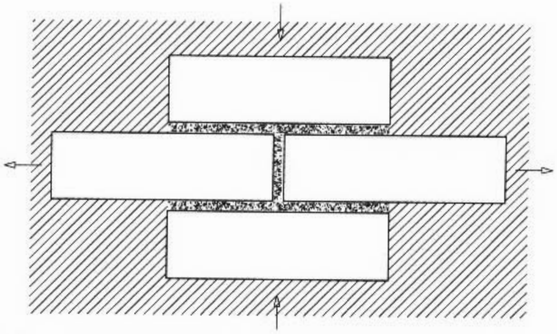
fig. 261

powerful team. Due to the direction of the bed joints, the effectiveness of the bond in traditional masonry is affected by the adhesion of mortar and brick as well as friction caused by axial loads. Different geometric patterns of masonry bond also influence a wall's structural behavior. Owing to experience in practical use, German codes do not allow tensile stresses perpendicular to the bed joints. The principle of transferring forces by overlapping members is common in numerous building methods and materials—for instance, the friction grip joint of two steel plates, or the common lap joint of reinforcing bars in all reinforced concrete structures (figs. 262, 263). In these examples, the amount of transferable force is being controlled by usual methods of design. Construction in masonry, on the other hand, has the property that the lateral resistance of the masonry increases with the weight of the axial loads. No other building material shares the property that its structural performance grows with increasing levels of compressive stress! This is why conceptual design and construction of masonry structures is exciting work. Provided that it is used in the appropriate form, traditional masonry easily fulfills the requirements of steel structures.

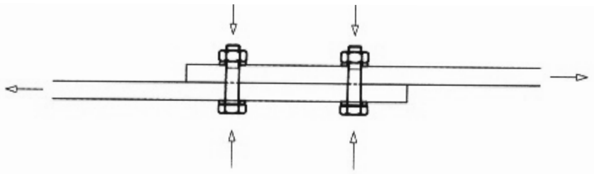
fig. 262

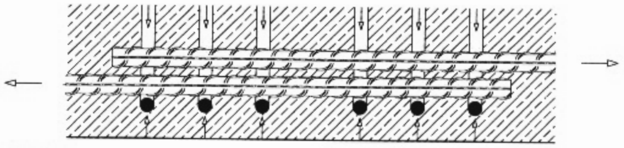
fig. 263

Shaping

In linear spanning structures, the type of member that carries distributed loads in compression to the ground is the arch. The high dead load produced by massive solid materials adds to the funicular curve of the arch, thus developing its shape (fig. 264). A structure that follows this curve carries loads to its supports under axial compression and without bending. The shape of this curve changes with different types and distributions of loads. So, besides a symmetrical

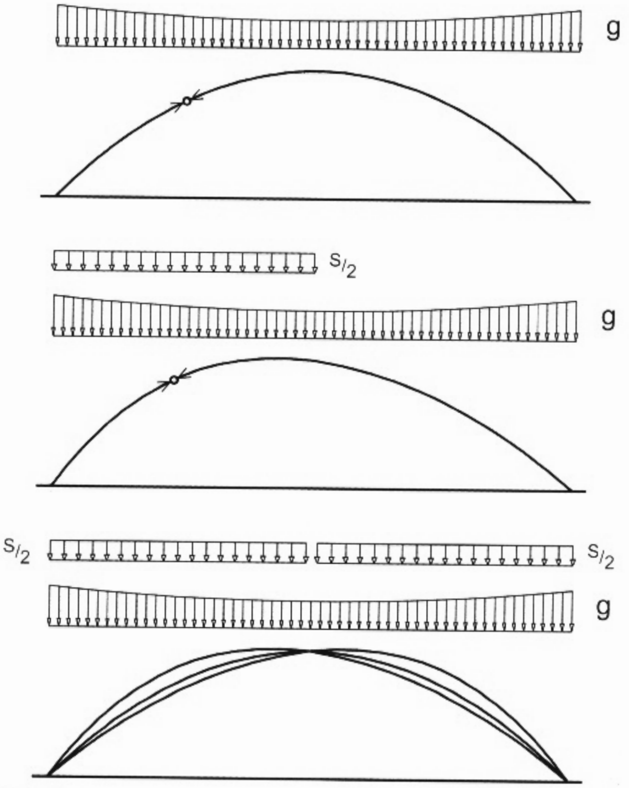

fig. 264

6 George R. Collins, "The Transfer of Thin Masonry Vaulting from Spain to America," *Journal of the Society of Architectural Historians* 27, no. 3 (October 1968): 176–201. For more detail on Guastavino, see Edward Allen's essay on pages 66–75 of this volume.

curve that results from the evenly distributed dead load, there are numerous other curves that appear with the different loads the structure must resist. Because plain masonry has no tensile strength perpendicular to its bed joints, a simple rule must be followed: a masonry vault has to envelop this range of curves within the core of its cross section. This may happen in two different ways: one way is to enlarge the area of the cross section, thus increasing material and load; the other way is to change the shape of the cross section appropriately, while keeping its area constant, thus following the principles of lightweight structures (fig. 265). In this case, stiffness is produced by shaping rather than by adding material and mass. A slender masonry arch that is also curved perpendicular to its span would easily fulfill the structural requirements of a shell arch, provided its shape has been developed correctly.

In circular plans, domes look almost like a three-dimensional arch structure. The question arises as to whether or not for a given load there also exists a best shape, analogous to the funicular curve of the arch. It follows that we can ask for more than the absence of bending; we can try to identify a shape of shell within which the stress is of the same magnitude at every point and in every direction. This leads to a dome of constant strength.[7] Another significant shape is that of the shell of revolution that has no stress in the ring direction (fig. 266).[8] Although these dome shapes were developed from a theoretical point of view and practical aspects have not been fully considered, a knowledge of them is helpful in understanding the structural behavior of differently shaped structures. Various other shells of revolution are suitable for masonry building material. The conical shell, for instance, causes compression in both the annular and meridian directions—a fundamentally sound condition for stone construction.

To find the appropriate shape for a masonry structure, both numerical and experimental methods are suitable. Many historic structures have been developed using hanging models. Tower Bridge in London shows explicitly that a tension structure follows the laws of compression, but the other way around (fig. 267). The bridge was completed by the engineer Barry Wolfe in 1896 and uses the "strong" material steel. The available methods of calculation probably did not allow a safe assessment of the effect of the slender stiffening girder, so the engineer designed the suspension girders in a shape that envelops the curves that would be taken up by a freehanging cable under moving loads. Depending upon the position of a moving load, either the upper or lower chord of the suspension girder is stressed. The high strength of steel results in small cross-sectional areas and thus a comparatively low level of dead load in the structure. Before the bridge

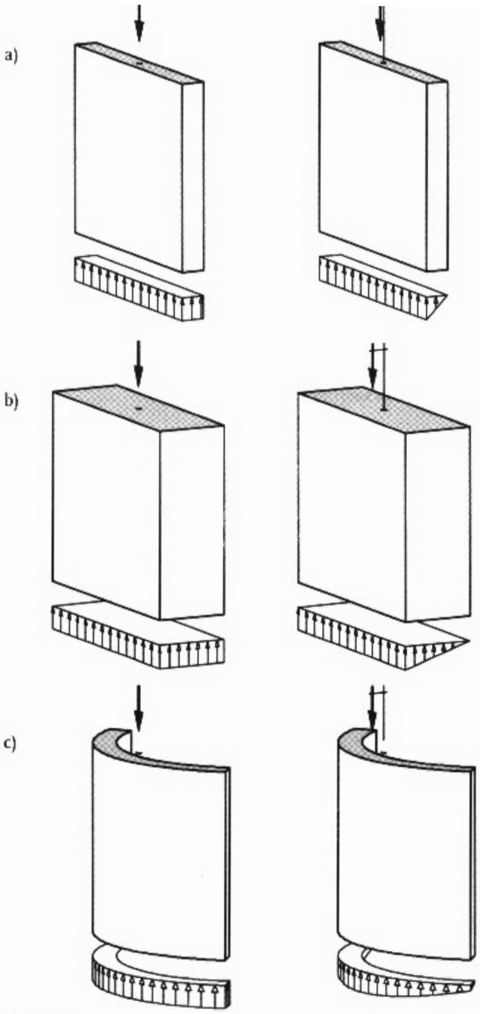

fig. 265

fig. 266

fig. 267

fig. 265: Eccentric load in
a) thin masonry,
b) thick masonry, and
c) shaped masonry

fig. 266: Significant shells of revolution:
a) dome of constant strength, and
b) shape with no stress in ring direction

fig. 267: Barry Wolfe, Tower Bridge, London, 1896. Suspension girders approximate a three-hinged, statically determinate system.

was completed, the medievalizing facing brickwork of the towers was publicly criticized. The engineer, who probably would have liked to show more of this interesting steel structure, kept a low profile during this discussion. The weight of the brickwork was a welcome ballast to stabilize the structure when one-sided loads were on the bridge.

What is to be learned from this for the design and construction of shell structures made of plain masonry? The shape may be found by inverting a hanging model. The structure should be planned in such a way that tensile stress perpendicular to the bed joints is avoided. Taking the catenary as the funicular curve of the arch, an additional curvature perpendicular to the span envelops the range of funicular lines that match the numerous moving loads. A shape that is developed in this way acts structurally like a thin-walled shell arch.[9] Depending upon the position of moving loads, the compressive stress concentrates in either the upper or the lower part of the cross section. The comparatively high level of dead load that is given by the material is useful to control the influence of moving weights and to provide sufficient axial load. As a single design criterion, enveloping the range of funicular curves would not be sufficient; the thin-walled arch has to resist bending moments perpendicular to the span that appear particularly with moving loads. The resulting stresses parallel to the bed joints have to be checked carefully during the structural analysis. With respect to this bending effect, a sufficient amount of compressive stress perpendicular to the bed joints (axial load) is necessary to develop the full potential of masonry. In all slender structural members that carry loads under compressive stress, the safety against buckling has to be investigated carefully. Shaping the shell arch in the way suggested has a positive effect on the prevention of buckling, possibly ruling it out completely because the buckling figure of an arch is geometrically similar to the funicular lines of changing asymmetric loads.[10]

Construction

Before taking on the experimental construction of the first shell arch prototype, we took into consideration the following issues. The orientation of the bed joints had to be perpendicular to the span. To achieve the desired structural behavior in the masonry, the joints had to be made in an expert manner using highly adhesive mortar. Accepting requirements of industrialized building methods, we decided to exploit the advantage of prefabrication, namely the elimination of expensive formwork. The prefabricated elements could be built upright using standard techniques of masonry construction. In a sense, brick itself represents the principle of prefabrication. Of course, the prefabricated elements must meet the highest tolerance requirements in order to fit the final geometry of the structure when assembled on site. To survive transportation without damage, a cement mortar with good adhesion characteristics would need to be used. The resistance of the unloaded masonry elements had to be investigated, especially for the conditions imposed during transportation. Tests to evaluate bending strength showed that the mortar had sufficient adhesion. Fractures usually appeared in the bricks, not in the joints.[11]

Thoughts of prefabricating elements of a shell structure quickly ran to issues of curvature, which are central to the form. The numerous elements that complete one shell are all of varying spatial curvature. Consequently, a flexible formwork that could be used to build all sorts of shaped elements was developed.[12] As is well known, to build a planar brick wall, laying the courses along straight string lines is the proven method. In spatially curved shells, on the other hand, the masonry has no straight joints. The principle of the formwork developed in our research was based on the idea of replacing the traditional straight string lines with spatially curved, thin steel rods that would guide the bricklayer in the same way but along a different path. The guiding steel rods were held at the free end of cantilevering slide bars. These slide bars were clipped into a steel frame. The position of the slide bars was controlled exactly by the lines on a computer plot, thus the highest level of geometric precision was achieved.

The steel rods can be taken as an exact form to follow when laying the bricks. Working with this formwork is comparatively easy. As the bed joints have a constant thickness, the mass of mortar that is taken on the bricklayer's trowel remains constant. The time required for creating masonry in this formwork is about 50 percent greater than for ordinary brick walls. The bricklayers need no particular skill for this kind of work. The prefabricated masonry units were removed

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[7] Georg Megareus, "Die Kuppel gleicher Festigkeit," *Der Bauingenieur* 20, no. 17/18 (1939): 232–34.

[8] See P. Bouguer, "Sur les lignes courbes qui sont propre à former les voûtes en dôme," *Mémoires de l'Academie Royale des Sciences* (Paris, 1734).

[9] See Lajos Kollár, *Statik und Stabilität der Schalenbogen und Schalenbalken* (Berlin: Ernst & Sohn, 1973).

[10] Martin Speth, "Schalenbogen aus unbewehrtem Mauerwerk," *Das Mauerwerk* 1 (1999): 2–7; idem, "Schalentragwerke aus unbewehrtem Mauerwerk," (Ph.D. diss., University of Stuttgart, in preparation).

[11] Bending stresses of this kind would also appear in the completed structure under varying loads. To gain confidence in both the geometry and construction of the initial shell arch, a model made from small blocks of wood was first built at a reduced scale. The model was helpful in that it provided answers to a number of questions that had not been anticipated beforehand.

fig. 268: Positioning of the final element on the first prototype of a shell arch made of plain masonry, 1997

fig. 269: First prototype of a shell arch made of plain masonry, 1997

fig. 270: Shell arches, used as a shelter at the Lower Saxony Building Industry Confederation, 1998. The higher shell according to type b2, the lower according to type b1 in fig. 272

from the formwork after twenty-four hours. Before transporting them to the site, they were laid in sand for two weeks for final hardening. Using two suspension belts, transportation was very easy and safe.

During construction of the arch, the prefabricated elements were supported by only two thin timber ribs. The joints between the prefabricated units were filled with quick-setting, non-shrinking mortar. (When completed, the structure could theoretically operate with dry joints between the bricks.) To take up the horizontal thrust, two tension members of steel were joined to the two ends of the arch; they were stressed by a hydraulic jack during the final phase of the installation (fig. 268).

The first prototype of a shell arch made of plain masonry had a span of 33 feet and a constant thickness of 4.5 inches. The long free edges show the slenderness of this structure. The curvature varies along the span and ends smoothly at the supports (fig. 269). The structure here follows the principle of a two-hinged arch. Although there is no perfect hinge in this structure, the zones of low curvature close to the supports approximate areas of less bending stiffness. Because the deformations of the structure are minimal, these zones of low stiffness simulate structural hinges. The free edges are in a vertical plane, so it is easy to add one arch to the other. If two edges are structurally connected, further advantages of a folded structure may be exploited.


fig. 268


fig. 269

Morphology

Our experience with this type of shell arch encouraged us to make further investigations into the possibilities, limits, and morphology of shells using this technique. Of course, there is not as much variety in the shell structures of this type compared to reinforced varieties; our shell structures follow the strict rules of their material properties and structural behavior. Nevertheless, they are relatively thin when compared with masonry in common practice.

Two shell arches were used as a shelter at the Lower Saxony Building Industry Confederation.[13] The span of these arches was 49.5 feet and the rise to span ratio was 1:4 (fig. 270). The tension members that resist the horizontal thrust were part of the foundation. The higher we built an arch, the lower were the forces in it; in our understanding of plain brickwork, however, this was not necessarily an advantage with regard to structural behavior. Changing loads and stresses resulting from temperature variations can only be accommodated with a sufficient amount of axial compression perpendicular to the bed joints. (This is why thin shell arches with a high rise-span ratio must be inspected carefully.) In the case of temperature load, using the statically determinate principle of a three-hinged arch is helpful in avoiding dangerous stresses within the construction.

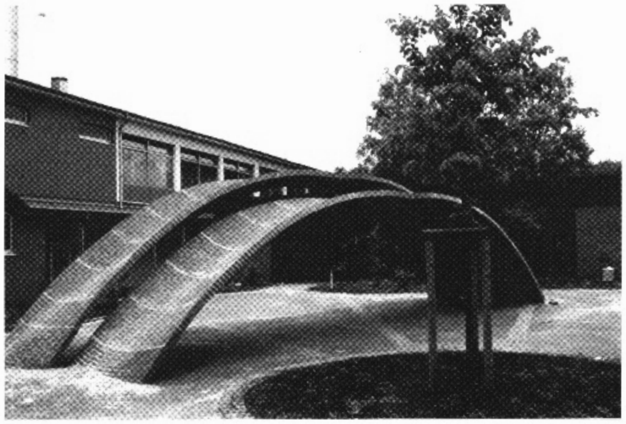
fig. 270

fig. 271: External trass plaster in combination with a hydrophobic paint

fig. 272: The particular morphology of shell arches of traditional masonry: two-hinged arches with a rise-span ratio of 1:8 with a1) positive curvature, a2) negative curvature, and a3) as an inclined shell arch; b1) and b2): three-hinged arches with a rise-span ratio of 1:4 with different positions of hinges (b1, near the ground; b2, about three feet above ground).

fig. 273: Discontinuous roof as shell arch of traditional masonry

fig. 274: First prototype with asymmetric loading in place

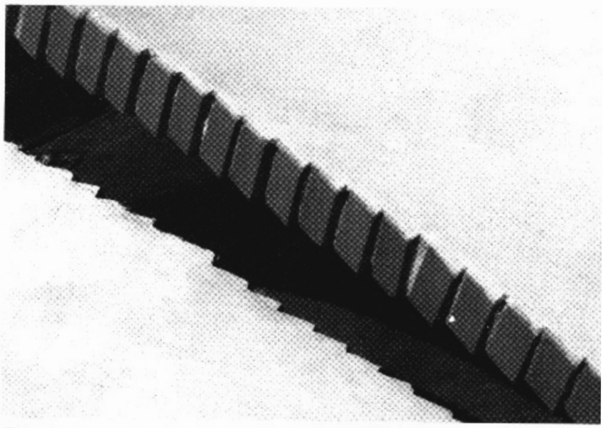
fig. 271

The detail in figure 271 shows the external plaster we put on the shells for waterproofing. We have had good experience with a trass plaster, in combination with a hydrophobic paint **(fig. 271)**.[14]

Concerning the morphology of this type of shell arch, we can say that for small rise-span ratios (1:8, for instance), two-hinged arches are reliable for spans up to 65 feet **(fig. 272a)**. In this shell arch it makes no great difference whether it is positively or negatively curved. Shell arches with higher rise-span ratios of 1:4 should preferably follow the principle of the three-hinged arch **(fig. 272b)**. The hinges do not need to be perfect. With respect to the stiffness of the structure, it is sufficient to shape the shell appropriately. The shape of discontinuous roofs can be seen as a number of catenaries with varying rise-span ratios; thus, traditional masonry is a suitable building material for this type of shell arch **(fig. 273)**.

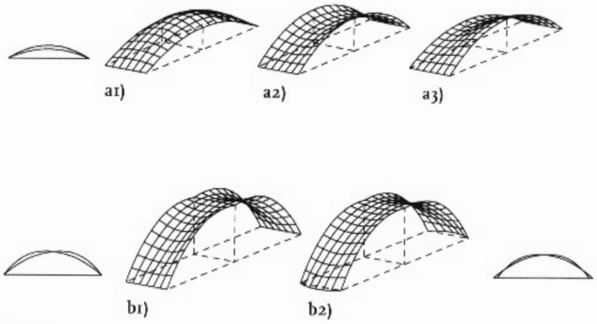

fig. 272

Structural Analysis

Using available methods of calculation, the elastic behavior of the shell arch under design loads can be simulated accurately, but there is no computational method that can assess the failure of the structure. At present there are no methods of calculation available that accurately describe the mechanical properties of masonry with respect to its anisotropy and the gaping of joints. In such shell arches, the resistance to perpendicular bending effects is reduced significantly by gaping joints. In addition, temporarily gaping joints have lost their adhesion and thus operate only by friction. As a result, the gaping of joints, which is permitted in most of the national codes, should generally not be allowed in this type of construction.

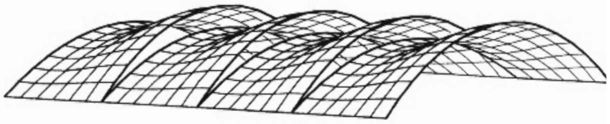
fig. 273


fig. 274

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[12] Holger Kreienbrink, Henning Schulz, Martin Speth, and Ingo Stelzer, *Vorrichtung zur Herstellung planmäßig gekrümmten Mauerwerks*, German patent specification DE 198 25 101 C2, Munich, 2000.

[13] The shells were prefabricated by bricklayers in the first and second years of their apprenticeship. The team of bricklayers changed every two weeks. This practical test made clear that the formwork developed was indeed easy to use.

[14] Trass is a material similar to pozzuolana found in the Eifel district of Germany. It is used to give additional strength to lime mortars and plasters. *Larousse Dictionary of Science and Technology*, s. v. "trass."

fig. 275: Charles Dutert, Machine Exhibition Hall, Paris Exhibition, 1889, perfect hinge

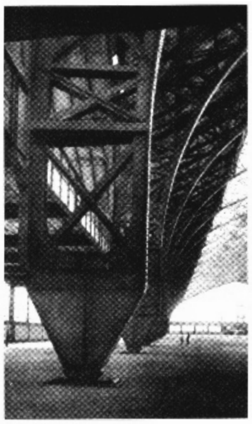
fig. 275

To find the ultimate load-bearing capacity of a shell arch, load tests were undertaken on the first prototype.[15] The goal was to increase the load until failure of the structure occurred. First, ballast was put on continuously as if snow loads were acting on the whole arch. The deflection was measured with high-precision instruments at twelve reference points. Good correlation between theoretical analysis and the measured results was observed in these tests, suggesting that the load could possibly have been increased ten times without any failure or damage to the arch.

The more critical situation is the case in which the load is acting on only one side of the arch **(fig. 274)**. This is the theoretical analysis of a case that is set by German codes, in which half a standard DIN (German engineering standard) snow load is acting on one side of the arch. The structural analysis showed that the compressive stresses were distributed throughout the arch. On the side where the load acts, compression concentrates in the upper part of the section; on the other side, it concentrates at the free edges. This matches the theory of the funicular curves of the arch, as expected. It is very important to avoid tensile stresses parallel to the span with any possible load. By increasing the load these should soon appear, but in this case there was no correlation with the theoretical model. The load had to be increased more and more, until finally testing was stopped due to a lack of additional ballast. By then, eight times the load with which, theoretically, tensile stresses should appear in the free edges had been applied.

These tests, and everything learned while building the shells, show that the models typically employed in the structural analysis of brickwork do not make use of the full potential of this material. This should not lead, however, to an overestimate of the structural capabilities of brick shells. It should be noted that due to moving loads, bending cracks parallel to the span (rather than compressive failure) would cause this type of structure to fail.[16] It should also be stressed that the collapse of a structure of this type is expected to happen spontaneously. This is a significant difference between masonry shell structures and those made of ductile materials. In the latter, failure is usually predictable in advance of a collapse, when deformations increase dangerously.

Taking into account these qualifications, our experience has shown that it is possible to construct shells made of unreinforced, traditionally worked brickwork. This material and structural type should be tested further. Particularly suitable for the construction of shells are the techniques of traditional manual production and prefabrication, which guarantee and exploit brickwork's high degree of stability. Of particular importance is the masonry bond, which enables us to draw on the full potential of classical brickwork. The design of the shell shapes must take into consideration the structural behavior of the material, with all its pros and cons. The variety of possible shapes may be limited compared to those of reinforced concrete construction, but the advantages of very thin unreinforced masonry walls may still warrant its use.

In a sense, we are at a stage of development comparable to that of Charles Dutert (1845–1906) and his designs in steel for the Machine Exhibition Hall at the 1889 Paris Exhibition **(fig. 275)**. The perfectly built hinge guaranteed that the stress on a statically determinate system could be accurately predicted. At the same time, the hinge is also a symbol of the machine itself. The quasi-hinges of our shells developed directly due to the requirements of the material on the supports **(fig. 270)**. In steel structures, perfect hinges became less important, as the full potential of this material—its ductility—was discovered. The question as to whether the semi-hinges will remain or not in our unreinforced masonry shells will have to be left to future experiments investigating this promising type of construction.

[15] For a complete review of findings, see Christian Hesse, Otto Heunecke, Martin Speth, and Ingo Stelzer, "Belastungsversuche an einem Schalentragwerk aus Ziegelsteinen," in *Ingenieurvermessung 2000, Eighth International Course on Engineering Surveying*, ed. Klaus Schnädelbach (Stuttgart: Konrad Wittwer, 2000).

[16] See Speth, "Schalenbogen ans unbewehrtem Mauerwerk," and idem, Ph.D. diss.

A PROSPECT FOR STRUCTURAL CERAMICS

Antonio Dieste

Dedicated to Elizabeth Friedheim de Dieste, my mother

In considering the work of Eladio Dieste, I propose to separate the analysis of technical and economic issues from architectural considerations. My father's architectural work cannot be continued. As with any other artistic expression, his formal creativity is personal and non-transferable. This is not to imply that his works, writings, and teaching are to be forgotten. Quite the opposite, it is possible to continue using the technologies that he created. This continuity of use, however, will only be fruitful if those technologies are adapted and developed. It is not enough to repeat what has been done before. In Dieste's words, "it is necessary to think everything anew."

But to rethink everything does not mean to walk again down the same path, adjusting details. It is necessary to encounter new paths, which is difficult because it requires inspiration. Nonetheless, inspiration is not enough. The leap of intuition that is required can only be recognized when we are truly immersed in the problem. We need rigor, dedication, and effort. Dieste conceived structures, developed the corresponding construction and calculus procedures, and designed the mechanical and hydraulic jacks that he needed and made them economically feasible. With this working method he made good architecture.

With a modesty that I deliberately will not qualify, Dieste said that every building belongs to society as a whole. Certainly, all that he did was not done by him alone, as many collaborated with him at different stages in his life. In order not to offend by omission, I forego naming them all. Nevertheless, there is no doubt that he was the motor **(fig. 256)**.

When considering Dieste's production, we must take into account that the vast majority of the works were completed successfully in economic competition with alternative solutions. It is not surprising that these roofs whose forms derive from technical considerations have an architectonic quality that largely transcends them. Rafael Dieste (1899–1981), Eladio's beloved uncle, wrote a poem, "Sorpresa del Molinero," that evokes such transcendence:

> Hiciste un molino
> creyendo que sólo
> para moler trigo.
>
> El agua encauzaste
> creyendo que sólo
> para que trabaje.
>
> Pero el agua dice
> sentencias y coplas
> que no le pediste.
>
> Y al agua responde
> pensativo y lírico
> el molino dócil.
>
> Haciendo un molino
> y encauzando el agua
> dibujaste un signo.
>
> Y absorto investigas
> viendo la molienda
> lo que significa. [1]

The technical and economic features of Dieste's production may permit its continuation, though not without innovation. Why is a technique that developed successfully in Uruguay and then vigorously expanded into the neighboring countries of Argentina and Brazil now falling behind?[2] In Uruguay, during the last twenty-five years, the cost of labor increased more than the cost of basic construction materials: two to three times more than cement, for example, and four times more than steel. The reinforced concrete industry's response was technological; different structural designs emphasizing simple construction and improved equipment, formwork, production machines, and transportation of mixed cement were all introduced. By comparison, reinforced ceramics became cost ineffective, and the economic need to innovate emerged.

The technique for building in reinforced ceramics will need to develop in all of the following ways if it is to remain economically viable:

> Moveable Formwork or Molds—It is enough to compare the early, heavy wood molds to the metal ones used today to realize what a long way we have come. However, the jacks for lifting formwork could be improved, as well as the maneuvering system that allows the tie-rods to pass through the structure that supports the formwork as it advances from one modular position to the next.
>
> Materials—It will be necessary to involve the manufacturers in order to obtain special pieces of ceramic materials at a standard price. We have, in particular, thought about a piece that we call "the ravioli" for its formal likeness to the homonymous pasta.

fig. 256: Eladio Dieste, Church of Christ the Worker, Atlántida, 1958. The photograph of mason Vittorio Vergalito building a wall of the Atlántida church embodies my gratitude to all the workmen involved in Dieste's constructions.

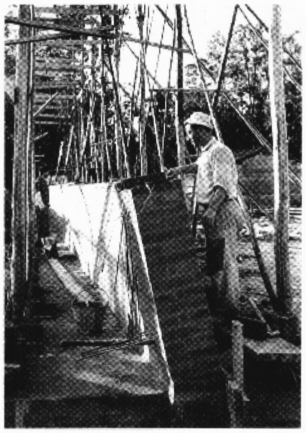
fig. 256

A component with that shape would enable mortar to be placed in a single layer while leaving the necessary space to guarantee adequate coverage of the reinforcing steel. We also envisage the use of alternative materials in combination with ceramics. Glass bricks, for instance, could be used in order to obtain natural lighting without losing the continuity of the vault.

Rapid Form Removal—There are no high-initial-resistance cements in Uruguay. To date, setting accelerators have not been widely employed because their chlorine content is potentially harmful to the durability of the reinforcing steel. The use of steam to achieve a faster setting of the cement, together with an adequate initial cure, may prove very efficient, enabling the completion of one module per mold per day in any climate. The necessary equipment is not excessively costly. In Uruguay, a more precarious system of electric heating has been successfully applied in winter.

Lifting of Material—For the lifting of ceramic pieces and the bars or reinforcing grids, a mid-size crane with a small load capacity is adequate. In terms of mortar, the existing pumping equipment is not fully adaptable; it is evident that a low-output mortar pump is required, even more so if the ceramic units employed allow a single application of mortar.

Prefabrication—It is obvious that prefabrication can play a leading role in the construction of movable formwork, as this type of structure is always modulated and the necessary crane for the setup of the pieces (posts and beams) is self-propelled and available practically anywhere. The possibility of premanufacturing part of the vaults themselves is not as evident; however, with the work of Martin Speth in Germany, a promising panorama on this field has opened.[3]

Durability—Even if today it is an unbelievable absurdity for us (the "university scum,"[4] in the words of Gabriel Zaid), it was believed, in Uruguay at least, that "concrete is eternal." Only recently have we begun to realize our error. Studies on the durability of concrete obviously existed earlier, but most of us had not looked closely at their implications.

The reinforcing bars in structures of reinforced ceramics have problems similar to those of reinforced concrete, with the added disadvantage that an adequate coverage (depending on the type of ceramic unit used) would entail very wide joints. Furthermore, the inevitable repairs are difficult to carry out without spoiling the aesthetic quality of the structure.

Even if it is true that many structures of reinforced ceramics have responded well to the passage of time, in some cases of particularly high exposure (a marine environment, or places where permanent condensation forms on the interior surface of a vault), problems of corrosion in the reinforcement have occurred. In one case—the only case of which I know—the chemistry of the ceramic material was the cause of the problem.

The geometry of the ceramic units is a determining factor in the thickness of the reinforcement coverage that can be guaranteed. Physical properties of the units, such as resistance and porosity (intimately linked to one another) are of tremendous importance. Consequently, the future development of the technique of reinforced masonry construction implies an advance in standards of specification and testing. Alternative reinforcing materials should be evaluated:

> Stainless steel, or galvanized and/or epoxy-covered steel—Although expensive to date, the relative cost of the material will likely go down. Structures employing these products may require very moderate amounts of steel (less than 3/4 pound per square foot in single or double vaults), creating additional cost savings.
>
> Polymer bars reinforced with fibers—Carbon fibers, though still very expensive, have very promising properties.

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[1] Rafael Dieste, *Obras completas* (Sada/A Coruña: Ediciós do Castro, 1995), 1: 484. An English translation of this poem by Ann Pendleton-Jullian appears on page 11 of this volume.

[2] I exclude here works built in the last few years in Spain because they belong to the universe of special constructions to which my economic analysis does not apply. I also leave aside some special works like the churches of Durazno and Atlántida. Of Atlántida Dieste said, and honestly believed, "it cost the same as a shed," which is strictly untrue. But in order to complete this work he had to deceive himself and, with his enormous charm, bring others—in good faith—along in this deception.

[3] See Martin Speth's essay on pages 223–30 of this volume.

[4] Gabriel Zaid, *Obras*, vol. 3, *Crítica del mundo cultural* (Mexico City: El Colegio Nacional, 1999), 429–35.

Cathodic protection—In the bridge at Maracaibo, Venezuela, cathodic protection was used successfully in protecting the most critical zone of the pylons—their juncture with the spanning structure. I do not know of the use of such protection in laminar structures, but it is another open possibility for research.

Fire- and vandalism-resistant tie-rods—Structures with exposed tie-rods are very sensitive. At the Port Warehouse in Montevideo, a fire cut one of the tie-rods. The double-curved vault, which has a 164-foot span, fortunately did not suffer any considerable damage, but the replacement of the damaged tie-rod was very dangerous. The design of future projects must take this into account.

Joints—Modern standards discourage the design of structures in which the failure of one module or element would trigger a chain of failures. Self-supporting vaults clearly belong in this category. The solution is to include joints in the project. The corresponding additional cost is negligible.

The preceding list is hardly a complete record of the conditions that frame the possible development of shell structures of reinforced brick. The problem has many dimensions and, happily, perhaps multiple solutions.