double functioning elements in architecture

Masters' thesis

by

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Virginia Polytechnic Institute and State University
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abstract

With the increase in the number of functions in the modern age, it has become quite a challenge for an architect to satisfy the requirements and still have an appropriate architectural expression for the materials and the underlying structure. Such challenges may be found both in nature and man made machines, giving rise to elements with multiple functions.

This thesis attempts to explore such precedents offered in both architecture and other areas, and apply the ideas and principles in the design of a primary school.
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The surface of a jet airplane has no openings, until you see a part of the wall dropping down to become the door, a door which is also a stair. This simple but ingenious solution never ceased to impress me.

It is not uncommon to find such elements in machines, which are faced with many constraints of economy of space and material usage.

Elements with double functions or double meanings have been a constant source of delight to me. One would not be hard pressed to find examples of such elements in other forms in man made objects as well as in nature. Living organisms offer a huge challenge to God to fit in literally thousands of functions in a tiny frame. Hence it is inevitable that many of the parts have more than one obligation. For example the bones of most mammals are structural and also contain hollow spaces in them to accommodate the marrow to produce the blood cells. The roots of trees are foundation supports as well as receptors of the ground water.
The field of literature is not alien to the usage of double meanings. Puns and double entendres have been used throughout history, ranging from comic books like Asterix to the likes of Shakespeare. It is interesting to see how the use of puns can create confusions using similar sounding words or phrases, depending on the perspective of the reader, it may have a different meaning.

Many of the tessellations produced by M.C. Escher are a play of solids and voids in such a way that the background space around an image is another significant image in itself. Numerous artists have created paintings where you can find human faces and other objects hidden in the image. The above sketch shows two images, one of an old lady and also a young woman in the same picture.
The designs of many hi-tech buildings also show a great deal of integration of the various building systems of the building. The windows, roofs and skins of these buildings serve multiple functions. One of these ideas that struck me most was the design of the umbrella of the Stansted airport by Foster, where the columns have been expanded to accommodate the subsidiary services. The space-enclosing nature of these structures became one of the main themes for my thesis.

Even in some of my earlier designs I had unwittingly tried to integrate various systems in a single element. Most notably, in the project for the art gallery skylight system, I had used steel plate beams, which had a shape that could not only manipulate the daylight, but also contained the conduits for the electrical lighting, and the hollow space in it became the return air duct.

All these influences finally culminated into deciding the topic of my thesis, “double functioning elements”.

Fig 1.4 Stansted Airport

Fig 1.5
the design

To explore the double functioning elements in architecture, I have designed a primary school. The scope of the design includes the design of the classroom clusters and the auxiliary spaces like the music room and the library. The entire site development is not considered for the design.

the site

I selected a site with climatic and cultural conditions in which I anticipate would be more closely related to my future career. So the site is located in the city of Hyderabad, India. The hot and dry conditions of the city and the non-dependence on the mechanical systems gives an opportunity to include several open spaces in the building.

The double functioning elements in the building are more in the behavioral aspect than about the services.
The site is heavily contoured one with a small hillock formed in a part of it. The level difference between the highest and the lowest points is about twelve feet.
the courtyard

The two most important aspects of the design are the classroom clusters and the courtyard. The courtyard is basically a series of steps and terraces, which not only negotiate the different levels of the ground but also connect lower and the upper levels.

The common rooms used such as the music room and the library, which need to be acoustically separated from the classrooms, are located in the courtyard. The stepped terraces of the courtyard also become a part of the sky-lighting system for these rooms. The levels of the courtyard ultimately culminate into a grandstand for the playground beyond, in the form of the library roof.
fig 2.4 lower level plan  (not to scale)
fig 2.5   upper level plan (not to scale)
fig 2.6a  partial section through courtyard
fig 2.6b  partial section through courtyard
The primary unit of the design is a classroom cluster. The building has ten clusters, each containing two classrooms and restrooms. The in-between space becomes the outdoor classroom, which can be used for the extracurricular activities.
fig 2.8  cluster section
The thickness of the walls is two and a half feet to combat the heat, as thermal mass. The space formed within the cavity has many different uses such as a working desk, display shelf, sitting space, for service lines etc.

The entire construction of the classroom is in precast concrete.
the stepped roof

The stepped roof of the rooms occurring in the courtyard (the music room, library etc.) are made of cast-in-place vertical members and floors, and the recurring horizontal members of the steps are made in precast concrete. A uniform thin-set monolithic terrazzo finish is used for all the horizontal surfaces, with a variation of the color and texture from the classroom spaces to the common areas.

fig 2.10    wall section
interlocking functions

Many tessellations made by M.C. Escher, are interesting examples of showing that the residual space formed in making one image can itself become a significant entity in itself.

The sketch of a corner window was an early study to explore an architectural counterpart of the above mentioned idea of interlocking functions. The residual space created by the L-shaped window is used to make a sitting space, which in turn forms a storage cabinet below it.
The double functioning structures have been used since the earliest examples of architecture. They can be particularly seen in Baroque architecture where their massive walls and piers have been scooped out to make space for subsidiary functions. These elements are usually structurally superfluous, expanded much beyond the minimum requirements, but have a purpose beyond the primary one of holding the building up. The dense structure to support the arena of the Roman Coliseum is used for dungeons. The flying buttresses of many cathedrals have been articulated to form usable aisles.

Even Kahn’s famous ‘servant spaces’ may owe their origin to the houses designed by Palladio. Kahn noted a hierarchical grid in the plans, with major spaces occupying the larger modules, and the servant spaces (the store rooms, staircases etc.) interwoven between these spaces, occupying the smaller volumes.
hollow stones

“Today we must build with hollow stones, ...to house the services,... 'The nature of space is further characterized by the minor spaces that serve it. Storage rooms, service rooms and cubicles must not be partitioned areas of a single space structure; they must be given their own structure.”

Louis I. Kahn

When it comes to hollow structure, Louis Kahn has had a great deal of contribution on the subject. His ideas regarding the expression of the structure pitted against the growing services in modern buildings, which tended to conceal the structure, called in for the development of what he called “hollow stones”. The structures Kahn strived to design would have inherent space which could accommodate the servant spaces for the buildings.

Though the idea of the hollow structure which could accommodate the mechanical services of the building appeared as early as the 1951 Yale Art Gallery, it was restricted to the roof and floor systems. The lesser known Trenton Bath House designed in 1957 represented the culmination of this new ordering principle. The idea was realized in three dimensions. The piers which supported the pyramidal roofs were hollow. In some instances, columns act as pass through entrances, shielding the changing rooms, and at other places, they contain toilets and sinks and also harbor the chlorination equipment for the pool.
The projects for the Richard’s and the Salk Laboratories, though different in their design conceptions, had one thing in common, the porous roof. Both these buildings employ a system of vierendeel trussed roofs to provide the inherent space for accommodation of the services. Though the roof structure is double functioning, the vertical movement of the services takes place through a system of more orthodox brick towers. That is to say that they are not integrated into the structure of the building.

Incidentally, the earlier discarded scheme for the Salk institute was considered by Kahn as an ideal design. It consisted mainly of box trusses spanning between the studies and the service towers with a series of folded plate beams spanned between the trusses. For Kahn’s engineer, Komendant, this was the most efficient structure, which utilizes minimum material for large spans. Kahn would have liked this design because the structure provided for integral open spaces, with the services and circulation taking place within the hollows of the structure.

But ultimately this exact co-relation between the architectural space and structure would pose a problem. The tight fit would result in lack of flexibility. Even though there was an abundance of opportunity to plug into the service ducts, the space below would still be controlled rigidly by the structural grid. Hence, the vierendeel scheme.

The finest of the refinements of the hollow stones can be seen in the hollow beams of the Yale Center for British Arts. The huge depth of the concrete coffered beams in the top floor, not only helps manipulate the quality of the natural light entering the galleries, but they also accommodates the air conditioning ducts in their hollows.
The hollow structure occurs in my design in the form of the precast concrete perimeter walls. The thickness provided to reduce the impact of the sun has given an ample opportunity to accommodate other functions within the hollows of the structure. The functions the wall can accommodate helps the classroom become autonomous by making use of the extended sill as a working desk, to have experiment setups, to place a desktop etc. The wall thickness also contains the space to run the electrical and plumbing lines to which these may be plugged in.

This also allows for personalizing the classroom, in a way that the wall contains space for the display shelves and also some sitting spaces.
The other instance of the occurrence of the hollow structure is the hollow column that supports the roof of the outdoor classrooms of a cluster. In my earlier iterations of the design, a wall, which also became the backdrop for this space, supported the roof. But by expanding the structural columns, they could accommodate restrooms and some storage space within it.

Fig 3.9 Plan - Hollow Column
metamorphosis

M.C. Escher produced a series of drawings entitled “Metamorphosis”. In these sketches, the boundary of the image starts to become more significant and ultimately forms another image by itself.

Fig 4.1

My initial sketch of a staircase shows similar ideas. The flatness of the staircase tread is amplified and modified to form a display shelf or a sitting space, among other things that may be possible.
The morphing plinth is almost a direct translation of the above mentioned idea of the morphing staircase. 
The site of the school is such that there is a level difference of about six feet between the lower and upper classroom clusters. The morphing plinth has been designed with a primary intention of reconciling the different levels of the site. It not only forms stepped terraces but also forms tree boxes, holds a pool of water and above all, forms spaces to sit, congregate, perform or do anything depending on the interpretation of the users. To use Herman Hertzberger’s words, these become ‘habitable spaces between things’.

The ‘plinth’ is not restricted to the ground but also merges into the upper floors, forming rooms within it. The steps form a system of the skylit roof for these rooms.
The stepped roof of the library, which provides the light to the library also becomes the grandstand for the playground beyond.

Fig 4.4  Grandstand facing the playground

Fig 4.5  View of Courtyard
The roof of the rooms in the courtyard transforms from being a staircase at one end and becomes the skylight / amphitheater steps as it reaches the other end.

The precast concrete beam extends out of the wall face, as an expression of the structure and construction. The section of the beam changes from a solid square to a U-shaped one as it comes out of the wall (where its structural capacity is not so detrimental) and becomes a rainwater spout.
perceptual duality

The picture shown here may be a duck or a hare, depending on which one you choose to see. The image has an inherent duality which invokes different perceptions without any change to itself.

Fig 5.1   Duck / Rabbit
The translation of this idea of an inherent duality of an element in my project was in the form of economy of the construction process. The idea was to minimize the number of precast elements used in the construction of the classrooms. There was an occurrence of many different horizontal members, window sill, lintel, service tray etc. An effort was made to design a generic element which can perform all these functions.

Hence there is a single element which occurs throughout the building in different forms, as a window sill (which doubles as working desk), lintel (also display shelf), sitting space, skylight and a service tray. The same element with some modifications also becomes a staircase.
Conceptually, the element consists of a combination of similar blocks and a set of the end pieces. The arrangement can be varied to form different lengths of the members, in the manner of making a model with Lego blocks. And depending on the location and orientation, the element functions differently.

Like the different colors of the blocks, the material and finish of the elements also change. Unlike the members of the interior spaces, the ones of the outdoor spaces (like the amphitheater steps), are finished in rough monolithic terrazzo, for the anti-slippery surfaces and also to match the texture of the rest of the plinth.
Though the generic nature of the square section was not a challenge, having the same particular end condition for both the members is interesting. The notch provided to receive the metal welds for the vertical members has been transformed into a rainwater spout for the beam.

This idea is not restricted to the horizontal members. The entire classroom is made of essentially three different components, each behaving differently in different conditions. The same section is used for the horizontal beams and the vertical wall members.
Similarly, the precast floor members and the wall panels are the same.
Parts of the wall are assembled in the factory to reduce the on site assembly. These pre-assembled walls along with the precast beams and floor panels are put together on the site to form the classrooms.
Fig 5.13       Exploded precast assembly

Fig 5.14
structural duality

The Kimbell art Museum ‘vault’ designed by Louis Kahn is an enigmatic structure. It has spans of about 100’, but the vault action seems to be in the perpendicular direction of it. The central part of the vault, which is supposed to carry the maximum stress, is scooped out to provide the skylights. It seems to defy many of the laws of physics. The answer to this lies in understanding the fact that the ‘vault’ is actually not a vault structurally, but a beam, about 8’ deep.

The earlier designs of the museum show columns at 20’ intervals, instead of the 100 feet of free span, when the structure was still considered to be a vaulted one. But a later realization, owing to Fred Anger’s book “surface structures”, that this can be designed as a folded concrete shell, increased the spanning capacity manifold.

It is also interesting to note that while the vault was an architectural module in the eyes of Kahn, a seagull shaped beam was the vision of Komendant, the structural engineer of the project.
What amazes me about this structure is how the realization of some hidden structural qualities can affect the architecture. There are some more examples I came across during my research, structures with such dual nature. Most of these structural aspects are not obvious to a casual observer, but nonetheless, these have a powerful impact on the final architectural product.

Another building with such a structure is the Commerzbank designed by Foster and Partners. A very important feature of the building is the sky gardens. These four storied gardens occur at regular intervals, and required a column free space. In another Foster building, the Hong Kong and Shanghai Bank, with a similar typology, the column free space is provided by huge hanger trusses. Though the trusses are elegantly designed, they ultimately obscure the column free sky decks with their presence.

The Commerzbank building is free of any hanger or a bridge structure to create these sky gardens; instead a simple frame appears to span these large spaces. How was this possible? The secret behind this is that what seems to be a normal frame, is actually a eight storied vierendeel truss. This deep structure allows such huge spans, without even being conspicuous. This truly frees the space of any structural members.
In some other cases, structural properties have been exploited even in seemingly non structural elements. The window mullions in Wright’s Fallingwater, even though they are structural, may be passed off by the observer as a mere window frame. These increase the effective structural depth necessary for the cantilevers, and still do not interfere with the horizontality of the building.

The ferro-cement leaves of the roof system of Piano’s De Menil Museum appear to be hanging from the steel trusses above. But in actuality, these ‘leaves’ form the lower part of the trusses and are structural. (Ironically, the steel is in compression and the concrete takes the tensile forces.)
The awareness of these hidden structural properties has helped me in my design on one minor but important occasion. As already demonstrated in the previous chapters, the staircases leading to the upper levels of the building are integrated into the skylights of the rooms in the courtyard.

Since the element which forms the staircase, was repeated in many different places and is a very important part of the design, I wanted to expose it, and the staircase gave me this opportunity. The staircase tread is extended beyond the wall which supports it, and for the first time it is seen in a sectional view.
But the smallness of the section posed structural limitations on the cantilever. In my earlier iterations of the design, the cantilever was only 1'-6" and had cast-in-place concrete intermediate steps.

But the planning modules required a cantilever of 4’ for a better fitting.

I realized that if the steps were cast integral to the horizontal member supporting it, instead of resting on it, the member would behave like a deeper beam. This greatly increased the structural capacity of the members and a 4’ cantilever was possible.
The increase in the number of auxiliary functions in a building has increased exponentially during the last century. The nature of these mechanical systems is such that they do, more often than not, tend to inhibit the proper architectural expression of the underlying structure and material. One of the main aims of my thesis was to explore the possibilities of the ‘hollow’ structures, which could accommodate these services and still could have an appropriate expression of the underlying order of the material and structure.

Though the thesis is restricted to the design of the school and some of the precedents (which have been the inspirations), its impact goes beyond. During the course of researching on the subject, I have been exposed to the works of various architects like Louis Kahn, Herman Hertzberger, Norman Foster, Renzo Piano, Nervi etc., and the logic behind those designs.

I have not only studied the final products but also the processes of making them, which gave an incredible insight into the minds of these people. Not only the power of the double functioning elements was clear, but also the limitations came into the picture.

The awareness of the double functioning elements as an architectural tool, has changed the way I would approach an architectural design in the future, so that the auxiliary functions and the building systems will not be an afterthought but an integral part of the design process and the architectural expression.
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illustration references

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