The Tectonic Thinking and Strategies in Louis I. Kahn's Art Museums

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Abstract: Through the use of tectonic form to integrate natural lighting and modern mechanical services into his art museum designs, Louis Kahn was able to give full expression to the spatial poetics of his tectonic thinking. By making a comparative examination of the literature and illustrations and presenting 3D models, we examine how, in the process of giving shape to space, Kahn was able to make the most of the inherent qualities of his materials to integrate the mechanical services into his three museums designs—the Yale University Art Gallery (1951–53); the Kimbell Art Museum (1966–72); and the Yale Center for British Art (1969–74)—while also making ample use of natural lighting. We then go on to investigate why Kahn adopted a design concept which used tectonic form and natural lighting to give expression to the inherent spatial characteristics of a museum. The results indicate that the architectural principle of complying with the structural form and order were the main factors influencing Kahn's approach to integrating the mechanical services and natural light into these three designs. It was also found that Kahn's pioneering use of passive natural lighting has had a significant impact on subsequent museum designs.

Keywords: Louis Kahn, art museum, mechanical services, passive natural lighting.

1. INTRODUCTION

Looking back at the architectural history of the twentieth century, it can be seen that even while the modernist international style was at center stage during the 1950s and 1960s, the American architect Louis Kahn was utilizing a design concept which was both monumental and modern, thereby going against the prevailing orthodoxy of modernist architects embodied in their motto "form follows function." Kahn emphasized that an architectural undertaking necessarily starts out from unmeasurable inherent qualities, proceeds to the application of measurable design and construction procedures, with the final result giving expression to the unmeasurable inherent characteristics of the building. In addition to showcasing the latest developments in materials and engineering technology, Kahn's work displays a deep sensitivity to the forms of ideal geometry. Moreover, his organizational concept of "served and servant space" has proven to be effective in minimizing the negative effects environmental control systems have on modern architecture. Wishing to make the overall construction process more visible from inside a building, Kahn rejected the international trend of the time in which a suspended ceiling was used to conceal the mechanical services. He wrote, "*I believe that in architecture, as in all art, the artist instinctively keeps the marks which reveal how a work was brought to completion. …It would follow that the pasting over the construction of light and acoustical material, the burying of tortured unwanted ducts, conduits, and pipe lines, would become intolerable.*" [1] In other words, it's essential to clearly display how a structure was built, and how its spaces are served. Kahn used the structural elements utilized in shaping a space to integrate the building's mechanical services, while also attempting to give expression to the overall logic of integration and the structural order of the interior space and external form.

While considering how to best give expression to the essential characteristics of an art museum under ideal conditions, Kahn instinctively selected light as one of his key design elements, in the belief that natural light is the key factor for expressing the organizational relationship between the construction process and the details of the materials being used. In his own words, "*If you try to think of points from which we can reach points of departure in architecture, we can very easily state that a space in architecture is one in which it is evident how it is made, and that the introduction of a column or any device for making a roof is already thought of from the standpoint of light, and no space is really an architectural space unless it has natural light. Artificial light does not light a space in architecture, because it must have the feeling in it of the time of day and season of the year—the nuances of this is incomparable with the single moment of an electric bulb*" [2]. On the best approach to utilizing natural lighting Kahn wrote, "*Each space must be defined by its structure and the character of its natural light. …An architectural space must reveal the evidence of its*

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making by the space itself. It cannot be a space when carved out of a greater structure meant for a greater space because the choice of a structure is synonymous with the light and that which gives image to that space" [3]. This is what he meant when he said, "*Structure is the maker of light*" [4]. Space is necessarily shaped by a structural form which is both complete and capable of ushering in natural light. Kahn's art museum designs clearly demonstrate his design concept based on integrated mechanical services and using structural form and natural light to express the unique qualities of a space.

This article traces the development of the design concept Kahn applied to his museum projects, beginning with his realization of the inherent spatial characteristics of an art museum. We also utilize detailed 3D models of Kahn's designs to present the organizational order and process he used for integrating natural lighting, the mechanical services, and the structural elements. Finally, we use 3D schematic illustrations to analyze Kahn's application of natural lighting in his three museum designs.

2. THE EVOLUTION OF THE INHERENT SPATIAL CHARACTERISTICS OF AN ART MUSEUM

When the Yale University Art Gallery—Kahn's first public building—was completed in 1953 and its unique structural form and spatial characteristics immediately caused a stir in the world of architecture. By that time Kahn had already realized that a building designed to function as an art museum needs to not only provide exhibition space, environment control, lighting, office space, and storage facilities, but must also take into full account what he referred to as the "desire to be" of a space. Moreover, with respect to what he called the "order" of an art museums space, Kahn pointed out the necessity of creating a flexible space for the display of artwork. He believed that every area should have its own independent and complete system for organizing space, rejected the parceling out of a large space into a number of smaller spaces, and had strong misgivings about fixed forms in the use of space. This gives visitors to the Yale University Art Gallery an opportunity to appreciate both the artwork and unique qualities of the space in which it is displayed. However, because of the political and economic exigencies of the time brought about by the Korean War, the federal government had place tight restrictions on the construction of large-scale public buildings, prompting Kahn to propose a design which emphasized both practicality and flexibility [5].

At the 1959 meeting of CIAM in Holland Kahn presented a paper in which he set forth his views on architectural design and how they had evolved since his work on the Yale University Art Gallery. He spoke about the important insights he gained while working on his designs of the University of Pennsylvania Medical Research Towers (1957–64), the First Unitarian Church (1959–1969), and the American Consulate in Portuguese Angola (unbuilt). Kahn also pointed out that modern architects need to realize the essential characteristics of a space and its desire to be, use the innate qualities of the structural system to integrate the mechanical services and practical functions, and use natural lighting to delineate the form of a space. Furthermore, he emphasized that modern architects should do more than merely formulate designs based on proven approaches and concepts. In discussing his art museum designs he stated, "*Now in the art gallery at Yale University - and I'll criticize my own gallery freely - I only came to a very slight conclusion there about order. The realization there was something which was not fully understood by me; had it been, the design would probably have been different. Though, I must say that it has certain aspects which are very good still. If I were to build a gallery now, I would really be more concerned about building spaces which are not used freely by the director as he wants. Rather I would give him spaces that were there and had certain inherent characteristics. Then the visitor, because of the nature of the space, would perceive a certain object in quite a different way. The director would be fitted out with such a variety of ways of getting light, from above, from below, from little slits, or from whatever he wanted, so that he felt that here was really a realm of spaces where one could show things in various aspects*" [6]. Based on this type of viewpoint, in his subsequent art museum designs Kahn began to re-evaluate "the nature of a place where you see paintings," eventually coming to adopt the integration of structural form and natural lighting as his main strategy for embodying the inherent characteristics of a space.

In regards to this, he later explained, "The glass wall on one side of the lobby maintains connection with the light outside, while the interior light, modeled by the building form, begins to assert itself. This light is the sacred light, the light that identifies a special place apart from the everyday world, that connects us to the unmeasurable. The sacred light emerges from the meeting of daylight and structure" [7]. That is to say, natural lighting is the key medium for displaying and transforming the inherent form of an object (place), enabling the subject to experience the inherent qualities of the object via the substantial elements which shape a space. For Kahn, natural light is what brings all objects into existence, and structure is what creates light. It can thus be seen that through the process of creating his art museum designs he formulated his realization about the highly poetic and interactive relationship between building, light, and subject.

In 1966 Kahn was commissioned to design the Kimbell Art Museum. R. F. Brown, the director of the preparatory committee, clearly stated his view that future art museums need to use natural lighting to create a space which harmonizes with human scale. By this time Kahn had a different realization of the inherent characteristics of space than when he designed the Yale Art Gallery. In his words, "*Natural light should play a vital part in illumination… The visitor must be able to relate to nature momentarily…to actually see at least a small slice of foliage, sky, sun, water. And the effects of changes in weather, position of the sun, seasons, must penetrate the building and participate in illuminating both art and observer… We are after a psychological effect through which the museum visitor feels that both he and the art he came to see are still part of the real, rotating, changeable world*" [8]. It was with this design concept in mind that Kahn decided to use a cycloid vault to shape the spatial order of the space and display the special characteristics of its light. The top lighting and courtyard formed by the cycloid vault creates an ambience in which visitors experience the cyclic natural changes which occur throughout the day.

The natural lighting technique Kahn employed in his design of the Kimbell Art Museum met with strong approval from P. D. Brown, the director of the preparatory committee of the Yale Center for British Art, and in 1969 Kahn was commissioned to design this new museum. While considering the unique qualities of this project, he became aware of the composite nature of the building the was commissioned to design. As he put it, "*The building site is located where the university campus meets the urban environment; moreover, the museum's collection is highly diverse*" [9]. To him, this was to be a conglomeration of two different types of institutions: a library and an art museum. With this in mind, in relation to these two types of buildings, Kahn began to consider the inherent significance a building itself, eventually developing a new understanding of the relationship between the organizational arranging of space and the configuration of a floor plan. He thus set out to create a space which would express and amplify the intimate relationship between people, books, and art.

The overall approach to the organization of space employed in his work on the Yale Center for British Art can be seen as an extension of the design concept in which structural form and natural lighting are used to reveal the intrinsic qualities of a space. After first considering the use of bridging structures, semi-circular arches, and vierendeel trusses, Kahn finally decided on a structural system consisting of triangular folded plate beams as the best way to usher in natural light. These structural forms apparently evolved out of his earlier designs for the Kimbell Art Museum, the University of Pennsylvania Medical Research Towers (1957–64), and the Salk Institute for Biological Studies (1959–65). By this time Kahn had already accumulated a wealth of experience and techniques through his investigations of structural form in relation to his earlier designs of a wide array of buildings, and he now skillfully applied this to organizing the spatial structure and integrating natural lighting into his museum designs. All three of his museum designs clearly exhibit his use of the spatial characteristics displayed by the structural elements. Even so, the major differences that do exist between these three designs are mainly result from the fact that it was only in the later stages of his career that Kahn came to fully realize the significance natural lighting has to inherent spatial qualities of an art museum. Thus it is especially in the latter two art museums that the visitor enters into a dynamic ambience manifested by the changes of natural light, a place where art, space, and self interpenetrate.

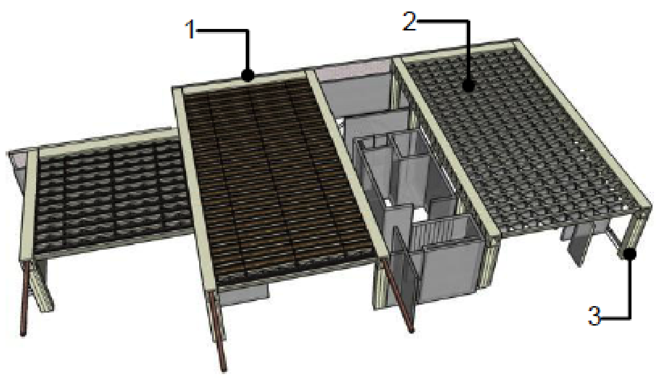
3. INTEGRATION OF THE STRUCTURE AND THE MECHANICAL SERVICES

3.1. The Yale Art Gallery

After the Yale Art Gallery was completed in 1954 Kahn put forth his views on how mechanical services should be integrated into a building. In this connection he wrote, "*We should try more to devise structures which can harbor the mechanical needs of rooms and spaces and require no covering. Ceilings with the structure furred in tend to erase the scale*" [10]. Kahn felt that using a suspended ceiling to integrate the mechanical services ruins the sense of order which comes from integrating them into the structure itself; it also causes the building itself to lose the distinguishing characteristics, which are necessary for conveying its organizational logic. Thus architects need to bring into full play the inherent qualities of the building materials and use the substantial structural elements to integrate the mechanical services.

While considering designs for the Yale Art Gallery which would allow the mechanical services to be integrated into the structure, Kahn aimed to make the most of the particular characteristics of reinforced concrete to integrate the mechanical services during the process of constructing the structural system. The components of the structural system are support columns, a tetrahedral floor system, and rectangular folded-plate beams (Figure **1**). On the center of the floor, in order to integrate all of the mechanical services without the distribution of the tetrahedral floor system, he replaced the RC floor slab with a versatile metal-mesh ceiling. Because the school wanted the interior space to be highly flexible, the design team used 4m × 8.4m structural modules to make the building more adaptable to different uses. At the same time, this structural system was able to easily satisfy the unusually stringent building codes of the time.

The tetrahedral RC floor system is composed of three types of concrete structural elements: 1) the upper level slab (4 inches thick); 2) long joists inclined at about 20° (5 inches thick); and 3) triangular slanted braces (3.5 inches thick) (Figure **2**). The entire structure was formed using on-site concrete pouring, with the surface of the concrete completely unadorned, allowing marks on the structural elements to reveal the construction process. Kahn believed that the joints where different materials meet are the source of ornament for the building itself, and also manifest his design concept of showing "*how it was done*" [11]. At the same time, it was in the process of designing the tetrahedral floor system that Kahn first formulated his ideas of served and servant space.



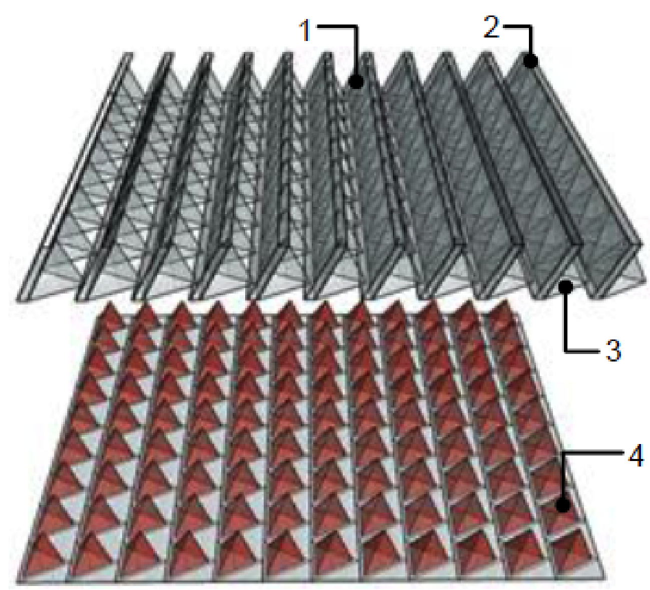
1 Rectangular folded plate beam.

2 Tetrahedral floor system.

3 Support column.

Figure 1: 3D Simulation model of the structure.

The assembly process of the tetrahedral floor system and the mechanical services can be divided into two stages. In the first stage reusable pyramid-shaped, triangular, and rectangular formworks were used to produce the moldboards of the triangular side braces and the slanted joists. Next, concrete was poured into the joists through the upper end, so that the braces and joists form into a single unit, with the reinforcement bars protruding out of the upper part of the joists for use in attaching the floor slab. In the second stage, before pouring the concrete, the air ducts and electrical wiring were installed in the space in between the braces and joists, and acoustical forms were placed above as a permanent structural element underneath the floor slab. Next, the protruding reinforcement bars were connected and the floor slab concrete was poured, thus completing the tetrahedral floor system (Figures **2**, **3**). Locating the mechanical services in the triangular space within the tetrahedral floor system was done in accordance with the building's structural order. How space is served and how it is formed are both displayed in structural form and assembly process of the tetrahedral floor system.



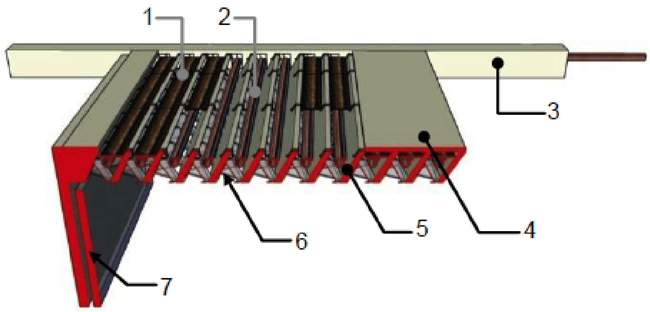
1 Rectangular formwork.

2 Concrete pouring point.

3 Triangular formwork.

4 Pyramidal formwork.

Figure 2: 3D Simulation model of the first stage of the construction of the tetrahedral floor system.



1 Acoustical form; 2 Air and electrical ducts; 3 Rectangular folded plate beam; 4 RC floor slab; 5 Inclined joist; 6 Triangular side bracing; 7 Double wall enclosing heating pipes.

Figure 3: 3D Simulation model of the integrated mechanical services of the tetrahedral floor system.

This floor system is 60% heavier than an ordinary floor with a 40-foot span. A review of the flooring system published in Architectural Forum pointed out five areas in which it has distinctive characteristics: 1) aesthetics; 2) lighting; 3) acoustics; 4) structure; and 5) environmental control [12]. In addition to exhibiting the order of the structure, the floor reveals the organizational relationships which exist between the various structural elements, resulting in a type of spatial aesthetics which conveys a sense of realism. With respect to lighting, the empty pyramidal-shaped spaces made it possible to tuck away the lighting fixtures, which could be reconfigured to suit the needs of different activities. The lower portion of the joists could be used to secure the partitions. With respect to acoustics, in addition to the acoustical forms in the floor's lower portion, the spaces and slanted angles of the floor slab also have sound-absorbing qualities. The floor system combines a space-frame system and a reinforced concrete structure to carry the structural loads, and its fire-prevention properties far exceed what is required by the local building codes.

Kahn believed that an architect should be a creator of space, and should avoid concealing anything which reveals the building's structural logic and design concept. Thus, the integrative design of the tetrahedral floor system was Kahn's initial attempt to integrate a building's mechanical systems into its structural elements by bringing into full play the qualities of the building materials. In discussing his design of the Yale Art Gallery he mentions his idea of building with hollow stones. In his words.

"In Gothic times, architects built in solid stones. Now we can build with hollow stones. The spaces defined by the members of a structure are as important as the members. These spaces range in scale from the voids of an insulation panel, voids for air, lighting and heat to circulate, to spaces big enough to walk through or live in. The desire to express voids positively in the design of structure is evidenced by the growing interest and work in the development of space frames. The forms being experimented with come from a closer knowledge of nature and the outgrowth of the constant search for order" [13].

The tetrahedral floor system was Kahn's way of realizing his concept of integrating the mechanical services by working with "hollow stones." On the one hand, the structural form of the floor system was a way of integrating the mechanical services, and on the other hand, it displayed the particular qualities of the space endowed with structural logic, while also avoiding the negative effects exposed mechanical services can have on spatial order.

3.2. The Kimbell Art Museum

While electric lighting provides most of the illumination in the Yale Art Gallery, in his design of the Kimbell Art Museum Kahn's decided to maximize the use of natural lighting. A series of design sketches for this new project reveal that Kahn intended to utilize natural lighting and structural form to manifest the character of the space, for which purpose he experimented with a wide variety of structural forms which would facilitate both the use of natural light and also the integration of the mechanical services. He finally decided on a design in which natural light is ushered into the interior by narrow skylights installed at the apex of a cycloid-shaped vaulted ceiling, a form which endows the building with a sense of spatial harmony on a human scale. Yet, because such an opening at the apex of the cylindrical vault compromised its structural integrity, a problem which was solved by the addition of vaulted units with a structural span of 33 meters by 6.7 meters.

In order to solve this problem, structural engineer August E. Komendant (1906–1992) successively proposed three different ways of improving the structural system: 1) strengthen the areas adjacent to the skylights by increasing the depth of the cross-section at the points which bear the greatest tension; 2) stabilize the shape of the vault by adding posttensioned, arch-shaped, end diaphragms to the ends of the cycloid vaults; and 3) add post-tensioning to the vaults RC structure, and also add post-tensioned stringers to the points which receive the greatest strain.

Analyzing of the structural system of the cycloid vault, it can be seen that its force-receiving characteristics are similar to those of a simple beam. The opening at the top of the vault is bridged by short transverse beams connected to the structural pillars at the four corners. The structural system is shaped like a bird with outstretched wings in flight. Thus, by adjusting the structural form and making use of prestressed RC technology, Komendant finally found a way to make the structural form sufficiently strong (Figures **4**, **5**).

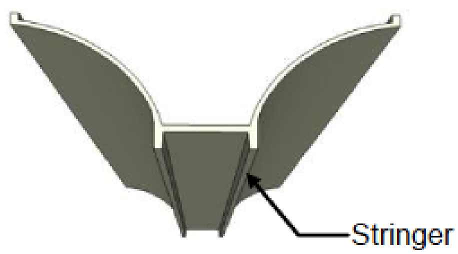
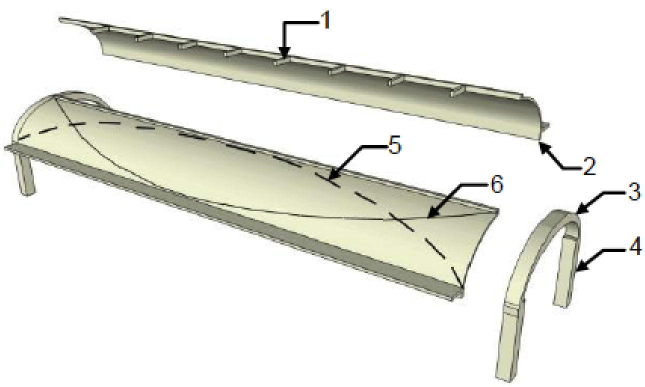


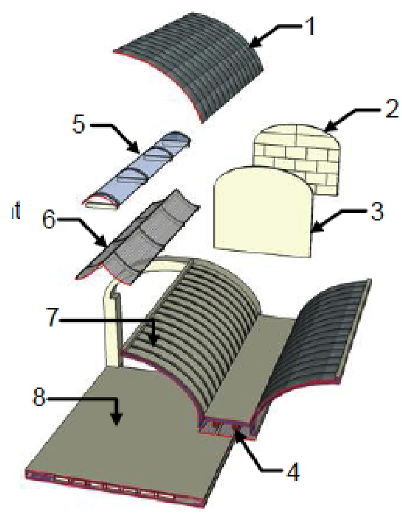
Figure 4: Cycloid vault structural elements.



1 Short transverse beams.
2 Stringer.
3 arch-shaped end diaphragms.
4 Support column.
5 Compression.
6 Tension.

Figure 5: 3D diagram of cycloid vault structure.

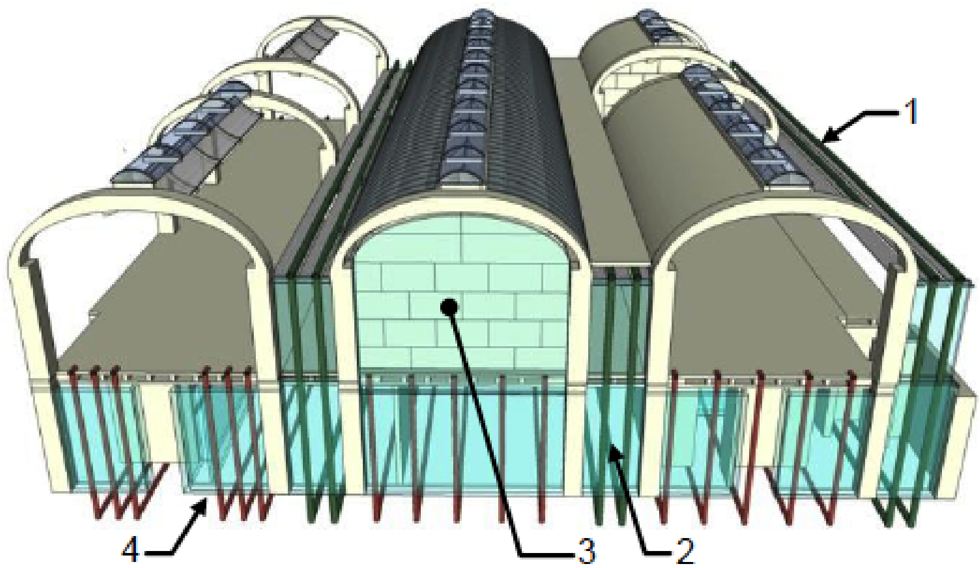
The first stage in the construction process of the cycloid vaulted ceiling was to use RC to manufacture the structural support columns and the arched end beams, and then reinforce the vaults. In fabricating the formwork for the cycloid vaulted ceiling, it was necessary to adapt the strut technique used in shipbuilding, and the hinged wooden truss support bases in between could be freely opened and closed, making it possible to reuse the formworks during the concrete pouring process. After the formwork of the lower part of the vault was stabilized, the vault's steel reinforcement bars were fastened together and the post tensioned cables were buried. Next, the perpendicular formwork stabilization bars were installed on top of the reinforcement bars. In order to reduce the lateral stress and the possibility grain separation while pouring the concrete for the curved surface of the vault, the concrete was poured in successive one-foot increments using a small horizontal formwork. In the final stage, once the concrete had cured, only the small horizontal formwork was removed, the perpendicular formwork stabilization bars remained in place and were used to fix the lead plate to the outer surface of the vault (Figure **6**).



1 Lead waterproof plate.
2, 3 Travertine panels.
4 Mechanical services space.
5 Alabaster plexiglass skylight.
6 Aluminum light reflector.
7 Formwork stabilization bar.
8 Waffle slab.

Figure 6: Cycloid vault 3D simulation model.

While designing the overall structural order of the Kimbell Art Museum, Kahn also gave due consideration to the question of how to integrate the mechanical services. In order to minimize the interference mechanical services can have on a space, he used integration of the structural form to increase the efficiency of the spatial organization, and also applied his concept of served and servant space. Kahn's idea of servant space can be seen in both the vertical and horizontal dimensions. In the vertical dimension, the servant space mainly consists of the support columns



1 Transmission channel enclosed within the stringer and aluminum cover.

2 Vertical transmission channel between columns.

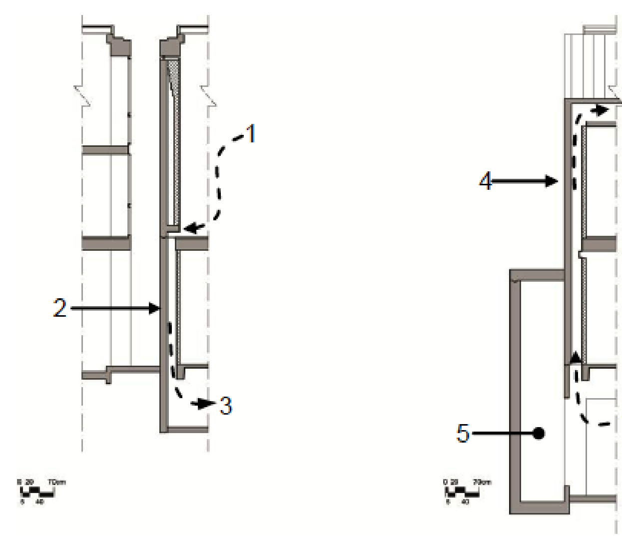
3 Double wall.

4 Mechanical services room.

Figure 7: 3D Simulation model of the structure and mechanical services.

and the double walls. The mechanical services are enclosed in the vertical transmission channels enclosed by the support columns, and are distributed to the adjacent served spaces by using the void inside the double wall. On the horizontal dimension, the servant space consists of the underground mechanical services room and the Transmission channel enclosed within the stringer and aluminum cover. After leaving the mechanical services room, the ducts first pass through the vertical servant space, then pass through the transmission channel enclosed by the stringers and aluminum cover, after which they enter the exhibition space. Moreover, Kahn attempted to use different structural forms to separate the different service functions. For integrating the air-conditioning system, Kahn designed various forms of double walls to separate the intake and exhaust points. The lower sections of the double walls have long, level openings for the return air ducts, and the double walls enclosing the incoming air ducts are directly connected with the stringers (Figures **7**, **8**).

In contrast with the Yale Art Gallery, this design integrates the mechanical services into the structure in a way in which the utility ducts remain separate from the structural components, facilitating maintenance and replacement of the mechanical services. With respect to flexibility and the restrictions which result from the



1 Return air.

2 Double wall.

3 Mechanical services room.

4 Double wall.

5 Air channel.

6 Outgoing air.

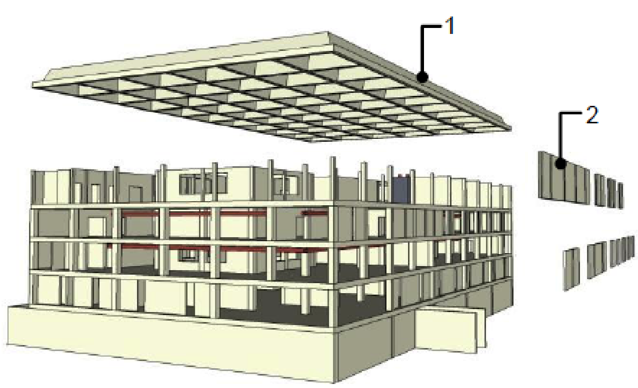
7 Mechanical services room.

Figure 8: Cross-section of the ventilation system incorporated into the double walled structure (L: Intake; R: Outtake).

transmission of mechanical services, both the horizontal and vertical servant spaces of this design lend increased freedom of configuration to the served spaces. In addition, in using this way of integrating the mechanical services, the organizational logic of the servant spaces accords with the structural order of the cycloid vaulted ceiling. By connecting the void between the structural columns and modular spatial form of the cycloid vaulted ceiling, Kahn succeeded in developing a structural combination consisting of the horizontal and vertical servant spaces attached to the served spaces. Therefore, the integration of the mechanical services could be completed between the substantial construction of the served and servant spaces.

3.3. The Yale Center for British Art

The structural form of the Yale Center for British Art is composed of an RC column and beam framework and a stainless steel enclosure. Due to construction and budget limitations, apart from the precast V-shaped folded concrete plates, the entire structural system was manufactured on site using 6m x 6m structural modules and poured concrete (Figure **9**). Kahn's intended the Center's structural form to be reminiscent of the brick façade of the Exeter Library, in which the thickness of the brick piers gradually decreases with height. Following the same structural logic, the Center's support pillars are not only tapered, but also retreated inwards, partitioning the façade into shadowed recesses and clearly displaying the building's inherent structural logic (Figure **10**).



1 V-shaped folded concrete plates

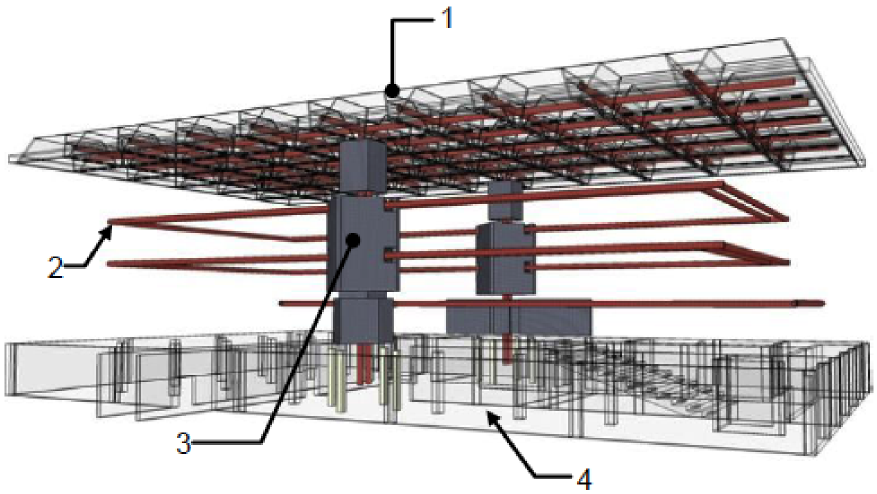
2 stainless steel exterior

Figure 9: 3D diagram of the structure.

The enclosing façade is composed of reflective glass and acid-etched stainless-steel panels. Kahn felt that the gray color of acid-etched stainless steel goes very well with the hue of concrete, which, when combined with glass, produces a stunning effect of alternating transparent, opaque, reflective, and dark surfaces capable of reflecting the changes in the exterior light and weather. Describing the intended interplay of dark and light, Kahn stated, "*On a grey day it will look like a moth; on a sunny day like a butterfly.*" [14] This was the first time Kahn used metal materials on a large scale for a building's exterior. By taking advantage of the intrinsic qualities of industrial materials such as unique texture, standardization, and fabrication, Kahn created a building with a monumental style, something quite different from his earlier museums.

Figure 10: Inward inversion of the supporting columns. (Source: Wiseman, C. (2007), Louis I. Kahn: Beyond time and style, New York: W. W. Norton and Company Inc., 249).

In regards to the served and servant space, in the early stages of the design Kahn placed both the mechanical services and the emergency exit stairways inside independent towers located at the building's four corners, with a vertical stream-lined shaft at the center of the plane. This center-corner configuration and having independent spaces for the served and servant spaces accentuated the a spatial order based on the distinction between primary and secondary space. Due to budget limitations, however, the design was later simplified, with the towers at the four corners being replaced by two independent mechanical services transmission shafts located in the interior. The logic of the servant space configuration was to place the mechanical services transmission route inside independent vertical stream-lined shafts which would link up the mechanical services—in both the vertical



1 V-shaped folded concrete plate beams (heating and cooling ducts).

2 Heating and cooling ducts.

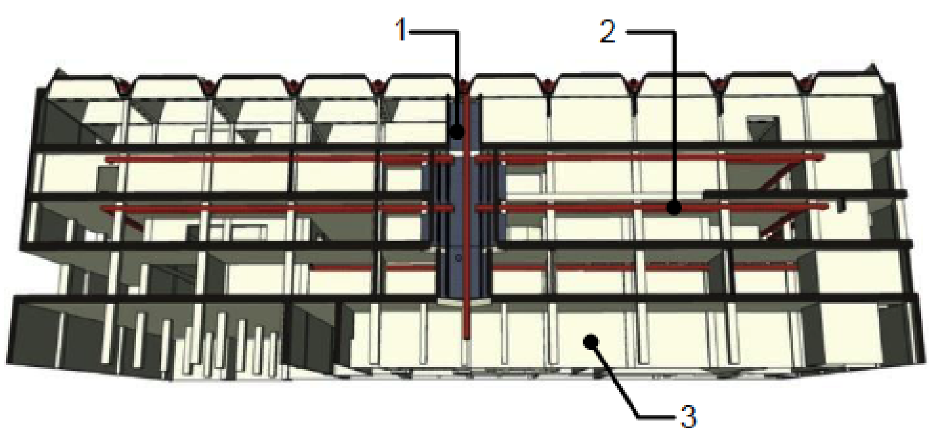
3 Mechanical services transmission shaft.

4 Underground mechanical services room.

Figure 11: 3D simulation model of service space.

and horizontal directions—on each floor with the mechanical services room in the basement, and the size of the shafts could be adjusted to suit the needs of each floor. In this way the transmission route for the mechanical services became an independent functional space (Figure **11**).

The integration of the main structure and its mechanical services at the Yale Center for British Art was an extension of the techniques Kahn applied at the Salk Institute for Biological Studies [15] and the Phillips Exeter Academy Library [16], namely the incorporation of mechanical services by covering or exposing them using structural elements. The design called for the use of natural lighting for the top floor exhibition space, leading Kahn to utilize a V-shaped, RC, folded-plate roof structure which incorporated the air conditioning ducts and skylights, similar to that which he proposed in an early draft of his design for the Salk Institute. These structural units were combined to form double-sided, orthogonal forms to match the Center's square structural modules. The skylights were fitted to the square voids in the middle of each module (Figure **19**).



1 Vertical mechanical services transmission shaft

2 Air conditioning ducts

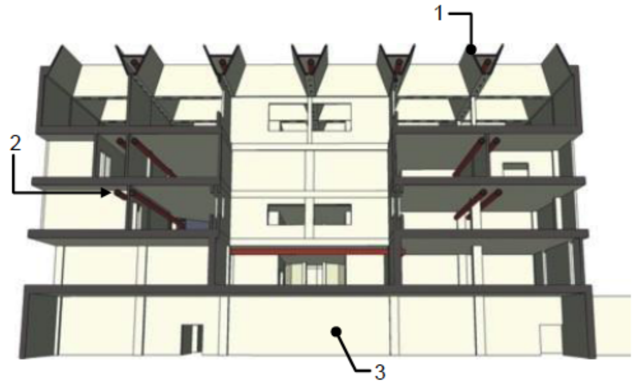
3 Underground storage and mechanical services space

Figure 12: 3D integration diagram of space, structure and mechanical services.

While on the top floor the heating and cooling ducts were incorporated into the folded-plate structure, on the other floors Kahn used straight, round, stainless steel ducts exposed and suspended from the structural frame. In this configuration the ducts enter the space from the centrally located mechanical services shaft, and then extend throughout the entire floor (Figure **12**). However, in order to prevent the exposed ducts from destroying the spatial order, he used a twin-duct looping configuration to integrate them into the structural modules of the framework. In this way he clearly articulated what he meant by "served space" (Figures **13**, **14**). Kahn believes that by incorporating the exposed pipelines with the structural order, it is possible to avoid the problem of the mechanical services disrupting spatial order, allowing the integrated system to be better understood. Kahn regarded such a duct configuration to be rather like a sculpture which belongs to the museum's permanent collection. This approach to integrating the mechanical services while keeping them exposed to view reveals the unique characteristics of a space has already become widely accepted, even amongst architects of the modernist school of thought. It was while designing the Center that Kahn felt compelled to defend the aesthetics of exposed utility ducts, stating.

Figure 13: Exposed integrated outtake ventilation pipes.

"If we were able in our structures of the future to isolate the equipment of the mechanical as though it had its own aesthetic existence, just as the spaces have their own, then we would free the building of all the subterfuges we use to conceal the services of the building. In the Mellon Center for British Art and Studies, I tried to express more dramatically this very point. In the original studies I made for Mellon, there were instruments outside which looked or will look like something independent. Instruments of different natures are for the supply of air, the exhaust of air, the machinery that goes into making the air the way you want it on the interior of the building" [17].

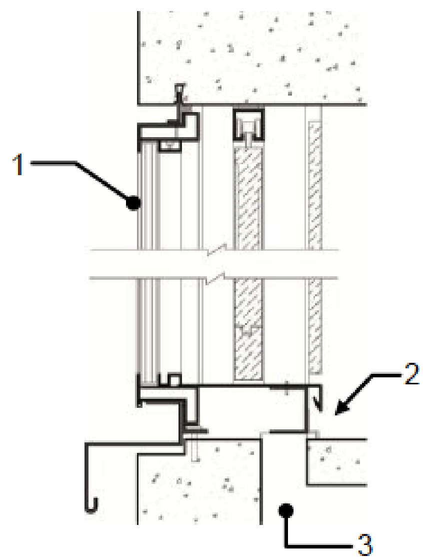


1 V-shaped folded plate beams.

2 Air conditioning ducts.

3 Underground storage and mechanical services space.

Figure 14: 3D Simulation model of outtake ventilation pipe distribution.



1 Acid-etched.

stainless steel outer wall.

2 Return air duct.

3 Hollow slab.

Figure 15: Detailed cross-section of acid-etched stainless-steel walls and hollow slab.

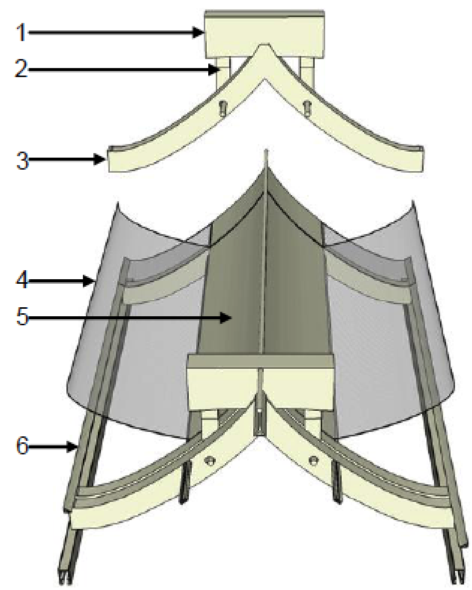
In addition to exposed exhaust ducts, in order to reduce the number of mechanical service ducts, Kahn incorporated the return air ducts into the structure of the outer walls and hollow slab (Figure **15**). In this way he brought together the special qualities of the industrial metal material and the structural form of the RC to solve the problem of how to integrate the return air ducts. With regards to the use of metal materials, Kahn used stainless steel not only for the mechanical air conditioning ducts, but also to cover the mechanical services shaft outside (Figures **11**, **12**). Also, while both the shaft and the exterior panels both use acid-etched stainless steel, only the steel used in the former has a glossy finish. Kahn aimed to use the same material with two different textures to accentuate functional differences and the primary-secondary logical relationship. Thus we can see that with respect to both steel and RC, Kahn's goal was to give full expression to the material's intrinsic qualities, while giving due consideration to the form and details of the structure when deciding how to integrate the mechanical services.

4. NATURAL LIGHTING

In considering the spatial qualities of these three museums, it is clear that they differ most in terms of structural form and use of natural light. As Kahn explained it, "*The structure is a design in light. The vault, the dome, the arch, the column are structures related to the character of light. Natural light gives mood to space by the nuances of light in the time of the day and the seasons of the year as it enters and modifies the space.*" [18] Thus the use of natural light and structural form in these three designs can be seen as the progressive result of Kahn's ongoing exploration of the intrinsic quality of a museum.

In his design of the Yale Art Gallery Kahn had not yet put formulated his later design concept in which natural light is the main source of illumination for both the artwork and the space itself. Instead, most of the lighting is provided by electric light fixtures incorporated into the structural voids of the tetrahedral floor system. It was only with his work on the Kimbell Art Museum that he began to implement his design concept which utilizes natural light and structural form to manifest the unique spatial features of an art museum. Early sketches and discussion of the project by lighting engineer Richard Kelly reveal that Kahn attempted to incorporate various innovative natural lighting systems into the structural form as a way of molding the different types of light which occur throughout the day to create a variety of lighting effects and also to differentiate the distinctive spatial attributes of the different areas within the Museum. Thus, the main points to be considered by the Museum design team were the introduction of natural light, as well as its reflection, filtering, and diffusion.

Once the overall design was decided on, Kahn used the opening at the top of the cycloid vaulted ceiling to usher in natural light, and the opening was covered with opalescent plexiglass skylights capable of filtering out harmful light rays. After passing through the skylights the aluminum plates—opaque in the center and pierced on the sides—reflect the light onto the surface of the cycloid vault, the curvature of which then evenly diffuses the light downwards throughout the exhibition space below. Electric track lighting is attached to the bottom of the aluminum plates (Figure **16**).



1 Transverse beam at top of vault.
2 Metal structural hanger.
3 Single-piece double brace.
4 Multi-apertured aluminum plate.
5 Opaque aluminum plate.
6 Track lighting holder.

Figure 16: 3D Simulation model of aluminum reflector.

It should be pointed out that in order to avoid the damage which would have been caused to the artwork by direct sunlight two different types of reflectors were used. For the exhibition space, Kahn enlarged the area of the opaque central section of the reflectors to prevent low-angle midday sun from entering. For the other areas, such as the lobby and lecture hall, he reduced the opaque area so as to allow a small amount of direct sunlight to enter (Figures **17**, **18**). In other words, the different types of light created by these two types of reflectors help to define the spatial attributes of a given space. In this way Kahn succeeded in creating a quality of light highly suitable for the exhibition of artwork, and which gives visitors a distinct sense of how the ambience of a space changes with the natural differences in light which occur throughout the day.

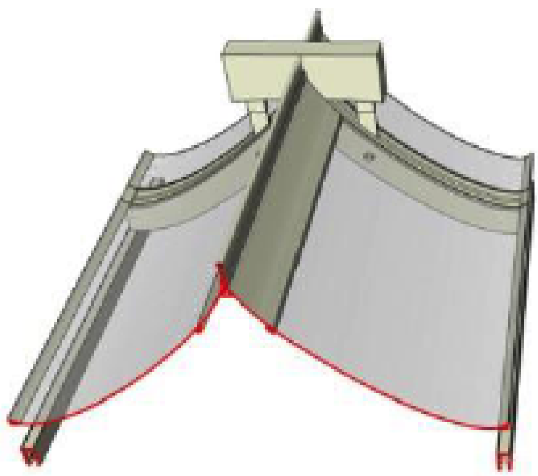


Figure 17: A cross-section of the aluminum reflector in public spaces (Left).

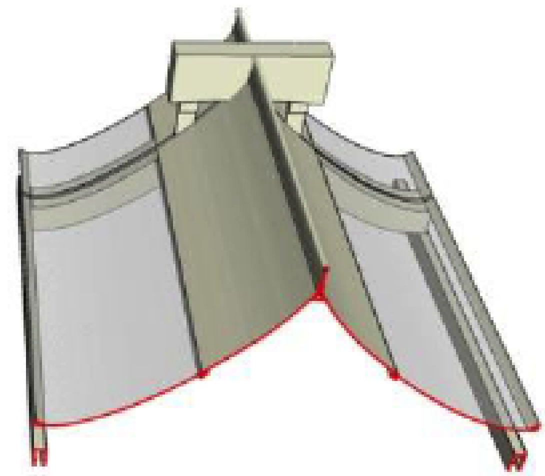
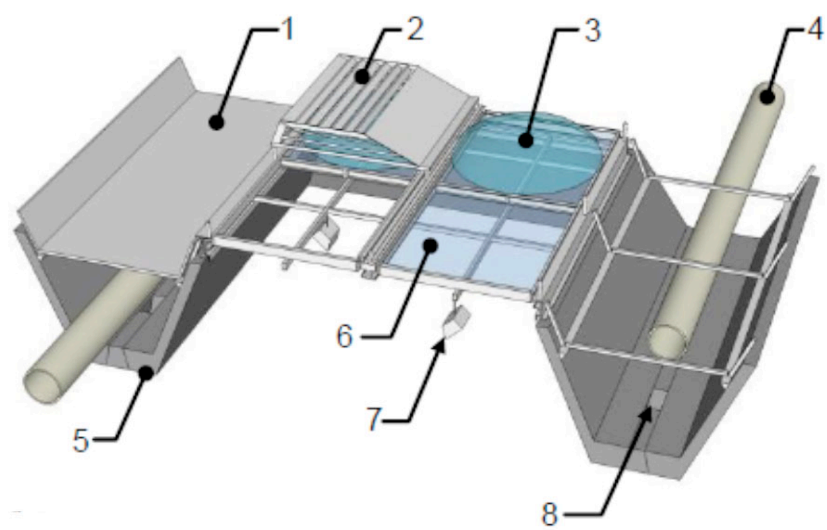


Figure 18: A Cross-section of the aluminum reflector in exhibition spaces (right).

In comparison to the lighting system designed for the Kimbell Art Museum in which the partial obstruction of sunlight creates a relatively high degree of contrast, the natural illumination at the Yale Center for British Art is more direct and evenly diffused. The artwork in the exhibition space can be completely exposed to modulated natural light. While deliberating on the



1 Metal shrouding.
2 Shutters.
3 Double-layered plexiglass bubbles.
4 Air conditioning ducts.
5 V-shaped folded-plate beam.
6 Double plastic prism.
7 Electric light.
8 Air outlet.

Figure 19: 3D Simulation Model of the Structure Integrating Ventilation and Lighting Properties.

question of how to minimize the amount of ultraviolet light—more intense in sunlight coming from the north, and harmful to both artwork and visitors' skin—entering the building, Kelly formulated what he called his "light theory," and accordingly differentiated three levels of natural light: 1) direct; 2) reflected; and 3) filtered and distributed. Kahn and Kelly aimed to design a natural lighting system which would allow more sunlight to enter when the sun was at a lower angle, allow less to enter around midday, and altogether prevent the entry of sun from the northern direction [19].

Their solution was to incorporate the skylights on the top floor into the precast, RC, folded-plate beams. While developing the detailed skylight design, the constant challenge was, once a sufficient amount of sunlight was brought inside, how to soften and evenly distribute it throughout the building's interior. At the time of Kahn's untimely death in 1974, the design team had reached consensus only on the configuration and mode of distribution; it was only with the assistance of Kahn's colleague Marshall Meyers that the details of the skylights were finalized.

In accordance with Kelly's above-mentioned light theory, the design details of the skylights could be divided into three major parts: 1) A shutter device. Louvers were positioned so as to modulate the incidence of natural light entering from the south, east, and west, using optical calculations to determine the optimal angle for each individual louver; A metal cover was used to completely block direct sunlight from the north; 2) A filtering device. Double-layered plexiglass bubbles with an anti-UV coating on the inner layer were used to reduce the amount of UV rays entering the interior; 3) A dispersion device. A double plastic prism was used to evenly distribute the filtered light throughout the exhibition space (Figure **19**) [20]. Similar to the way he adopted a space-specific differential lighting scheme for the Kimbell Art Museum, Kahn decided to not install the light diffusion prisms on the skylights above the Center's central courtyard, so as to produce a quality of light distinct from that of the exhibition areas. Thus, while the quality of the natural light in the exhibition area remains relatively steady, that of the central courtyard changes throughout the course of the day, creating a variety of visual effects.

CONCLUSION

Wishing to display how space is constructed and served, Kahn rejected the common practice of using a suspended ceiling to conceal the mechanical services. Moreover, he emphasized the importance of experimenting with a wide array of structural designs in order to find a way to integrate modern mechanical services into the structure itself. Kahn encouraged contemporary architects to integrate the mechanical services by bringing into full play the inherent qualities of the building materials and by giving due consideration to the structural form and its substantial elements. In his museum designs Kahn used natural lighting and structural form to shape the unique qualities of a space, at the same time attempting to convey the building's structural logic and the logic of integrating the mechanical services. While doing so, Kahn's primary concern was the principle of structural form and order.

By examining Kahn's three museum designs it becomes apparent that subsequent to designing the Yale Art Gallery he began to make increasing use of natural light to manifest the inherent qualities of a space. He thus found it necessary to open up the roof structure, which, in turn, made it necessary for the horizontal mechanical services transmission lines to make greater use of the vertical structural elements. As a result, such independent vertical structural forms as double walls and mechanical services shafts became the key elements for integrating the mechanical services. Based on the structural design concept whereby both served and servant space both require an independent space, beginning right with the structural voids of the tetrahedral floorslab system, the structural form of the transmission lines evolved into a service space capable of accentuating the inherent qualities of the served space. Kahn's spatial organization clearly revealed the relationship between natural lighting roof structure and the vertical structural elements used to integrate the mechanical systems.

In all three museum designs the main approach to integrating exposed transmission lines was by conforming to the order of the structural module and incorporating them into the structural logic of the framework. With concealed mechanical services, however, the approach was to incorporate them into the structural elements, resulting in the development of such novel structural forms as the tetrahedral floorslab system, double walls, stringers, intra-pillar channel, and V-shaped folded-plate beams. Moreover, Kahn's design concept of integrating exposed ducts by regarding them as a type of sculpture inaugurated a whole new approach to the aesthetics of space and extrinsic form in high-tech architecture, quite distinct from the contemporary preference for using suspended ceilings to conceal the mechanical services [21]. In the case of the Yale Art Gallery, however, it is clear that enclosing the mechanical services within the tetrahedral floor system has made maintenance and replacement highly problematic.

In the process of considering how to integrate structure and natural light, based on the design concept of “using the structure to create life-giving light,” while using structural form to configure the spatial order, Kahn aimed to fashion the quality of the natural light being ushered into the buildings interior. He experimented with a wide array of subtle differences in the quality of light to see how they would affect the mood of a particular space. He also used the marks visible on the prominent structural elements to display the special characteristics of the materials being used as well as the comprehensive structural logic of the space as a way of manifesting in a concrete way a type of structural logic both rational and poetic. The combination of an open cycloid vault and reflector Kahn used for the Kimbell Art Museum transformed the natural light into silvery strips, creating a rhythmic spatial order in which the space takes on a different ambience according to the time of day. The sharp contrast between the strips of light thus created comprehensively manifests the forms in the exhibition space. By comparison, the natural lighting system of the Yale Center for British Art is more comprehensive with respect to incidence, filtering, and distribution.

Natural light has to be evenly distributed in order to minimize the harmful effects that it can have on artwork while also providing optimal lighting conditions for works which are less sensitive. [22] In terms of spatial form and the use of natural lighting, this approach to passive natural lighting has had a profound impact on the development of subsequent art museum designs. [23] At the beginning of the 21st century it is clear that the concepts of “Sustainability” and “energy efficiency” have already come to the fore, but it was decades ago that Louis Kahn began formulating his concept of using structural form to integrate mechanical services and bring natural light inside, devising a way of building museums which replies the qualities of an environment by starting from the building itself. [24] With minimal use of automated high-tech equipment, his museum designs utilize only the media of structure and natural light to create an intimate and natural ambience. This way of using the rational construction process to transform an inherent quality of an element of the natural environment as it is ushered into the building’s interior space gives visitors a distinct impression of entering a realm where self, art, building, and nature harmoniously coexist. The significance of Kahn’s legacy lies in the emphasis he gave to making the inherent qualities of the space itself the starting point of design, as well the foresight he had with respect to sustainability and strategies of the passive design for the museum space in the future [25].

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