6-2011

Fallingwater: Structure and Design

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Fallingwater is the country home designed in 1935 for the wealthy Pittsburgh merchant Edgar Kaufmann Sr. by the architect Frank Lloyd Wright.[1] Since its completion in 1940 it has enthralled the American public and architectural enthusiasts; received countless awards and recognitions; and is generally held as one of the greatest pieces of architecture of the modern world. It is the most well known residential building in the world excluding those made for royalty.[4] Whether this great fame is deserved or not is a matter of opinion but there are a number of features of this buildings design that cause it to be held in such high esteem. An important part of Wright's method was an integration of nature and the surroundings into the building, which became a central theme of the Kauffman house. His departure from the rigid “Victorian box” of earlier styles into a more open plan is also dramatically exemplified by this building. Wright's daring and audacious use of new materials in an unprecedentedly bold structure astounds even modern visitors. These factors and the thoroughness of design all come together to make his architecture, incredibly influential on architecture, society, and culture in general.Fallingwater is a primary example of this influence. These factors also show that Frank Lloyd Wright's Fallingwater is a masterpiece of art and structural mechanics. Studying its design and constructing an architectural model of it will result in a deeper understanding of the principles of architecture.

Figure 1.. Fallingwater

Frank Lloyd Wright was born shortly after the end of the Civil War and died soon after the launching of Sputnik.[4] By the time Fallingwater was commissioned he had already had a long and illustrious career that had seemed to be in its twilight. Fallingwater marked the beginning of resurgence in his career and saw the creation of many of his most important and innovative designs, Fallingwater chief among them. Many of the ideas for this house at Bear Run Pennsylvania had been developed by Wright earlier in his career but they came into total fruition at Fallingwater. One of the most important themes in his design was his idea of organic architecture. Organic Architecture is the use of the principles of nature in the design of a building. In organic architecture the natural properties of building materials are respected and cultivated. The form and the function of the structure are considered as one idea, and the site structure and context of the building are designed to be complementary. Wright also championed American Democratic ideals and strove to create a truly American architecture. This was typified by his Usonian style: economical, simple, and beautiful. He also loved to emphasize the power of the horizontal line: evoking equality, opening up space, and connecting a buildings inhabitants with their natural surroundings. This is best seen in his Prairie style houses where he first began using the cantilevers that became so integral to the design of Fallingwater. With so many innovative design ideas it is not surprising that Wright was prolific and incredibly influential. He designed over one thousand buildings in his career. Wright, like many creative geniuses, was also extremely egotistical and domineering. In his mind nothing was more important or closer to perfect than his vision. This behavior resulted in a number of leaky roofs, sagging terraces, and arguments with clients. It also resulted in some of the greatest architecture ever designed. Fallingwater is a product of both Wright's design ideas and personality, as well as those of his clients and the context of the time. Understanding each of these components and how they interacted can give a fuller and richer understanding of this great building.

Architecture is an art form as old as human society. It meets the basic need of humanity to be protected from harm. Throughout history though architecture has answered and reflected human needs greater than those basic needs for survival. Architecture gives tangible form to human interactions and societies. It organizes space and can have powerful effects, both good and bad. Architecture can give people comfort, ease their lives, and be a thing of great beauty. For architecture to be so powerful and helpful is not a simple task though. It requires great understanding and care in design. An architect must be knowledgeable in fields as varied as geometry, aesthetics, physics, art, philosophy, and human psychology. There are certain basic principles of good design and knowledge of these is necessary in order to fully appreciate Fallingwater.

The Roman Vitruvius wrote the first known treatise on Architecture, and its lessons are still fundamentally important today. He argued that good architectural design must be based on three principles: Function, Structure, and Beauty. Function encompasses the cultural and personal needs that a building design must meet. Structure is the use of available materials and technology to keep the building intact. Beauty is the aesthetic appeal of the building.[8] To successfully design a building all three of these ideas must be considered and harmoniously integrated.

The problem and solution of an architectural design question can also be broken down into parti and program. Parti describes the essential design concept, or the simplest reduction of the building form. The program is the clear solution to the functional needs of the client. This method was used in the Beaux-arts school in Paris. It is another important way to organize and develop a successful building design. In this method, the architect devises a compatible parti and program for a project and expands on this fundamental idea to create the final building.[8]

There are many choices the architect must make in designing his creation in order to fulfill his parti and program, or Vitruvian triad. Some of the most important decisions include whether the building should be symmetrical or asymmetrical. A symmetrical building is often very regular and formal whereas an asymmetrical building is looser and more comfortable. The building can also be additive or divisive. That is it can be composed of the addition of smaller forms or of subdivisions of a larger form. An additive plan is often picturesque, organic, and dynamic. A divisive plan is regular, structured, and balanced. A building can support its loads using arctuated (composed of arced forms) or tribeated (composed of rectilinear beams and columns) systems. There are also many different pairs of choices which can be emphasized or de-emphasized. A buildings form can be planar or plastic where two dimensional planes are the main constituent, or three dimensional forms are the primary components. Further, the form can be created as a solid or void. This creates a feeling of security and strength, or lightness and longing respectively. The building can be rectilinear or curvilinear; closed or open; have clarity or obscurity.[9] A building can also combine and juxtapose different methods. Each decision creates meaning, feeling, and reactions from the buildings users and must be given careful consideration.

In looking at the larger picture the architect must also consider more general organizing principles: scale, proportion, rhythm, and shape to name a few. These decisions further influence how people interact and feel in the structure, and their proper application creates cohesiveness in the subject.

However important architectural design is, it cannot be thought about without consideration of structural principles and constraints. Structural principles must be met not only to prevent a failure of a building, but also because considering these constraints in the original design leads to the best results. While a full overview of structural mechanics is beyond the scope of this paper, an understanding of basic principles allows insight into the various applications for architecture.

The most important idea in structural design is intuitive, that there are physical forces that a building must resist to stay intact. This basic idea is quantified by Newton's laws of classical mechanics. Many extrapolations can be made regarding building from these simple laws. Newton's first law states that a body will remain at rest unless acted upon by a force. His third law states that for a body at rest, each action has an equal and opposite reaction. A body at rest is in equilibrium. This is the ideal condition for a building both in terms of safety and comfort. Using mathematical equations derived from Newton's laws, it is possible to calculate and design a building to be in equilibrium.[2]

To design a building to be in equilibrium all of the forces and interactions on the structure must be understood. These various forces can be divided into different categories. The first load to be calculated in a construction project is the dead load of the building. The dead load is the weight of the building's components (including floors, beams, columns, and roof). This load is usually the most substantial of any. There are also live loads which include the people, furniture, and other objects that only exert a force on the building some of the time. Both these groups of forces change slowly and are categorized as static loads. The forces that develop and change over time are called dynamic loads. These include effects such as wind and earthquakes. Dynamic loads can be dangerous because the same load applied quickly can be equal to many times its statically applied weight.[2] This is illustrated by the impact of a hammer on a nail, compared to its weight rested on a nail head. Forces may act more like a static or dynamic force depending on conditions.

Different materials and components can behave in many different ways when different forces are applied. The most basic reactive forces that occur under loads are tension and compression. Tension is the force that develops when a material is pulled and compression occurs when a material is pushed. Structural elements such as beams can develop both tension and compression simultaneously. A material may resist tension or compression well, or both. Regardless of the type of materials though, loads are carried to the ground through the “easiest” path, the one that requires the least work by the structural members. This is termed the law of least work.[2] This is important to know how to design an efficient structural solution for a building.

The force per area that acts on a material is called the stress and a materials reaction to stress is called strain. Strain is measured by the deformation from original dimensions. A material's strength is its resistance to strain, but it is not the only characteristic that is useful in a building material. A material’s stiffness is also important. If a material bends under a load and returns to its original position, it behaves elastically. If it does not return to normal after unloading then the material behaves plastically. No material is perfectly elastic or plastic. The ideal building material is elastic at normal loads and becomes plastic greater loads. This is necessary because if a material were too inelastic, it would be brittle and fail without warning (the reason glass cannot be used like steel). If a material were too plastic on the other hand, the deformations under forces would increase over time and it could not support the necessary loads.[2]

The different characteristics listed above explain the various ways in which building materials may react or fail. At the most basic, a beam or similar member will bend when it is loaded at a right angle to its axis.[2] This will result in a compression or tension in the length of the beam. This simple concept can be very useful in building. Knowing where tension and compression will develop allows a designer to pick the perfect material and system of supports. The “I” beam is a good example of this concept. The “I” beam is more efficient than a regular beam because material is localized to areas that resist the majority of the force.

With a sufficient knowledge of these basic structural principles it is possible to begin to design effective structural systems. In architecture the concerns of beauty and function must also be considered, so the optimal structural solution is not always the best option. A parabolic funicular curve may be the most efficient way to carry a load, but it is not the most useful shape for housing many human activities and needs. In designing a building an architect (with help from structural engineers) must decide on a parti utilizing both structural concepts as well as aesthetic ones. Equal to the number of structural problems is the number of structural systems available to an engineer and architect. The building design can be arctuated or tribeated (composed of arches or of posts and beams).[9] The designer can make use of beams, columns, arches, floors, and domes as forms. Masonry, wood, concrete, steel, and glass as can be used as materials just to name a few of the possibilities. The simple geometric and compositional options available can be combined in uncountable ways to answer any structural or programmatic problem.

In Frank Lloyd Wright's design of Fallingwater, he incorporated many different design concepts into the overall structure. An important concept for Wright was what he called balance or reflex. This refers to the design relation of diverse building components. Balance and reflex can be seen throughout the building but the best example is in the hatch stairs. These stairs point against the flow of the river, creating a juxtaposition and balance. Balance and reflex can also be found between the set of terraces and the set of waterfalls. The intersection of the terraces mimics the intersection of the waterfalls.

Figure 2. Relation of terraces to waterfalls

Balance can also be seen throughout the building in the balance of horizontal and vertical members. Another important concept is motifs. This refers to themes which recurring throughout the building. An example of this is the curve which can be seen all over the building from the parapets to the hatch opening to the bookcases. Another motif is water flow. Not only does the presence of water pervade the building but many components of the house mimic the rivers flow. Honest use of materials is a concept Wright developed as part of his organic architecture. It can be seen in Fallingwater in the stone which alludes to the rock strata of the surrounding country, the glass which is used as a gentle counterpoint to the glassy reflection of the water, the concrete shaped and modeled after its primitive ancestor adobe, and the steel which is used in strong strait lines painted red to invoke the ore it is made from.[5]

Figure 3. Masonry reflecting the local rock strata.

The “honesty” of the structure is also shown through the observable and intuitive balance of forces. It is possible in viewing the building to see where the forces flow and resolve themselves into the rock bed. Wright was also in love with powerful horizontal lines because he believed they conveyed his 'romantic humanistic' ideals. These horizontal lines are powerful in Fallingwater because the ubiquitous cantilevers are connected by glass which evaporates the vertical dimension of the structure. This gives a strong contrast between shelter and outlook which is innately appealing. This is strongly felt in Fallingwater because of the dark and cavernous interiors that open strait out to dramatic sunlight terraces. Wright was also a master of subtle geometric regulations. In Fallingwater this is beautifully achieved through a 30-60-90 triangle based off of the plane of the falls. All of the geometric organization of the building can be developed off of this triangle.[3] Wright also made use of a datum level at the level of the bridge and boulder base to give regularity and intuitive sense to his construction. While this is not a complete list of the ways in which Fallingwater is organized, it does convey the complexity and thoroughness of its design. For anyone who originally doubted, this has hopefully shown how artfully designed and organized this building really is.

Frank Lloyd Wright was never formally trained in engineering or structural mechanics, but he had an incredible intuition for how to support and balance forces and materials. He was also continuously in search of new materials, new technologies, and new ideas for solving structural and technological problems. Similar to his artistic principles, his structural ideas were often drawn from nature.

For the creation of many of his buildings, Wright used the cantilever as a primary element. In Fallingwater it became the primary structural and design element. The cantilever is a basic and supremely useful structural system. It is composed of a beam balanced about one support. This support where it is anchored is called the fulcrum point. The two free ends of the cantilever are counterbalanced to create a translational and rotational equilibrium in the element, thus making it an effective building component. Wright derived his use of cantilevers from the form of tree branches or the outstretched human arm.[6] Cantilevers can be seen in his work from his prairie style to his Usonian style, and in some of his greatest buildings including Fallingwater and the Imperial Hotel in Tokyo. The cantilever gains its structural stability from balance about its fulcrum point, and Wright was a master at using this balance to create dramatic outstretched planes in his work. This innovative and intuitive structural concept was the driving force that allowed his architecture to achieve such emotional and expressive

Figure 4. The many cantilevers of Fallingwater

greatness.

Fallingwater is composed of three horizontal trays, in the form of cantilevers. The building is anchored at a point above a natural boulder. Here four piers, or bolsters, are anchored and act as the fulcrum of the building. Out of this rock support rises the highest part of the home, a vertical core of stone walls which surround three vertically stacked rooms. This structure because of its weight and rigidity has the ability to act as the fulcrum for each successive terrace. Other walls or partitions act to brace each tray from twisting along their great lengths.

To achieve such dramatic cantilevers Wright could not rely on the standard wood, because it does not have the necessary compressive and tensional strength to span such lengths unsupported. To achieve his design he used a relatively new technology at the time, reinforced concrete. Reinforced concrete is composed of poured concrete impregnated with a steel framework. This is done because concrete has great compressive strength and steel has very high tensional strength. When they are joined correctly they produce a material that is stronger than the sum of its parts because it is comparatively strong and lightweight. These various structural innovations allowed the construction of such a dramatic building, but the final product was not perfect.

In the late 1990's an analysis was done to find the cause of chronic cracking in the main and master terraces. Both trays had deflected (sagged from original position) up to seven inches. It was found that the master terrace on the second floor was not acting as a cantilever; rather it was transferring its load via the steel window mullions down to the main terrace. It was also found that the main terrace was insufficiently reinforced with steel supports to support the load of both the main and master terraces. These problems were likely due to an inadequate amount of steel reinforcing as well as poor contracting work in their construction. To remedy this problem a technique called post tensioning was used. Post tensioning is similar to the use of steel to reinforce concrete because it involves adding steel cables to a building element, and then tightening the cable to create a built in compressive force in the member to resist tension. This process was done on main beams and joists, raising the terraces by half an inch and resulting in a self supporting structure.[7]

An excellent way to convey an architectural concept or to better understand one is to produce a scale model. Since it is obviously impracticable to recreate a building from scratch, or to create one without sufficient planning, a model allows a thorough dimensionalized understanding of the structure that would be impossible without some other type of tangible three dimensional construction. In order to be of use though, a model must be carefully planned and constructed though.

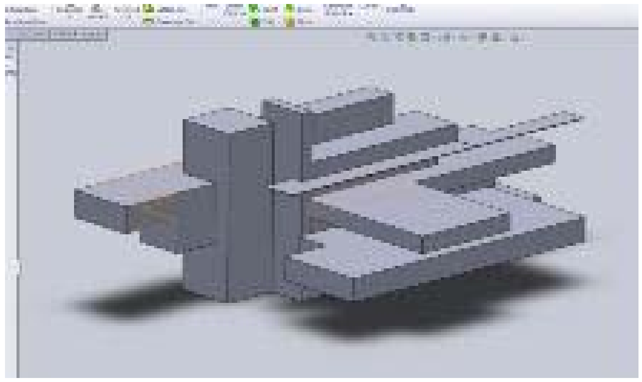
To begin, the type of model must be chosen. There are a variety of different categories of models to fit different specific requirements including topographic models, urban models, structural models, and internal models. Before beginning a model the choice must also be made of how detailed it will be. Models can be conceptual, construction, or exhibition models. Each type is successively more detailed. After the basic decisions are made it is necessary to have detailed schematics for the proposed construction such as topographic plans, floor plans, sections, and elevations. It is also helpful to have a strong understanding of the building's form. This can be achieved through preliminary sketches of the building. Several questions should also be asked before starting the model to determine what the expected end product is. These questions may include: what is to be represented, What aspects of the plan are most important, should the building stand on its own or have representative surroundings, who will be the audience? An understanding of these questions and the end goals will dictate answers to key design questions. Another primary concern is the scale. The scale determines the detail of the model, its relation to the viewer, and how easy it is to manipulate and interact with.[10]

Material selection is an important choice to make after beginning design questions are answered. Paper, cardboard, wood, foam, polystyrene, and metal are all common materials used in models. A variety of adhesives are needed to combine all of the materials and paint is often needed to achieve the desired final result. The choice of materials should reflect the desired design or building being modeled, and they should also help to achieve the goals of the model regarding the chosen audience. For an architect this may include using highly reflective metals to convey a futuristic design for a new commission, or polystyrene to effectively mimic topography. Tools such as a ruler, square, knife, pliers, glues, sand paper, scissors, and paint brushes are also necessary to create a model form the original materials.[10]

Once all of the planning is complete, a specific working order is normally followed. First a baseplate is constructed to hold the model. This baseplate must support the entire work and make the work stand out as a separate entity. The topography should then be constructed to give a location for the model to be placed. Positioning of the green, traffic, and water sites should then be done to establish the general orientation of the model. After these preliminary steps have been taken, the most important building of the structure can be done, and the insertion of the building into its surroundings. Finally details such as plants and human figures can be added to enhance a sense of scale.

Because I had no prior experience in model construction, I chose to begin with a CAD model of Fallingwater. This allowed a design that could be easily edited as I grew more knowledgeable and experiences. The information from this CAD model was then sent to a laser cutter to cut the pieces for the physical model. These pieces were assembled to create the final model.

I chose to build the model at a scale of 1:48 from the original building because this size would allow sufficient detail but also allow manageable construction. In order to build the model accurately, photographic reproductions of the original working blueprints were ordered from Columbia Universities' *Avery Architectural Library*. These to-scale blueprints were measured and used to create the CAD files in the program *Solidworks*. This was a multi-step process. To begin a massing model was made.



This is a simplified model of the building's major forms. This helps to develop an understanding of the building components and the complex interactions between them. With the knowledge gained from the preliminary massing model I was able to begin the complete model. For this model I chose to divide Fallingwater into various components based on interaction of forms and type of material. This decision was made in order to simplify the design process and facilitate the translation from digital model to physical model. Each part was constructed in *Solidworks* by drawing various polygons and making extrusions and cuts on the resulting form. Each of these components was designed as a *Solidworks* "part." These parts were then arranged in an "assembly" by assigning special relationships between the surfaces of each part.

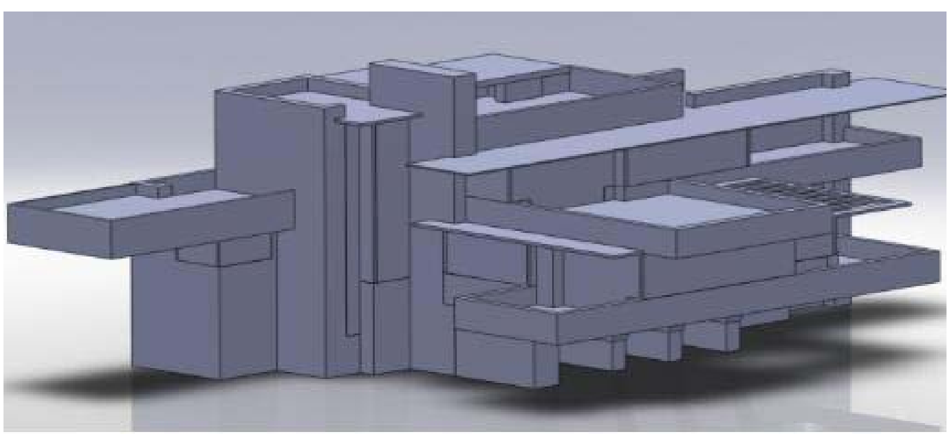


Figure 7. Final CAD model

With the digital model complete the next step was the creation of the physical model. The digital model could be used as a template for the physical model pieces with certain adjustments. First the surfaces of the CAD model were edited to reflect the thickness of the wood to be used in the physical model. These surfaces were then converted to .dxf files and sent to the laser printer. The information from these files allowed precise cuts of every piece from the model. The materials chosen for the model were birch plywood and hardboard.

Figure 8. A small sample of laser cut pieces

The birch was chosen for its strength and aesthetic qualities, and the hardboard for its durability and the clean cuts it allowed. These pieces were then assembled into the constituent parts, which were then assembled into the full model. The completed model was assembled on a two by four foot birch plywood baseplate. This allowed room for the model and landscape features. The final step in the process was cosmetic touches to reflect the actual house.

Figure 9. Model before cosmetics

To mimic the unique stonework of Fallingwater an image of the masonry was edited to remove all information except the major edges. This file was then sent to the laser cutter and etched into thin birch plywood. By etching, the laser only burned away a small portion of the plywood leaving behind a detailed and three dimensional masonry wall. For the stucco portions of the building a thin layer of plaster was applied and textured with a sponge. This layer was then painted to match the original coloring. Plexiglass sheet was laser cut to suggest the windows of the building and covered in 2.5 mm half-round plastic bar to show the window trimming. From constructing this model I greatly increased my knowledge on architectural models in general. The most important points I learned were the importance of clean lines, meticulous planning, and precision, and attention to detail. Through this long process it was possible to construct a detailed and accurate model of this impressive structure.

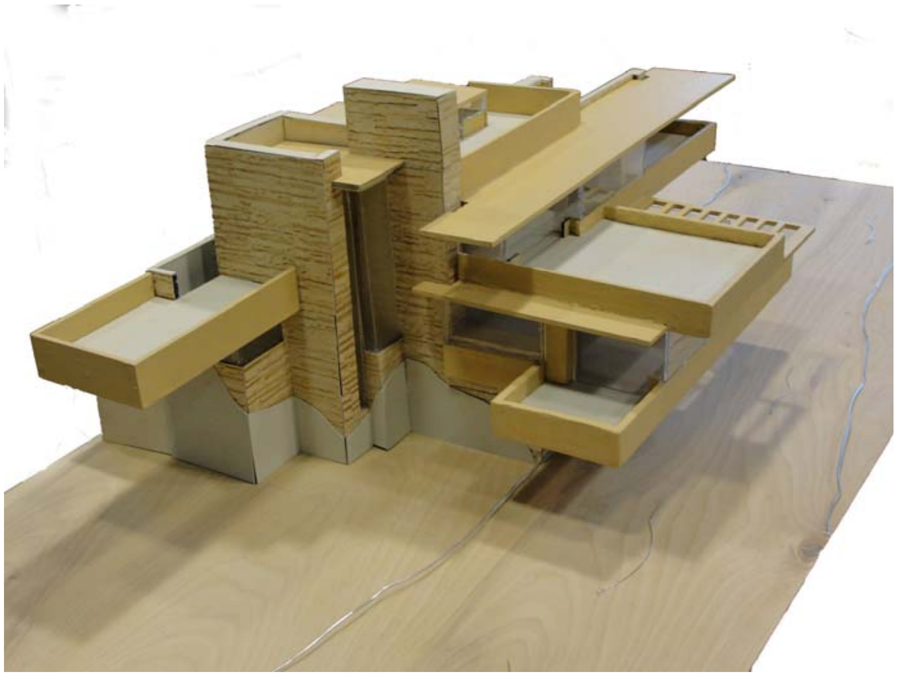


Figure 10. The final model

Figure 11. Final model

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