Structural Design Processes

Group A Team 4 Team4ExpEng@gmail.com

Sarena Wapnick
Viterbi School of Engineering
University of Southern California
Los Angeles, United States
swapnick@usc.edu

Ashley Garlan
Viterbi School of Engineering
University of Southern California
Los Angeles, United States
garlan@usc.edu

Colin Cheock
Viterbi School of Engineering
University of Southern California
Los Angeles, United States
colinche@usc.edu

Nicolette Romo-Zelada
Viterbi School of Engineering
University of Southern California
Los Angeles, United States
romozela@usc.edu

Kenta Lin
Viterbi School of Engineering
University of Southern California
Los Angeles, United States
kentalin@usc.ed

***Abstract*--In this paper, we explore the different design processes that civil engineers go through as they create multiple different types of structures. Civil engineering plays an important role in the creation of metropolitan environments and urban planning in regions across the globe. Because of the work of civil engineers, the design processes of modern structures have advanced to feed the needs of the world. Paired with advanced computer software, engineers have the ability to place their designs into real world scenarios and examine the strength and stability of their designs. While there is a general design process that civil engineers follow as they design structures, bridges, buildings, and aquatic structures each follow their own unique design processes. Bridges, including truss, arch, and suspension bridges each go through different design processes, but they all have similar materials and requirements of stability, wind-resistance, and visual appeal. For buildings, skyscrapers in particular, these structures have to be built to be tall and sturdy to fit their purposes, but they also have to be safe in the events of earthquakes and high speed winds. Aquatic structures, including irrigation systems and dams, have long served all civilizations, and the engineering techniques behind these systems are what allow them to function. Through current design processes, engineers have the ability to create structures that make everyday human life easier and safer.**

Keywords -- civil engineering, structures, design process, buildings, bridges, aquatic structures

I. INTRODUCTION

Since the dawn of mankind, humans have been constructing structures to better civilization and human life. The first engineers invented and produced new creations that are still modernly used. Starting with the developments of structures that date back thousands of years ago, those who have worked on structures have had to put hours into thorough planning and testing before their designs can be built. Because of this planning, a specific design process to create useful, safe, and visually appealing structures has been developed by civil engineers. Civil engineers are engineers who design and construct structural works, finding the most cost-effective and sturdy methods to create their designs. By following design processes, civil engineers can test and develop their designs productively. These finalized designs beautify cities and towns, allow for more efficient transportation methods, and help in the irrigation of farming. From aquatic structures to tall skyscrapers to long distance and landmark bridges, engineers have to design structures that can withstand large forces of compression, tension, stress, and nature. Advancements in technology and materials have allowed engineers to do this while using their creativity to produce marvelous structures. All structures that are currently used in everyday human life have been strategically produced and perfected by civil engineers and the design processes they use due to generations of hard work.

II. DESIGN PROCESS

A. The Common Steps of the Structural Design Process

Structural designs and construction processes typically follow a common set of steps which make up the civil engineering process. These steps include: Pre-Design, Schematic Design, Design Development, Construction Documentation, Permitting, and Construction Administration. Before any construction begins, the civil engineer must become familiar with the site and understand the client's needs and goals. Then, they use the client's demands and wishes to create a schematic design. In this stage, civil engineers develop several tentative designs and evaluate each concept to determine which design best fits the purpose and need behind the structure. Using the design selected during the schematic design phase, engineers move onto design development to refine the design. In this phase, the structure begins to take on more clarity and further details, including sizing and internal materials, are added to the overall design. Next, the engineers begin the construction documentation stage, in which they use the client's input to decide on factors such as the external finish materials and other aesthetic aspects. Then, these engineers undergo a permitting stage to get approval for the design based on city or county building permit regulations. If their design does not fit these permit requirements, they must adjust accordingly, so their designs are not illegal. Lastly, in the final phase of the process, the construction administration stage, construction takes place under the responsibility of a contractor. The contractor works with the civil engineer's blueprints and ideas to direct the construction of a structure [1]. From Pre-Design to Construction Administration, civil engineers complete calculations, models, and simulations to ensure their designs are safe and fulfill their purposes and requirements.

B. A Civil Engineer's Focus

Civil engineers are tasked with developing structures that are safe and stable and can last a long time. Safety, and consequently the ability of a structure to withstand large loads and the natural aspects of its environment, which can include wind and earthquakes, is one of the most important aspects to engineering a structure [2]. To determine the safety of a structural design, engineers measure the different forces that can be applied to a structure and how the structure will react under these pressures. These forces and reactions are found through the utilisation of physics and computer software. Through computer aided design, engineers can create scaled down three-dimensional models of their designs to simulate various types of real-world situations that a structure could potentially have to undergo [3]. Engineers also perform materials testing to ensure that the materials they use are economical and effective in their purposes. These tests can include concrete strength testing, laboratory testing of the soil, and fireproof testing [4]. Performing tests like a soil test gives engineers a better understanding of the ways in which the soil they are building on will support the stress of a structure and respond to movement during construction [5].

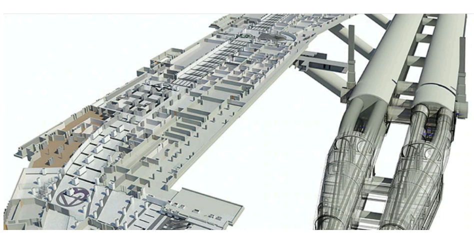

Fig. 1. A computerized 3D model of the East Side Access project's tunnel design underneath New York's Grand Central Station using the AutoDesk computer software. Source: [6]

III. BRIDGES

Every bridge follows a basic design process which includes defining the problem and purpose for the bridge, finding and following the design requirements, and planning the design for the bridge [7]. This planning takes the form of creating a structural model of the bridge, checking its stability and reliability, calculating the forces on the bridge, drawing plans for the bridge, and then building the bridge [7]. While this is the basic bridge design process, different types of bridges including truss, arch, and suspension bridges each have specific requirements and processes to follow in their designs. Engineers have to choose from these different bridge designs, as they decide what best fits the needs and requirements for the bridges they have to design.

A. Truss Bridge Design Process

Truss bridges are different from other bridges, as they follow a triangular format formed by joints and members (endpoints and sides of triangles) that create a bridge of high stability and strength. Due to the geometry involved in creating the triangles of a truss bridge, truss bridges undergo their own unique design process. In this design process, first the structural model is created and the design of how the triangles will be laid out to create a truss pattern is determined [7]. In this step, the engineer needs to design the upper and lower lateral systems for the truss and the interconnected members of the truss [8]. Then, the stability of the bridge is checked and the sizes of each of the members in the truss are determined and checked to make sure that they follow all guidelines and cost requirements [7]. After this step, the net forces, including those of compression and tension, are calculated on each joint to make sure that different plausible weights and winds will not overcome the bridge and cause it to fail [7]. These forces and stresses are first calculated with the dead-load (the weight of the bridge itself), and then they are calculated with live and dynamic loads [8]. The area of the truss exposed to winds is also calculated in this step to make sure the bridge can pass multiple tests to withstand large amounts of wind hitting the truss. Following this step, plans are precisely drawn to scale with materials needed, and a schedule is created for when the truss members and gusset plates of the bridge will be built and put together. Finally, the bridge is constructed.

Fig. 2. Truss bridge. Source: [9]

B. Arch Bridge Design Process

Arch bridges are different from truss bridges and suspension bridges due to the arch design. Arch bridges are one of the oldest types of bridges that were originally built of stone and brick, but are currently built of reinforced concrete or steel so that these bridges can extend longer and have greater spans [10].

As arch bridges are designed, one of the main design concepts that an engineer has to take into the account is the way that arch bridges deal with force and stress. For arch bridges, the right amount of force and weight has to be placed at the center at the top of the arch so that the bridge does not fail and break [10]. This is because the load, force, and weight of the bridge are carried outward from the center along its curve and transferred to supports at either end of the bridge [10]. The ground then pushes back up on these downward forces to create resistance and stability [10].

Because single arch bridges are not very stable under live loads, new designs of arch bridges with multiple arches where external arches connect to internal arches through hangers have been constructed and innovated [11]. The amount of arches and how these arches will be connected needs to be considered by engineers in the design process.

Fig. 3. Multiple arch bridge, where external arches are connected to internal arches through hangers.
Source: [11]

Engineers also have to decide whether or not they will use truss inside the arches to provide further stability and how they can aesthetically make their arches smooth continuous curves [11]. Arch bridges also need a "rise-to-span" ratio of 1:5 to 1:6 for stability [11]. This is another aspect that engineers have to take into account in the planning and detailed drawing aspects of the bridge structural design process. Also, when analyzing the amount of stress and force that a bridge can withstand, engineers have to choose the designs they will use for hangers on arch bridges [11]. These can include I-sections, circular hollow sections, and cables, and the chosen design depends on the criteria and requirements for the bridge [11].

C. *Suspension Bridge Design Process*

Suspension bridges are bridges with support cables connected by pylons (towers) above the deck of a bridge. Originally, suspension bridges were made from rope cables, but currently, these bridges use high tensile strength cables made from thousands of individual steel wires bound together [12]. This is an important aspect of suspension bridges in terms of cost and materials, which differs from other types of bridges, that engineers have to take into account as they choose what types of bridges they will use for different needs [12].

Other aspects that are unique to suspension bridges that engineers have to take into account are that suspension bridges are light and strong, so they can have a distance of up to seven thousand feet longer than any other type of bridge [12]. However, suspension bridges are also the most expensive type of bridge to build [12]. Therefore, engineers have to figure out how to make these bridges less expensive in material or size when constructing suspension bridges under rigid economic requirements.

When engineers are building these bridges they have to design tall towers that the suspension cables can rest on [13]. These towers can be made of either steel or concrete [13]. Engineers also have to consider that the cables have to be anchored to the ground through anchor blocks set in concrete so that the forces and stresses from the bridge can be transferred from the cables to the soil, just as in arch bridges [13]. Along with the towers and anchors, the cables themselves need to be designed based on the verification of 3 limits: the ultimate limit state which encompasses the amount of tension that should exist in the cables, the serviceability limit state which covers the levels of stress, strain, and vibration in the cables due to dead-loads, and the fatigue limit state for the stress and strain in the cables due to live-loads. These limits have to be considered in the design process to ensure that forces will not overwhelm cables and cause a collapse of the bridge.

To provide extra safety and ensure the stability of suspension bridges, some engineers will utilize truss patterns on their bridges to give sufficient rigidity to the bridge, just as in arch bridges [13]. Erosion (for bridges over water) and resistance to high speed winds also need to be taken into account in suspension bridge design and tested in this process to ensure that neither of these obstacles will cause the bridge to fail and collapse [13].

Fig. 4. Forth Road Bridge, Queensferry, Scotland -- suspension bridge.
Source: [13]

IV. BUILDINGS -- SKYSCRAPERS

Civil engineers must take multiple factors and parameters into account when building very tall structures such as skyscrapers. Along with making skyscrapers visually pleasing, engineers must follow schematic designs and use the most stable cost-effective materials that they can. Along with these key aspects, arguably the most important factors that engineers need to consider when executing the design process of skyscrapers are the natural disasters and events that are capable of destroying them. Skyscrapers must be built with preciseness and attention to detail in order to protect those inside these buildings. Because skyscrapers can reach great altitudes, they are subject to greater damages from the natural phenomenons of winds and earthquakes. Through the structural design process of skyscrapers, civil engineers have to come up with multiple solutions to these problems to figure out the best ways to execute these precise designs.

A. Wind

At ground level, people cannot feel the speed and strength of wind currents that are traveling at higher altitudes. The winds at the top of skyscrapers can reach one hundred mile per hour speeds on a regular day. While many believe that skyscrapers are built straight into the ground, making them completely static and unable to move, engineers have found that it is much more reliable to give these structures the ability to sway with the wind. This movement, which engineers need to take into account as they design skyscrapers, alleviates some of the pressure from the wind and can prevent structural damage. To allow this movement to occur, engineers can incorporate joints into their designs that are able to expand and contract with the wind [14]. As engineers design these buildings, they have to make sure that the building does not sway over 1/500 of the building's height. This is because, if the building moves farther than this number, people will be able to feel the movement from inside the building [14]. To counteract too much swaying, engineers have come up with multiple design elements that keep a building more stable. Buildings such as the Comcast Center in Philadelphia are equipped with liquid-filled dampers, and other buildings have used bolts and welds to counteract oscillatory movement [15]. The Shanghai World Financial Center was created with a large hole at the top of it to allow wind to flow through [14]. Whatever the solution, civil engineers have come up with multiple ways to solve problems caused by weather occurrences like wind.

Fig. 5. The Shanghai World Financial Center skyscraper with a hole at the top to allow wind to pass through. Source: [16]

B. Earthquakes

Another important factor that civil engineers must account for as they build skyscrapers are earthquakes. In trying to prevent the damage of these destructive disasters, engineers have created multiple ways to reinforce these structures that they have to consider in the design and planning aspects of the design process. One way is to build these structures on a flexible foundation of steel, rubber, or lead pads that allow these structures to move with the earth during earthquakes [17]. Another reinforcement technique that is used are shock-absorbers, which include dampers and pendulums. Dampers consist of piston heads in cylinders filled with silicone oil and are used as vibrational control devices within each level of a skyscraper [17]. When an earthquake hits, the building transfers the vibrational energy into the pistons, which absorb force from the building. In using pendulums, civil engineers place large weights attached to steel cables along a hydraulic system at the top of a skyscraper. This system can counteract the movement of a building, as when a building begins to move in one direction the weights move in the opposite direction to stabilize the building. A third way that engineers have reinforced buildings for earthquakes is by creating systems that redirect the frequencies and forces of earthquakes away from these buildings. This rerouting of energy involves placing concentric plastic and concrete rings around a skyscraper so that when an earthquake hits, its seismic waves travel through the rings instead of going through the structure [17]. Ultimately, these innovative designs and the engineering design processes behind them have revolutionized the safety of buildings and skyscrapers.

Fig. 6: The concrete and plastic rings around a building that redirect the seismic waves of earthquakes. Source: [17]

V. AQUATIC STRUCTURES

A. *Irrigation Systems*

Since the beginning of time, the natural resources of the Earth have been utilized to design, build, and produce aquatic systems that make everyday life easier. The earliest documentations of these water structures date back to ancient civilizations [18]. As more advanced aquatic systems were developed to make farming more efficient and widespread, China and Egypt began to use irrigation canals and water storage systems [18]. Further, historically famous aqueduct systems designed to carry melted snow from the Alps down to towns and cities were created in ancient Rome [18]. This water was used for consumption, bathing, and irrigation. The revolutionary techniques and design processes used in Egypt, China, ancient Rome, and other early civilizations in aquatic systems brought the world to the modern irrigation systems of today.

Fig. 7: The Roman aqueducts near Nimes, France that modernly deliver fresh water to Nimes from over sixteen miles away.
Source: [18]

According to National Geographic, the amount of irrigated land in the world doubled during the twentieth century to satisfy the global demand for food [18]. Modern irrigation systems use reservoirs, storage tanks, and wells to hold large amounts of water [18]. Then, gravity driven canals and pipelines are used to transport water from the storage sites to houses, farm lands, or facilities [18]. The utilization of gravity to transport water is used by civil engineers because gravity is an active force that affects all structures. In following the basic structural design processes for these aquatic systems, engineers have to decide what material they will use to hold water to be cost-efficient and effective in their purposes, and how they will best transport water for the desired results. They also have to design how the systems of water transportation will look and function to meet requirements.

B. Dams

Although dams were originally constructed for multiple years before being documented, large dams (at least 15 meters in height) only came into existence in the twentieth century. This was due to new discoveries in materials such as cement and concrete and innovative technological advancements [19]. With these new advances, civil engineers could perfect the design process for these structures and have more options in materials and sizing when designing dams. Dams and water storage structures--and the design processes behind these aquatic systems--are very important because they account for “95% of the total irrigated area worldwide which contributes about 40% of the world’s food production” [19]. Further, all dams fuel irrigation systems which are essential for civilization, farming, and life to provide sustainable living worldwide.

V. CONCLUSION

Through new technological advancements, civil engineers have been able to provide unique design processes and solutions for innovative structures that are safe, stable, and visually appealing. Civil engineering design processes have developed into what they are today because of the formulas, computer software, and creativity used by civil engineers. Coupled with the structural design process, materials testing ensures that these creations will last for multiple years. While all structures follow the standard design process, each type of structure including bridges, buildings, and aquatic systems follow their own unique design process. In their bridge design processes, truss bridge engineers have to largely take into account factors of compression and tension on joints and members and the forces of high-speed winds, arch bridge engineers have to focus on calculations of weight distribution of arches and hangers, and suspension bridge engineers have to attentively design cables and pylons for their bridges. In contrast, one of the most important factors in the design process of buildings--skyscrapers--is the safety and reinforcement precision behind these designs because they have to withstand natural disasters and phenomenon including high-pressure winds and earthquakes. Additionally, aquatic structures, such as irrigation systems and dams, are designed to revolutionize the way society farms, drinks, and lives. For these structures, engineers have to focus on the best ways they can allow water to travel and what materials they will use to accomplish this task. Through the designs of all of these structures, civil engineers solve the problems of the world and make it a better place to live.

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