Structure and Architecture

Lecture 2

Birth of Arches

If u look at arches this is an example of natural looking arch, which exists naturally in the world. But, we are not going to look at these arches in our subject today. We are going to look at manmade arches which have very systemic sense of how the load is transferred from one point to another point. By definition arch is a curved structure that spans the space and may or may not have load supporting on top of that. If you look at an arch and see how it works, it is a purely compression form of a structural member, which means that the amount of tensile stresses that the structure is carrying is zero, every load that the structure is carrying is purely a compressive force. Here, if you could see it can span a large area by resolving forces into completely compressive stresses in turn eliminating tensile stresses. This is sometimes referred to as the **arch action.** If you look at a normal compressive strength, which we saw in a previous episode a poster lintel fashion. If you could see the post how the load transfers in the posters on top surface of the post there is a compressive stress acting on the post, whereas the bottom surface of the post there is a tensile stress acting on the post. A **tensile stress** is nothing but a pulling force whereas a compressive stress is a pushing force. In arches the beauty of arches is entirely of a compressive stress nature there is absolutely no tensile stresses involved. This is a loading pattern in an arch typically the load comes from the top and the load gets bifurcated on to either sides and they are carried through the bricks or the stones or any materials placed in between and it is carried towards the supports. When the arch carries the load there is typically there are two components that the load is splitten to one is the **vertical component** and another one is the **horizontal component**. The vertical component is a purely compressive strength and horizontal component is also a compressive strength but it is called a lateral thrust. To explain how lateral thrust works, let us construct the arch first and then let us assume that the arch is carrying more load than it is designed for. In case when the arch is carrying more load than it is designed for the arch buckles under its own weight, which means that is too much of force acting on the arch and when the lateral forces are more than what the arch can carry there is an horizontal splay which the arch creates which means the supporting members go outwards. Which means that arch caves inn on its own .The arch is self supporting structure otherwise which in this case it is not a self supporting structure. The weight of with arch itself and the weight acting on top of it makes the arch splay outside and thrust defeats the arch purpose.

Interestingly arches have been in the construction industry for quite some time now. It was first discovered by Mesopotamians ,they were using brick constructions it was as early as second millennium BC .The Greeks also knew how to construct with arches, they did lot of underground structures most of the Greek construction using arches were confined to underground structures. But, it was the Romans who used the arches for its fullest potential they use the arches for practically every kind of building that they constructed palaces, temples malls, big complexes, sports arenas, any public building they had an arch. They even constructed kilometers and miles long aqueducts which carry water from the source to the city and they constructed entirely of arch members.

Like the roman arch itself is semicircular arch, if you look at this pictures here this is the **Triumph of the arch under the roman architecture**. The heights of the roman architecture can seen through this picture where you can see a large span of structures, large span entire road, and entire rivers being spanned just by the arches and how the arches are being constructed. They used materials like brick, concrete, stone and each of these materials they were able to express the structural integrity of the arch through the material. These are famous buildings which you can see in almost every roman city. The buildings are designed for one practical purpose. They have games and sports conducted inside these buildings the one on the left is the coliseum, one on the right is from the other roman cities .where you can find numerous series of arches staged on top of each other forming three storied, four storied buildings of completely arched construction and these buildings stand the test of time even after 2000 years.

Now let us go and see how an arch works or how a **loading on arch** happens .Every element inside an arch has to have a right place and a right job to do it. They cannot be in a wrong place or do the wrong job. If you see the top right picture there are series of stones which are arranged in this place also there are series of stones which are arranged in this fashion also. The main difference between the one on the left and one on the right picture is the how stones are arranged. If you could see clearly all the stones are placed in such a way that the load of one stone is easily transferable to the other stone purely by compression .Whereas in this picture a load of one stone is neither transferred to another stone or it is observed completely by the ground. All these individual stones are left individual they do not correspond to any complex system which means that they can buckle and fall under their own weight, right side is a typically wrong way how an arch is constructed whereas left side is a way an arch needs to be constructed. And, especially when you apply load on to an arch you have to be very careful because the load has to be applied directly at the middle or on top of the keystone .If the load does not act on the middle what happens is well you can see in the picture on the bottom left corner. Here the load applies on to this stone which means that these stones on the side cave inside, whereas creating an upward thrust on this area there by dislocating the entire shape and structural integrity of the arch itself. Any load which is applied other than on the key stone area is not a proper loading pattern for an arch. The loading pattern needs to be very precise and very calculatable.

Let’s move on and talk about the different **parts of an arch .**we have studied parts of an arch in junior classes even in our first and second years but ,then we will quickly brush through the parts of an arch once again so that we will understand how the an arch works better way. An arch typically stands on either an impost or a wall or posts which are located in these areas. The first stone on which an entire arch is built. First stone on the both sides are called the Springer stones. The other stones which are kept on top of the Springer stones are called voussoirs. The entire assembly of the stones from here till near top area is called the haunch, whereas the stone which is placed right in the middle on top is called the keystone. The upper side of the arch is called the extrados, and the inner surface of the arch is called the intrados. There is a line that connects the two points where the arch begins; this line is called the springing line.

We need to know this as in the next slide, we will be looking at different type of arches and most of these types of arches have one of this properties varying. So, we need to be conversant with the terminology. Moving on to the different type of arches, I have a numerous types of arches on the screen here and, can you identify which type each of these belongs to? Let me get through it. The first arch here is called **semicircular arch**. The distance between the two springing points is covered by an exact semicircle and from the center point of the Springer line the distance of the arch is equal to at the any point of the arch; that is why it is called semicircular of the arch. If you look the second arch here, this is also a type of semicircular arch but, we can see slight difference from the first one. The similarity is at any point on the arch the distance from the center is the same just like the semicircular arch. But, then it's entirely not a semicircular because the center of the arch is below the springing line. The springing line is right here and the center of the arch is below the springing line, which means the resulting part of the circle is not a semicircle but a segment, hence the name **segmental arch.** Moving on to the third arch, this arch has not one center like a previous two arches but this has two centers. The two centers are not on a springing point not on the center of the arch itself, but at equal distances from the springing point. This arrangement results in a type of curve, which we are comfortable and which we very well know with, this curve is called ellipse. Ellipse always has two centers and since it is a half a ellipse it's called as **elliptical arch.**

Moving on to the next part, here in this arch is very similar to the first and second type of arches. Again the distance between any points on the arch to the center of the arch is the same, but the only difference between these arches and the fourth arch is the center point of the arch is above the springing line. This is the springing line right here and the center point is above the springing line. Which means that this entire arch is standing on top of something called a stilted, hence the name stilted arch, Arches five and six have something very common which is unique of these two arches which no other arch type have .These are the only type of arches where the size of a arch is bigger than the Springer line itself . Due to that unique shape they are called horseshoe arches because they resemble a horseshoe. They are two different types the first one is called a **round horseshoe arch** and the second one is called **pointed horseshoe arch.** Let's move on to arches seven, eight and nine. in a simpler ,very simple layman's term arches seven , eight and nine can be called as pointed arches, but then we are not layman how we ? We are architects we need to define them by their clear exact architectural name. let's move on to arch number seven , if you at it this arch is made up of two arcs for circle whose centers are on both the sides .If you look at carefully the center of the arc are outside the springing points , hence this arch is called a **lancet arch**. Arch number eight is where centers of the two arcs which form the arches are exactly on top of the springing points. This is called an **equilateral arch.** Whereas in arch number nine it's a sink pointed arch center of the arcs which give the arches are located inside the springing point within the arch springing line. This type of an arch is called a **drop arch**. Moving on to a little more further complicated types of arches- arch number ten, eleven and twelve. So look at arch number ten you can see that there won't have one or two centers like the previous arches, they have four centers and if you could see them carefully they form different cusps within the arch itself, hence they are called **cusped arch**. In this case since there are like one, two and three lines they also called as a tripholiate arch. Moving on to the next arch ,arch number eleven has the centers not only on the inside but also on the outside of the arch as well . This arch is called **ogee arch**. More common name for this ogee arch is a mughal arch. It was the mughals who use this arch so often .moving on to the twelfth arch, it is a four centered arch typically because the arch itself is made of four centers. One, two, three and four here and this arch is very similar to the drop arch but then the drop is not that high is very shallow kind of an arch. Sometimes this arch is also called as Tudor arch.

Let us move on to a topic where we talk about **Structural advantages of different kinds of arches** .why do have so many types of arches? Wherein just one arch typology be sufficient to construct all our buildings. Why do we need so many arches? well two reasons -reason no .1 is because we don't want to look at the same thing over and over and over again , we want to see different things, reason no .2 is different arches have different structural abilities and different arches behave in a different structural way . Let us look at typically one such type which is a pointed arch. we all know that the loading pattern of an arch works like this the load comes from the top , from the keystone it gets distributed on either side and it comes down the load typically has the vertical component and the horizontal component. Let's take the case of this pointed arch , this M1 and M2 are the two springing points , this R1 and R2 are the lines from which the arch is drawn .This arch no- 2 is an equilateral arch whereas arch no -1 is a slightly more pointed arch , arch no -3 is a less pointed arch. If we could clearly map the structural components of this particular arches. We know that there is a vertical component of the arch, which goes directly through M1 and M2. There is also a horizontal component of theses arches which goes away from M1 and M2 inside the piers or the columns where it is supported on .these loads are lateral forces which we know. If you could compare this 1, 2, and 3 arches, arch no -1 because of its high has more of a vertical component and less of horizontal component. Whereas arch no-3 has less of vertical component, has more of horizontal component. Structurally if u prefer arch no - 1 because it takes care of vertical loading very easily and it gives very less roof for horizontal loads if the horizontal loads are reduced the main advantage that you get is you don't have to provide a big thick column or a pier. The thickness of the pier, column can be reduced. If the thickness of the column and pier reduced which means that your over all loading comes down, if your over all loading comes down you can built taller, higher and you can go for very large, huge dramatic structures. This is the reason why all the gothic churches or gothic cathedrals have pointed arches in comparison with Romanesque architecture, where all the arches are semicircular. In Romanesque cathedrals the height is not given much importance whereas in gothic cathedrals they go for a enormous amount of height. The verticality is a main element in gothic architecture .one thing which clearly got them the verticality is the pointed arch, that such is the structural advantage of pointed arch or a tall arch rather than a short arch.

Birth of Vault

Let us move on to another subject called **vaulting** .what is a vault? Let us define the vault in a very simple terms . We will talk about the one barrel vault which is the basic of all the vaults. Vault is an architectural term for an arched form used to provide a space with a ceiling or roof. Here this is an arch we know that this is a face of an arch, when face of an arch extruded it becomes a vault. You have an arch, you extrude the arch along the face of the arch it forms a barrel vault. This barrel vault is also called as a **tunnel vault or a vegan vault** .It is called tunnel vault because it is mostly used in tunnels. Under the earth structures below ground structure the best part about barrel vault is, when it is used below the ground you don't have to have any additional structural support. As the earth on either side of it takes care of all the lateral loads. But, in this arch when this barrel vault is used above ground you need to provide additional support on either sides to take care of the loading. The loading pattern on the vault is very similar to an arch. We know that in a arch when load comes on top it gets transferred on to the sides and typically there is a vertical component and there is a horizontal lateral weight component. This same principle is what applies in a vault also, the load is carried by all the voussoir stones on the sides and again typically there is a vertical component, the main compressive load. There is a lateral weight component which occurs on the sides, this is again a thrust. This is when I told you about underground structures. When the vault is being constructed underground the weight of the earth on the surrounding areas, these loads counteracts all these loads so that the vault is in shape. Whereas when it happens on above ground you need to counteract these forces by some other structures. We will be dealing with one or two of these structures in the later stages.

Let's move on to the next type of arch is called the **Groin vault**, which is a little bit more complicated than the previous arch which is called the barrel vault .groin vault typically results when two barrel vaults here meet . This is one barrel vault and this is another barrel vault. The both have the same radius, the both have the same distances, when these two meet perpendicularly this is how it looks from underneath, this is called a groin vault. If a series of two or more barrel vaults intersect at one another, the load which is transferred to the columns or the piers happens on the intersection areas and the thrust is transmitted to the outer cross walls.

Let us move on to a little more complicated vaulting system which is called the **ribbed vault**. A ribbed vault system is very similar to a normal groin vault, but then the only difference between the groin vault and the ribbed vault is wherever you have these joints. These joints are reinforced by ribs. These, c, b are called ribs .wherever you have an intersection of these lines, arches you have something called ribs. It's called a sexpartite vaulting because there are six ribs which meet in a particular unit of a vaulting system. Let's take an example of this particular system where you see 1, 2, 3 ribs are rising from this side and another 3 ribs are rising from this side so in this unit there are totally a six ribs. This is called a sexpartite vaulting system. A further more complicated vaulting system is called the fan vault. A fan vault results in a very beautiful vaulting system and gives a very pleasant look. Most of the gothic cathedrals, lateral gothic cathedrals use the fan vaulting system. The reason why the name fan vaults you might have all easily guessed because of the shape it looks like a fan. Look at the picture it looks like a hand fan typically so, hence the name fan vault. These fan vaults are much more complicated systems of vaulting than the previous groin vaults or barrel vaults or even the ribbed vaults. These are much higher levels of vaulting and clearly you can trace the evolution from barrel vault, through ribbed vault , groin vault now to the fan vaulting system.

Birth of the Dome

Now let us move on to the next interesting system, which is a **Dome**. This picture which you see here is a dome of a building called pantheon in Rome. Where the height of the dome architecture in roman times is achieved here. If you could clearly see the dome in section all you see is an arch .this dome is very big which you would have probably realized because of the scale which is given below. This dome diameter is more than 40 meters and there is ocular on top which is 11 meters approximately in diameter. We all know this data but what we didn't know was the reason why there was a big ocular right in the middle of the dome. An early roman say that the oculars is a main through which the men can pray to the god directly. Through the oculars they can look at the skies and through the skies they can look at their gods and they can take the blessings of the gods directly .oculars typically means eye oculars of the dome is usually referred to oculars of the god itself. Which means it's so even called in sometimes; some places the eye of the god. But then what really happened in this place is, the diameter of this top area oculars is like I said approximately 11 meters. Just like in an arch construction the top most point is something called a keystone where you put the keystone lock everything in to place. While they construct an arch what they do is they make a frame it's called a centering. Then the centering needs to be in place until the keystone is placed on the top. The moment the keystone is placed on the top and the arch is locked you can immediately take the centering off, because the arch then becomes a completely self supporting structure. Since a dome is an arch which is rotated on to 360^{o} on to its axis and it don't works typically the same principles .but since the dome is spherical a semi sphere, keystone is not a two dimensional structure any more but it is a jaunt three dimensional circle which has a small tilt on the top . This small tilt needs to be placed right on the top, where if you could see this picture. You need a large big element of this size to be kept on top of these two areas and remember that the diameter of this entire place is close to 11 meters, and this cannot fall down inside the temple in any point. So how do you place that? That was the serious question which the roman's faced and that particular point of time. Since they couldn't find an answer that is reason why the pantheon does not have a top. That is the reason why pantheon has an oculars right on the middle. The reason is not a spiritual symbolic element; the reason is a simple structural inability by the romans. These domes have very contrasting features compared to modern day domes.

This dome here was made of concrete and it was reinforced by hay by used all natural materials. The reason why you see these square boxes right here are, because the amount of concrete which is used to make this dome was very high. They wanted to reduce the amount of concrete, so they made this square design. So that the amount of concrete can be reduced by little bit , which can save their cost. But the domes which we make nowadays are much more complicated and much more interesting; because today we have a advent of shell technology we can calculate mathematical equations to a very precise number. The hyperbolic, parabolic structures are much more common today than it was in the previous day. If you could look at these pictures , these are modern day arches from these you can see that the advancement which we have had in field of arches in the field of geodesic domes are much more prominent in than any other fields . This is a reason why domes and arches are still being studied by structural engineers and architects around the world. Even after 2000, 3000 years of its discovery.

Now, we will move on to our final part of this particular structure, which is **Buttresses and Flying Buttresses** .what is a buttress? If you look at the picture, in this picture there is a load of the water coming on from one side and the wall which retains this liquid on one side. To counteract the load of the water, you need these triangle looking structures so that their loading can counteract the load of the water. These triangle looking structures are buttresses. Now, let's define a buttress. Buttress is an architectural structure built against or projecting from a wall which serves to support or reinforce the wall itself. if you think you haven't seen buttresses in day today life , then look at this picture am very sure you have seen buttresses in day today life . This is the dam the wall right in the middle needs to take the load of entire water that it retains. Since the wall cannot do this job alone. We have this helping structure to take the lateral loads. Same was the case with this dam. And, if you think that the buttresses are restricted only to dams. Think again if any wall is going to fall or if there is too much of loading on to the single wall you can find these buttresses. You can find buttresses very commonly in forts and in big palaces buildings where the walls are huge, thick just to retain the wall itself is big task there. So they provide what is called the buttress to support the load of the wall. Let's look at another interesting thing called the flying buttresses. Flying buttresses are typically buttresses but there is a very small difference. What is a buttress do it takes the load from a wall and it transfers to the ground that is what a flying buttress also does . But then the way that flying buttress works is slightly different. When a buttresses completely attach to the wall at all points from the starting point till the ground level the buttresses attached .whereas the flying buttress is not attached at all point , it is attached only at one point. So look at the picture on the left here ,this person right here is being supported by these two people and if you could see the load of this person is being taken by these two people in this case there is no load is acting on the person from the wall. But then a flying buttress typically takes load which transfers through the flying buttress it reaches down through the piers. Look at the pictures in the right, this here the load of the pier is too immense because there is loading coming from the top. The top of the thrust provides immense loading on to the piers. But then the pier can't take the load alone so the part of the load is being transferred to these sub piers which are connected by the main piers. by means of a flying buttress same as the case with these areas .

Let's see the **difference between buttress and the flying buttress .**if you could see this picture here, these two are the main piers that take the load of the main structure. We know that a arch or a vault gives horizontal thrust as well as vertical loads. Vertical loads can easily be taken care of by the piers themselves. But the lateral loads is what we have to worry about. These lateral loads can be very dangerous because ones the lateral loads goes beyond the certain limit, we saw how thrust acts on an arch. The arch splays out and it buckles under, so everything caves inn that cannot happen to our buildings. so what we do here is we either build an abutment or a buttress on a one side .where the entire structure is being supported by this structure on the one side or we build something called a flying buttress where a part of the load is taken care of through the these member called the flyers and then they transfer the load to smaller piers , which are on either sides .So this is the main difference between a buttress and a flying buttress. Here are some pictures of a flying buttresses , where you can see cathedrals, across Europe , from Italy to France to England to Germany and everywhere sporting this flying buttresses .sometimes the number of flying buttresses can be even three not just one in this case .