Introduction

This report is titled “The perfect arch” which could mean many things. It could mean perfect in respect to aesthetics, perfect in respect of load bearing or even perfect in respect of its practical use. It also becomes an expansive title once one begins to consider factors such as; in whose eyes is it perfect? Or who is qualified to decide what is perfect?

This report will investigate what makes up an arch and how it has helped us in construction. I will look at the structural behaviour of an arch and conclude how each part of an arch design could be perfect in someone’s eyes. I will also look at if “a perfect arch “ can exist and if so where and how.

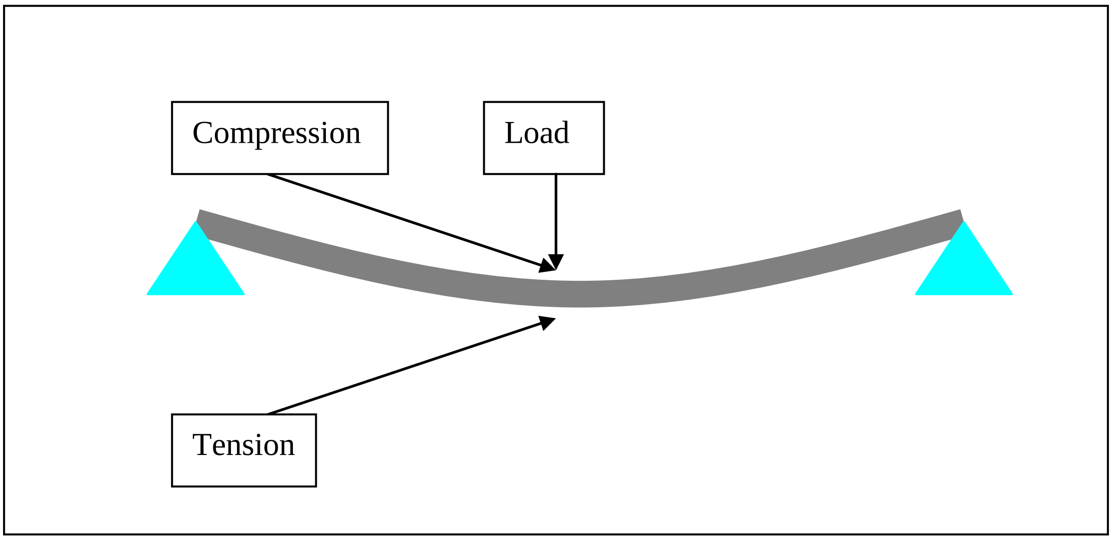
I will start by researching how an arch works and the possible uses of an arch. I will look at the advantages and disadvantages an arch has have over other structural designs, this will provide the tools to come up with a criteria of what makes “The perfect arch” which can be used to evaluate existing examples of arches and examine whether they were the right choice for the project at the time.

They say “beauty is in the eye of the beholder” and my initial thought to this title is just that. There surely cannot be such a thing as a perfect anything as everybody’s views are different. Most things in this world almost always end up as a compromise of a few things whether it be financial limits, material availability or simply physics of nature and because of this I struggle to see at this point how anything can be “perfect”.

How an arch works

Every technique used by man to span across two points suffers from two main forces, compression and tension. There are many other forces to consider when designing any form of bridge or span, such as resonance, weather, torsion etc but these tend to be different for every situation and should be individually assessed. Although tension and compression vary depending on the loads exerted on the individual project the principles of how to handle them remain pretty constant. The arch technique, if constructed correctly, only dissipates compressions, as tension is negligible.

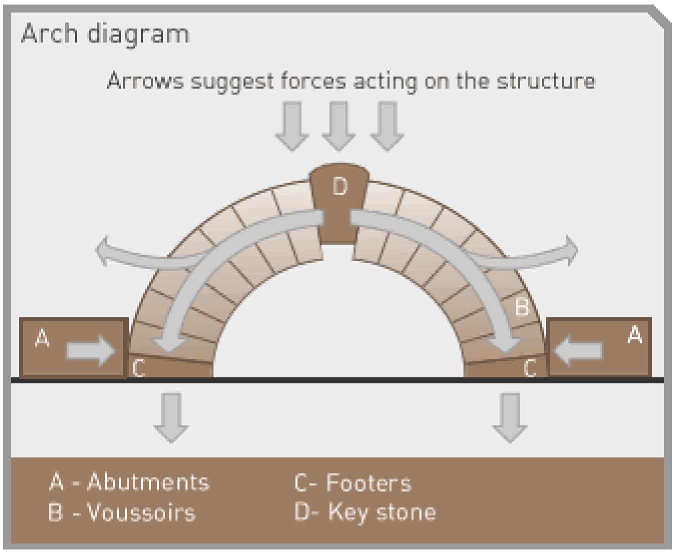
[Fig 2.0 shows compression and tension in a beam when under loading]



When a load is placed on the simple beam diagram shown above, the topside of the beam experiences compression and therefore gets shorter and the underside of the beam experiences tension resulting in the underside of the beam to increase in length. The middle of the beam in respect to height has negligible compression or tension. In practice this means that all beams need upright supports at regular intervals to prevent the beam from sagging and eventually collapsing. The distance of which a beam can span before needing an upright support depends on the material of which it is made from. However, most beam bridges do not exceed 80 metres (1) with today's materials.

An arch design eliminates the tension factor to a negligible level and dissipates the load down the natural curve of the structure into the abutments both horizontally and vertically. This can be seen in the Fig 1.1 below.

[Fig 2.1 shows how an arch handles loading (2)]



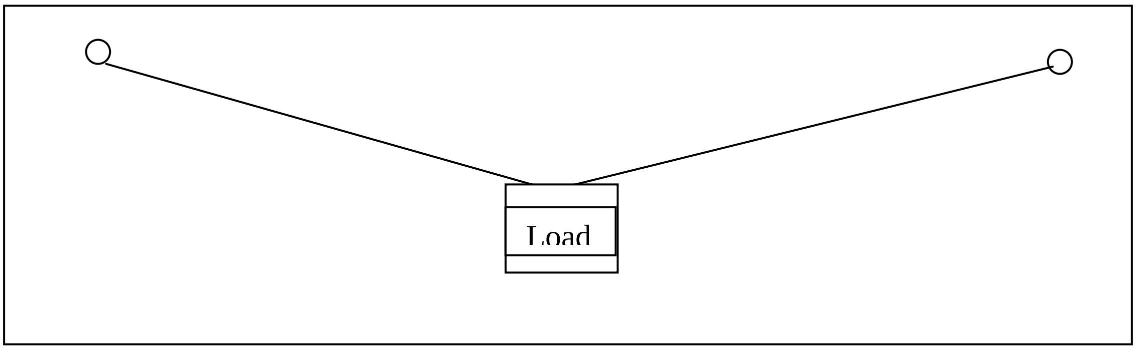
Because the forces all end up at the abutments either vertically or horizontally, the abutments need to be extremely secure in their position to avoid the arch to spread apart and collapse. This is why some big cathedrals and churches that use arches in their construction have extra abutments on the side of them to cope with the forces as shown in Fig 2.2.

[Fig 2.2 shows abutments to prevent collapse of the arch (3)]

zoom © Simon Dakeyne

To explain the theory behind the arch technique we can use a piece of string. “If the string is placed between two points and a weight is supported on the string, as shown in Fig 2.3, then the string will deform until an equilibrium position is reached. Since string cannot resist compression, bending, shear or torsion, but only tension, then the resulting structure can be referred to as a tension structure. For the given position of the weight there is a whole family of structures, the actual equilibrium shape being dictated by the length of string used. It may be noted that the tension structure has straight members” (4). This can be elaborated to show how, if uniformly distributed loads are applied, an arch shape is formed, if this is inverted the shape of the required arch is given which can be created to handle these loads. “This inversion technique was used by some of the designers of the classical cathedrals. String models were built and loaded with weights, which represented the loads that a roof element had to carry. By inverting the resulting form the shape of the required arch was obtained, which could then be built from individual stone blocks” (4)

[Fig 2.3 shows how a piece of string reacts to a central load]



As we add more weights of the same mass along the string we can see the arch forming more and more. This is the same as a chain hanging. As it has a uniformly distributed weight it hangs in a catenary curve, this is an arch.
The Romans used arch designs widely and discovered that by using wedge shape pieces to make up the arch it was possible to build arches using stone without mortar. When a load is applied, the wedges compress into each other and dissipate into the abutments as normal but the more load that is applied the more rigid the structure becomes. Some examples of this technique are still standing today some 2000 years later and have clearly passed the test of time.

[Fig 2.4 shows an example of roman arch building (5)]

Although the structure shown in Fig 2.3 looks unstable it has proved itself to be durable and functional. The Roman Empire used this technique for their water viaducts and was important to maintaining their way of life.

Applications of arches in construction

Arches are used everywhere in construction from houses to cathedrals. Their use in construction has varied throughout different time periods and as different materials have been introduced different building trends have evolved.

The Romans used arches to build their viaducts. This was most likely due to the available materials and the needs of the project. A beam and column approach to a viaduct would have been impossible as there wasn't a material available to them to use as a beam, wood could not of been used as it can only be made as long as the tree it came from which would have meant a lot of joining and a lack of stability.

[Fig 3.0 shows an example of a Roman viaduct (6)]

Arches are also used to span across doorways and windows. This is seen a lot in older buildings, possibly because of the decorative aesthetics and the grand look it produces. Nearly all churches and cathedrals use arches in their design, it creates an impressive, awe-inspiring look and makes the building look indestructible. This could have been an important factor to the creators in an uncertain time period.

[Fig 3.1 shows an example of arch doorway (7)]

Nowadays our design for buildings is generally governed by cost and grand designs are few and far between. Our society has changed a lot over the years and since world war two our buildings have lacked the over engineered grand designs that churches and cathedrals share. This could be due to a growing pressure of finding new space or even perhaps an undercurrent feeling in all of us that at anytime the building could be destroyed like in the world war two blitzes, especially today with the increase in terrorism.

Arches today are rarely seen other than in various forms of bridges. Since the introduction of reinforced concrete new designs have been used in numerous combinations of suspension, arch and beam bridges.

The arch technique is still regarded as decorative and today's modern structures use arches in their design.

Santiago Calatrava especially enjoys using arches in his designs. He has created many modern structures using curves and load bearing arches. His bridge of Europe is an arch suspension bridge that looks spectacular.

[Fig 3.2 shows Calatrava's bridge of Europe (8)]

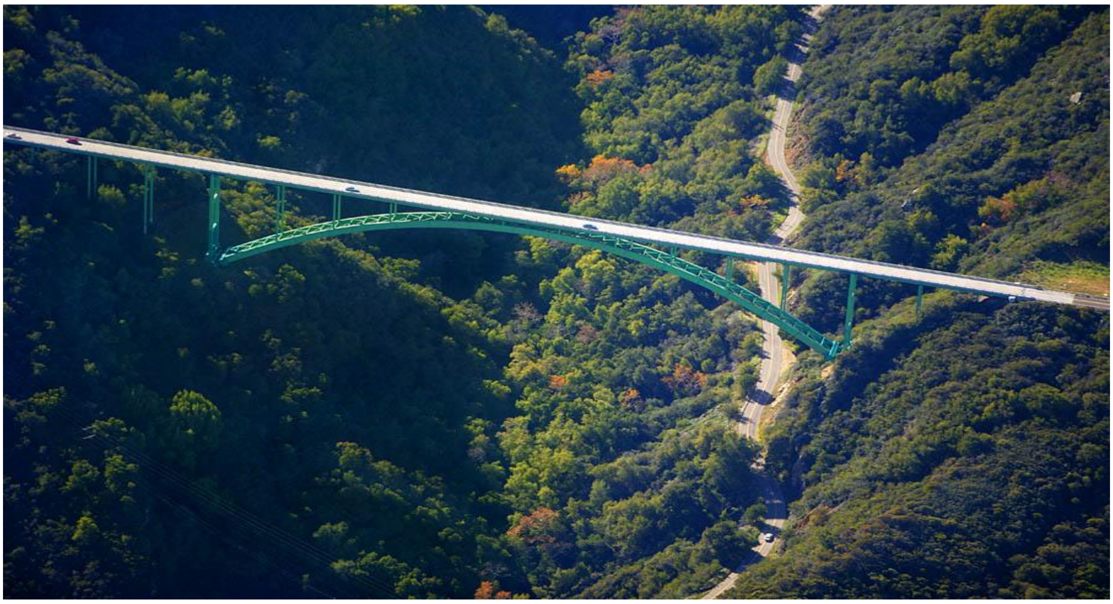
[Fig 3.3 shows a different view of Calatrava's bridge of Europe (9)]

Advantages of an arch

An arch design has many advantages over a simple beam design and therefore has many applications that a beam simply cannot provide for. Most beams struggle to span more than 250 feet where as an arch can span around 800 feet (10) sometimes more depending on the material used and the abutments. A beam directs the forces downwards onto its piers, “Beam stiffness diminishes dramatically with increases in length; doubling the length of a beam makes it sixteen times more flexible.” (11). Because of this they tend to get weaker as the span distance increases which leads to sagging and eventually collapse. An arch however is only limited by the fact that it has to be arched and that there is only so much distance you could span before the sheer weight of the structure would be enough to collapse it, stronger, lighter materials however could increase this span.

An arch does not require upright columns to support it and therefore means it is useful if you need a space without obstructions such as a large entrance to a building or a bridge with a river beneath it where boats need be able to pass under the bridge.

[Fig 4.0 shows cold spring arch bridge (12)]

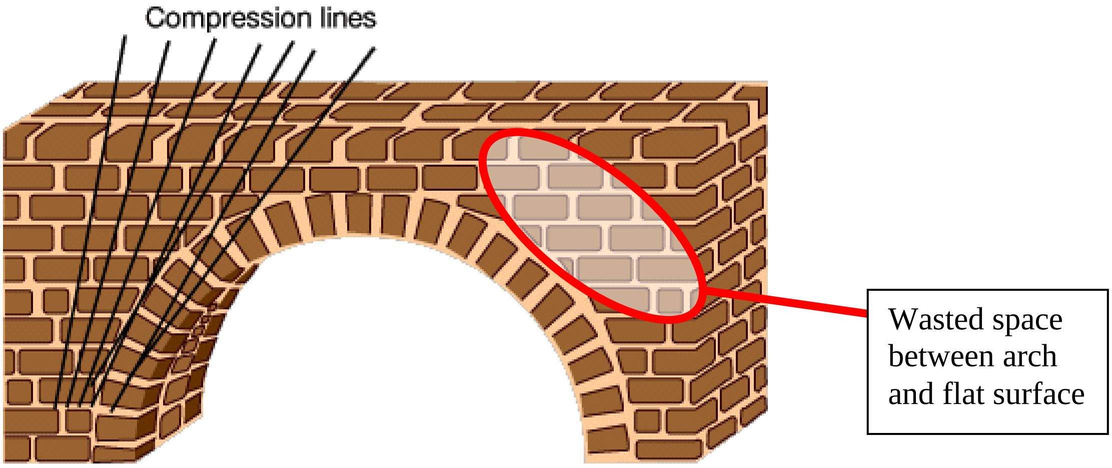


This is a good example of where an arch bridge is more appropriate than any other type of bridge. There are sturdy abutments from the banks of the hill and putting columns in the valley would be very impractical. Maybe a cable-stayed bridge could have worked but at the time of its construction this was probably the more viable option. This has a subtle look to it too and nicely fits in to its surroundings, which is an important factor to maintaining the elegant countryside around the bridge.

Disadvantages of arches

As well as some good advantages of arches in construction there are some disadvantages. You first need to be able to dissipate the forces that are collected at the abutments, and to do that you need to build firm supports. Also you are restricted in that the shape has to be an arch, and although you can still place a flat surface on top, if used as a bridge, in doing this more space underneath the bridge is lost

[Fig 5.0 shows a typical brick built arch bridge showing compression lines (13)]



You can see in fig 1.5 how much space is lost from having a flat surface on an arch. Using metal structures can reduce this but any structure of this kind will always need support from the flat surface to the arch to transfer the forces.

Another disadvantage of an arch bridge design is the amount of material that is required; the mass of stone required in a typical arch railway bridge for example is colossal compared to a different type of bridge such as a beam or suspension bridge.

[Figure 5.1 shows a typical train bridge viaduct in Brighton, UK]

However, this particular disadvantage can be controlled through design. The roadway can be placed either below, above or somewhere in between the arch. If the roadway is above the arch then we lose the space as indicated previously, if the roadway is below the arch then cables are generally used to suspend the roadway thus meaning that the arch is now out of the way of the roadway and anything underneath the bridge therefore no space is lost. Clearly if the roadway is somewhere between the top and bottom of the arch then a combination of the two methods is required.

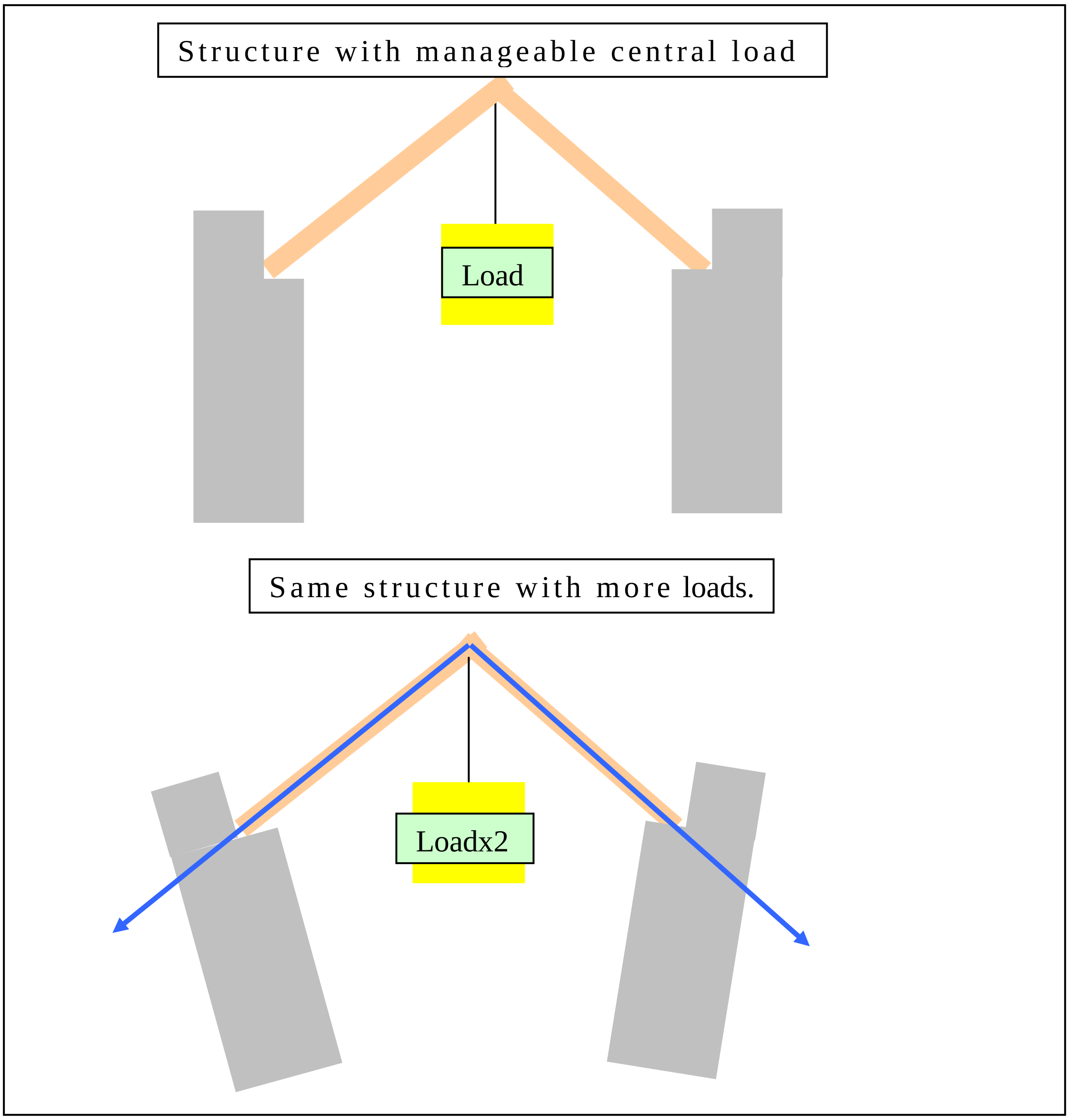
The ability of being able to place the roadway underneath the arch has only really become a possibility since the introduction of metal for bridge building and the suspension technique, which utilises the tensile strength of strong steel cables. Bricks and stone have fantastic compressive strength but not much tensile strength and therefore would not cope with the forces suspended below it. This is why arches in construction are so commonplace in old buildings; they simply didn’t have any better options.

Another problem with using arches is the accuracy needed to create a reliable structure; if the abutments are not correctly aligned or secure enough then eventually the structure will fail.

A structure made up of horizontal beams and vertical walls or columns, like a modern house, for example is easy to construct and there isn't much thought required from the builders. An arch however has to be right, if the supports are too high or do not fit together with the arch tightly then problems can occur such as the abutments slipping or toppling over.

The diagrams below indicate potential problems that can arise as a result of poor design or construction.

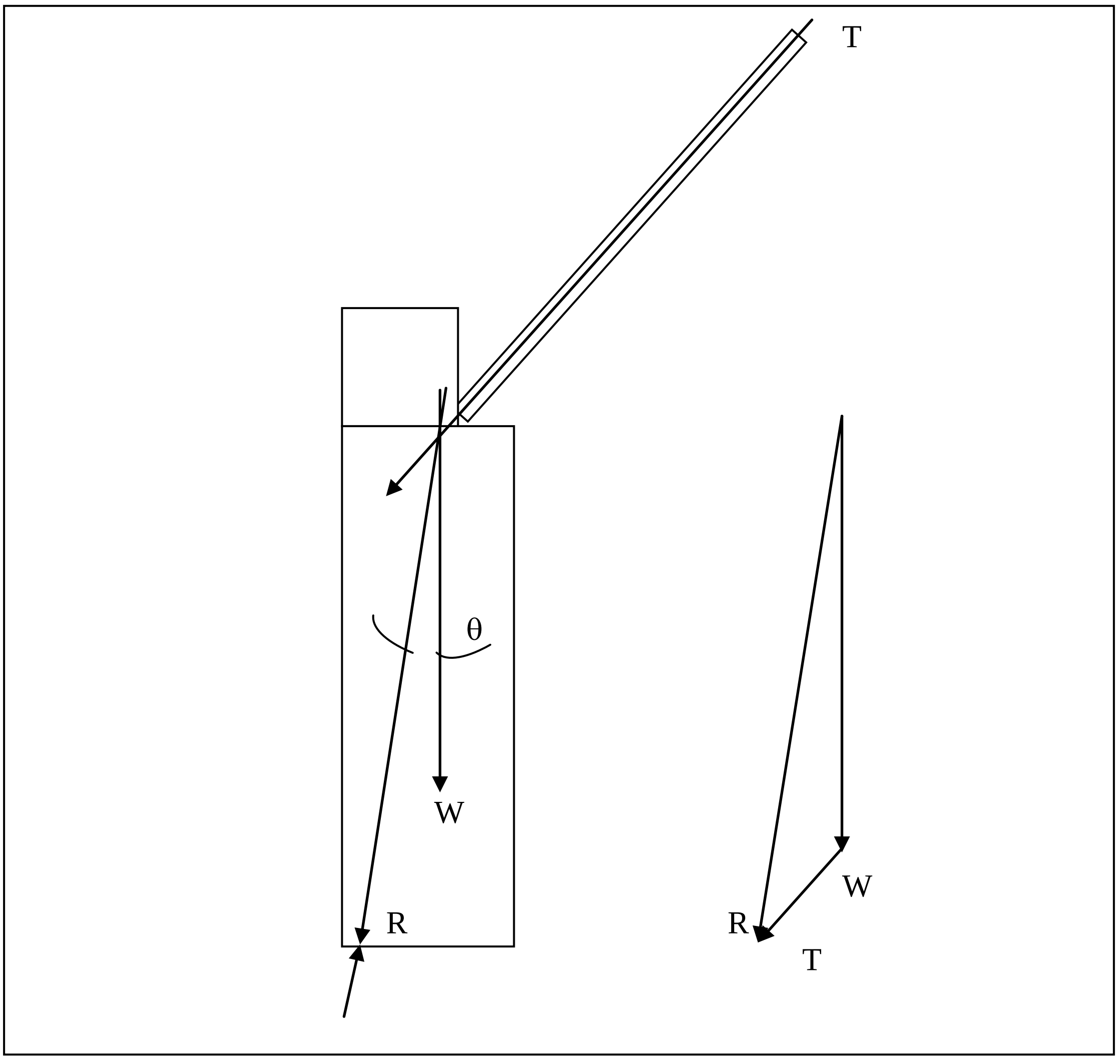
[Fig 5.2 indicates possible flaws in poor design/construction]



We can clearly see that when the structure is overloaded the load is being transferred down the blue lines and through the abutments. For the structure to be stable we need the load forces to transfer to the ground within the width of the abutments.

For an arch to work, the forces gathered from the loads must be transferred in to the abutments and into the foundations. Below is a diagram showing how the forces should act to create static equilibrium.

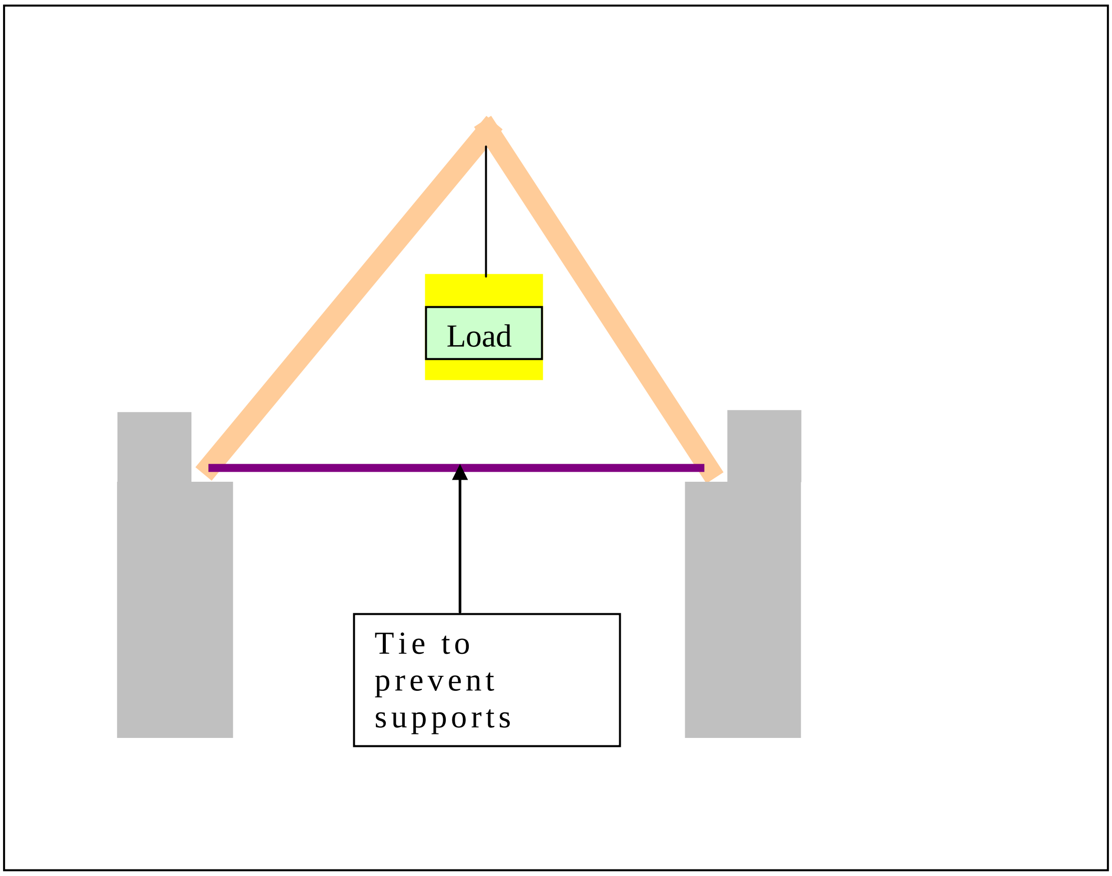
[Fig 5.3 shows how the resultant force can be transferred (12)]



If the abutments are not strong enough or positioned correctly to cope with the forces then there are a number of ways to overcome the problem to rectify the system.

One way would be to increase the width of the abutments, this would mean the resultant force from the weight of the abutment and the direction of force travelling down the arch would need to be deflected more before it would topple over. Another way of avoiding this would be to add weight to the abutments, which would reduce the effect of the resultant angle and potentially prevent the collapse of the structure. The pitch of the arch could be raised which would change the resulting angle and therefore direct the forces from the loads into the foundations. The simplest and possibly the most common solution to this situation is to “ tie the arch ”, this refers to the technique of tying the points of the arch that sit on the supports together which results in zero separation of the two supports. (12)

[Fig 5.4 shows a tied arch]



It would now be impossible for the supporting piers to separate.

This design is seen in roofs for lots of structures and is a cheap and efficient way of securing the system.

Conclusion

I have really enjoyed researching this report. I have learnt a lot about structural form and in particular the design of the arch. It has opened my eyes to a different approach to analysing structural designs and made me think twice about assuming the fate of a design just by observing the shape and form of it.

I don't think there is such a thing as "the perfect arch". I think that each design is created based on a number of variables, which has led the designer to that particular final design. We can however "play" with arches and manipulate the angles or curves on computer programmes to make the optimum arch but, perfect is a dangerous word as it implies that the object in question is flawless and I'm struggling to think of anything which is flawless. I think that all arches are beautiful in the respect of design and I personally love arches in construction and love the sweeping curves. The only part of the design that matters however is whether it fits the criteria for the job at the time.

I believe there are only so many ways of constructing materials together and the art of creating something truly beautiful and yet functional relies solely on the individual designer and individual project. The ability to see all the available possibilities of constructing the end goal is an essential skill in becoming a successful architect or engineer.

In addition, having self-confidence is key to a good designer. You need to believe in your designs and you need the courage to create structures that are different to "the norm". It's these structures that tend to stand out from the rest and become the "landmarks" of our time. Almost every man made landmark that is world renown today was controversial at the time as most of them didn't fit in to the surrounding environment, Eiffel Tower, Park Guell in Barcelona, Royal Pavilion in Brighton to name a few so I think its important to be bold and embrace change and try to use the beauty of arches and sweeping curves in our projects of the future.