Case Study

Arches Part 1: How History Shaped a Powerful Design Case Study

Developed and curated by the Ansys Academic Program

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Ansys Software Used

This resource uses Ansys Granta EduPack™ teaching software for materials education

Summary

Arches are features that can be seen in almost every city in the world. They have existed for a long time and were used to span open spaces. They have endured through time, often outlasting other structures.

In this case study we are exploring the reason for their existence, what makes them so special and what we can learn from them.

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1. What is so special about arches?

Think of the shape of an old bridge—they are often arches (see Figure 1). Why?

Figure 1: examples of arches; left: door opening, right: bridge

Well, the arch is an interesting feat of engineering. Arches are very useful if you want to get across a large open space, for instance a river, a deep valley. They can also be used to create large, dramatic entrances.

Arches are features that can be seen in almost every city in the world. Different forms of arches have existed for thousands of years, so it's not so easy to say when they were first invented. Research suggests that they have been in use since 2000 BC. However, it was the Romans, who made them very popular from around 500BC [1].

It does seem like an overkill, doesn't it? Building a complicated structure like an arch (Figure 1) just to span (build across) an open space when two columns and a beam (also called a lintel) will do the trick quite nicely (Figure 2). So why go through all the trouble?

Figure 2: Examples of modern-day lintels (horizontal beams)

THINK ? Can you spot the difference between Figures 1 and 2 (apart from the shape)?

2. Looking Back in Time

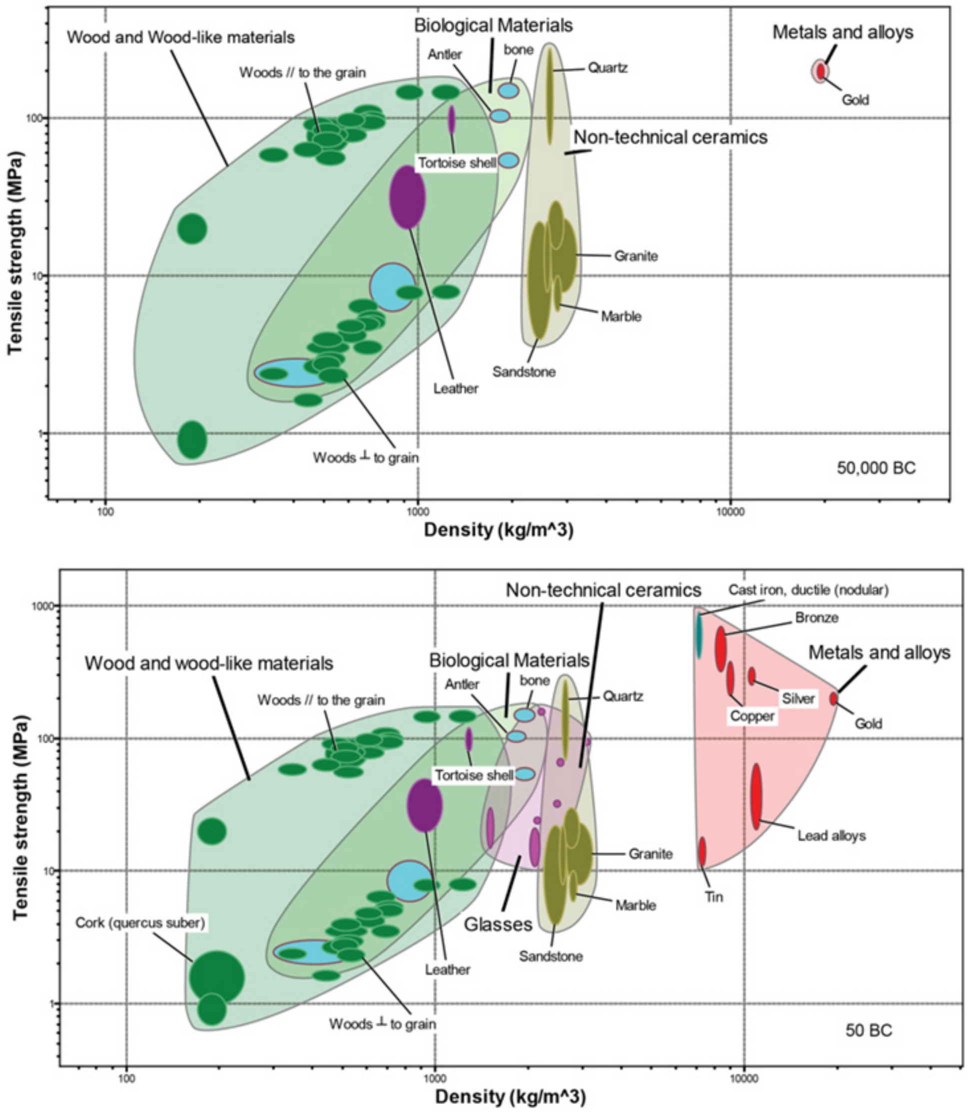
2.1 Construction materials

A first clue to this would be to take a look at the materials that were available for construction at various points in history. **Not all the materials that we are familiar with today have always existed.** Materials were to be discovered and then tested to figure out what they could be used for. Materials first utilized by mankind were those that were easily found in nature, such as stone, wood, bone, shells, clay [2]. And depending on the material's properties, such as strength, density, brittleness, some materials were much more useful for construction than others.

So what materials were available for construction in ancient Rome? What would have been available before then? In Figure 3, we can see some Ashby Property Charts comparing the strength of materials to their density at 50,000 BC (Figure 3a) and 50 BC (Figure 3b). You can see a clear increase in the number of available materials in Figure 3 from 50,000 BC to 50 BC, especially regarding number of metals used.

(a)

(b)



Take a loot at:
The evolution of materials Infographic

Figure 3: Materials strength vs density; number of materials shown limited by date first used: a) 50,000 BC; b) 50 BC; Figures created using Ansys Granta EduPack 24R1 Level 2 Database

Ashby Property Charts, also called Material Property Charts or Bubble Charts, can be created using Ansys Granta EduPack to help visualize and compare materials with one another based on properties. Learn more about Ansys Granta EduPack here and how to select materials for an application using Ashby Charts here.

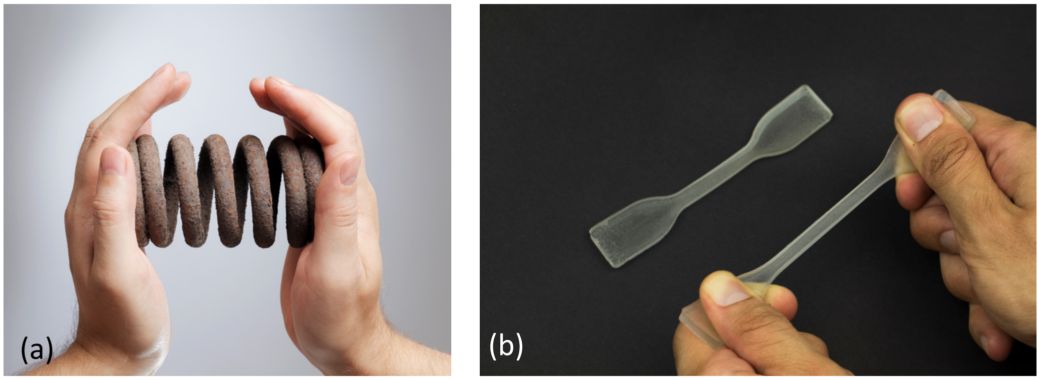
While Figure 3 illustrates which materials were available, it does not say what those materials were used for. Even though some metals were known and used at 50 BC, it is unlikely that those were used as construction materials. Metals are found as ore within rocks, and it takes a lot of work to get them out and make them into something useful. Materials like rock and wood are easier to use straight away. For small metal things like arrowheads and jewelery, using metal made sense, however making enough metal for big construction projects would have taken too much time and effort. **So, materials like stone and wood were preferred as materials for construction.**

Stone was an excellent choice for construction because it's strong, durable, and abundant. However, there was a challenge: it is also **quite heavy,** as indicated by its density (Figure 3). Given the **limited manufacturing and transportation capabilities of the time, large stone blocks had to be cut into smaller pieces** for easier transport and placement during construction. So rather than relying on a single large piece, **builders had to span openings using multiple smaller building blocks.**

2.2 Structural significance of arches

To understand the structural significance of arches, we first need to understand the difference in strength in *compression* and in *tension*. Compressive strength means how well a material can handle a force that compresses or squashes it, making it shorter or smaller (Figure 4a). On the other hand, tensile strength is about how well a material can handle a force in tension that stretches it out, making it longer (Figure 4b).

Figure 4: Illustrating the difference between a) compression (left), b) tension (right)



In simpler words, compression squeezes and tension stretches. Some materials can endure compression better than tension, or vice versa. Therefore, the strength of a material is often split into two separate properties, tensile strength and compressive strength. In Figure 5 we can see that types of stone (like granite and sandstone) have a significantly higher strength in compression than in tension, in some cases up to 10 times higher. Therefore, it makes sense to take advantage of this property (high compressive strength) as well as using smaller blocks of materials instead of large and heavy ones. **That's exactly what the arch does: several pieces squeeze together tightly** (see page 8).

Look around you and choose some objects (*i.e.* rubber band, eraser, spoon, paper) and play around with them. Squeeze them and stretch them. Can you feel a difference?

Different material families (ceramics, metals, polymers) behave differently in compression and in tension. Learn more about mechanical properties of materials here

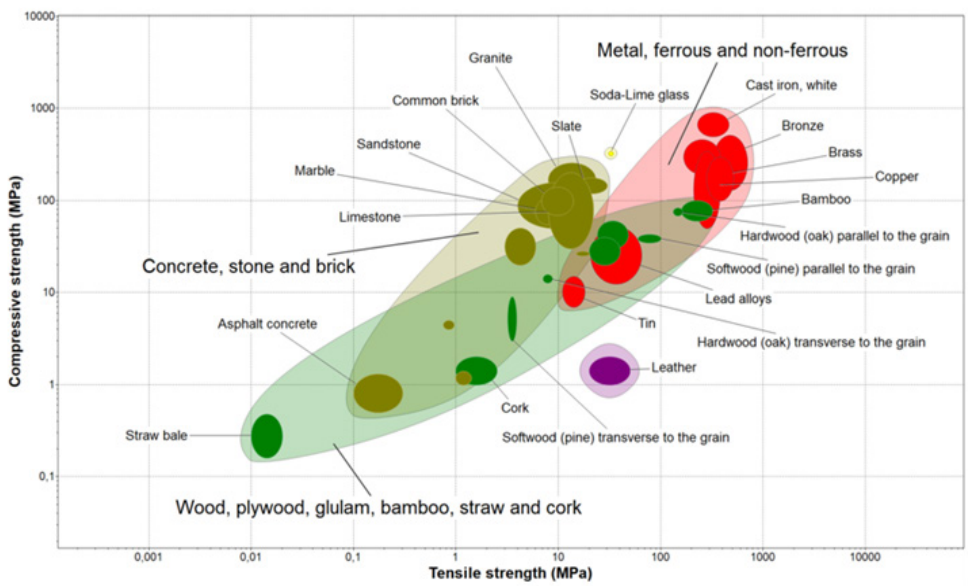


Figure 5: Compressive vs Tensile Strength for materials in 500 BC
(Plot made using Ansys Granta EduPack 2024R1, Built Environment Database)

3. Imagine this: Designing a Roman Bridge

Imagine you are an engineer in Roman times and want to span an open space (Figure 6).

Figure 6: Open space to span

What different designs exist for a structure to help us cross this open space?

3.1 Option 1: Cross the horizontal span with small building blocks

As mentioned previously, smaller blocks were easier to use for building due to ease of transport. But, using small building blocks to span the open space horizontally will not work, as they will have no support and the structure will simply collapse (Figure 7).

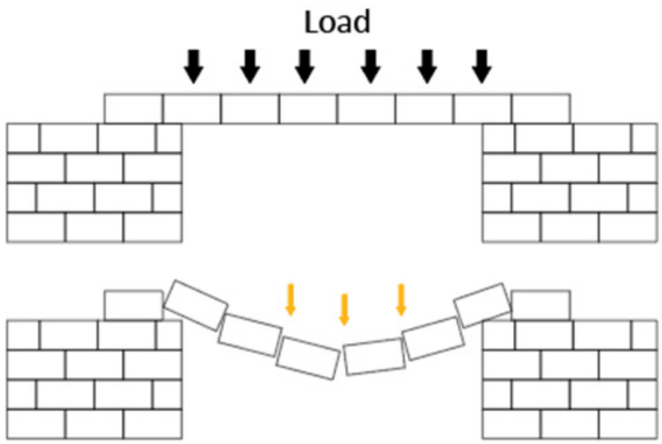


Figure 7: Using single blocks to span the open space (for ease of transportation)

> THINK
>
> But what if we had some sort of glue or other material to help stick the blocks together? What happens then?

3.2 Option 2: Cross the horizontal span with a single large beam

Using a longer beam to span the open space horizontally is generally a valid idea. However, **one large stone beam would have been too heavy to transport** and lift. And under a certain load, a beam made out of wood or stone would not have been stable enough, leading to **bending or breaking** (Figure 8).

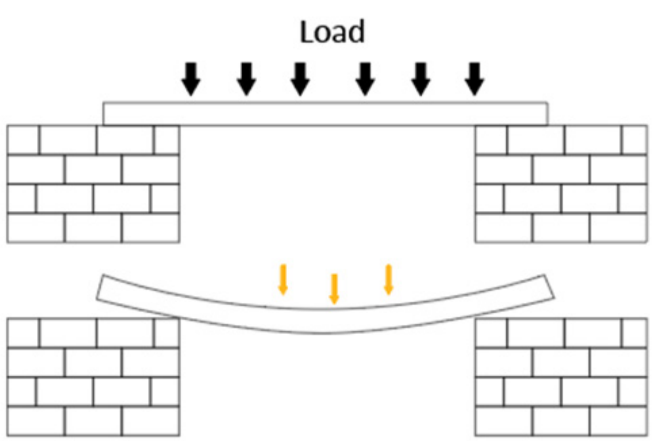


Figure 8: Using a horizontal beam to span the space

3.3 Option 3: Cross the horizontal span with an arch

We note that using smaller individual pieces is necessary for ease of transportation, as well as for structural reasons. **Therefore, we are looking for a structure made from several blocks that is still able to carry a load (for example, a carriage and horses).** Long ago, clever engineers solved this problem **by cutting the small pieces**, called voussoirs, into **wedge shapes** (Figure 9). This was a remarkable invention because it allows the voussoirs to **lean against each other and hold each other in place**. When a load is placed on the arch, the individual blocks press tightly against one another, making use of the material's high compressive strength.

(The structural signigicance of arches and the forces acting within an arch are explained in more detail in "Arches Part 2: Why the Shape Works: Understanding Forces".)

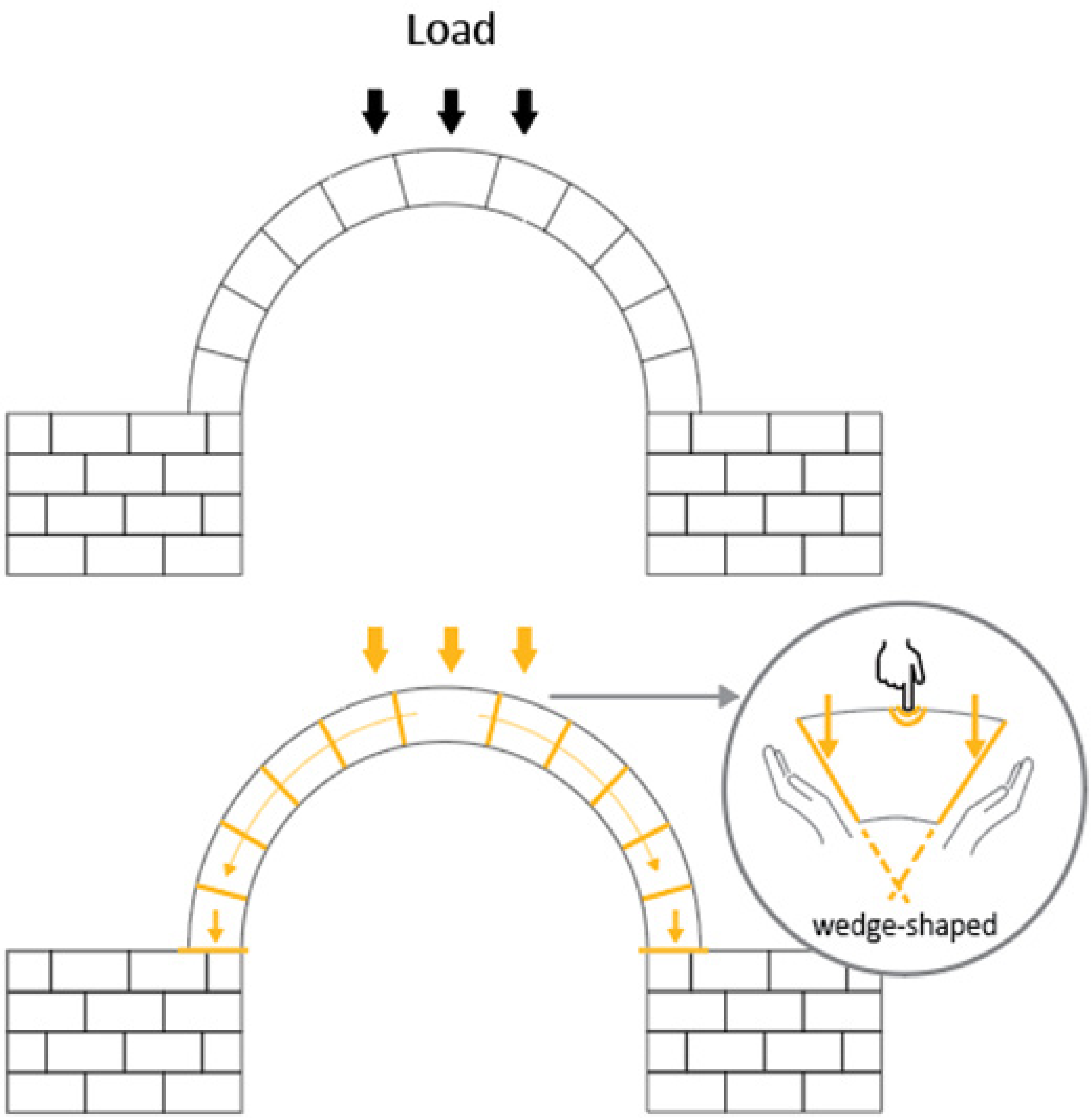


Figure 9: Using an arch to span the open space

4. Summary

In summary, arches were a groundbreaking invention because of their unique stability, despite the construction challenges of the time. Early builders could not simply choose any shape they liked, but had to work within the limits of available materials, their physical properties, and the tools and manufacturing techniques they had. Today, new materials and manufacturing methods allow engineers to create beams in specific shapes that can span large distances and support significant loads (Figure 10).

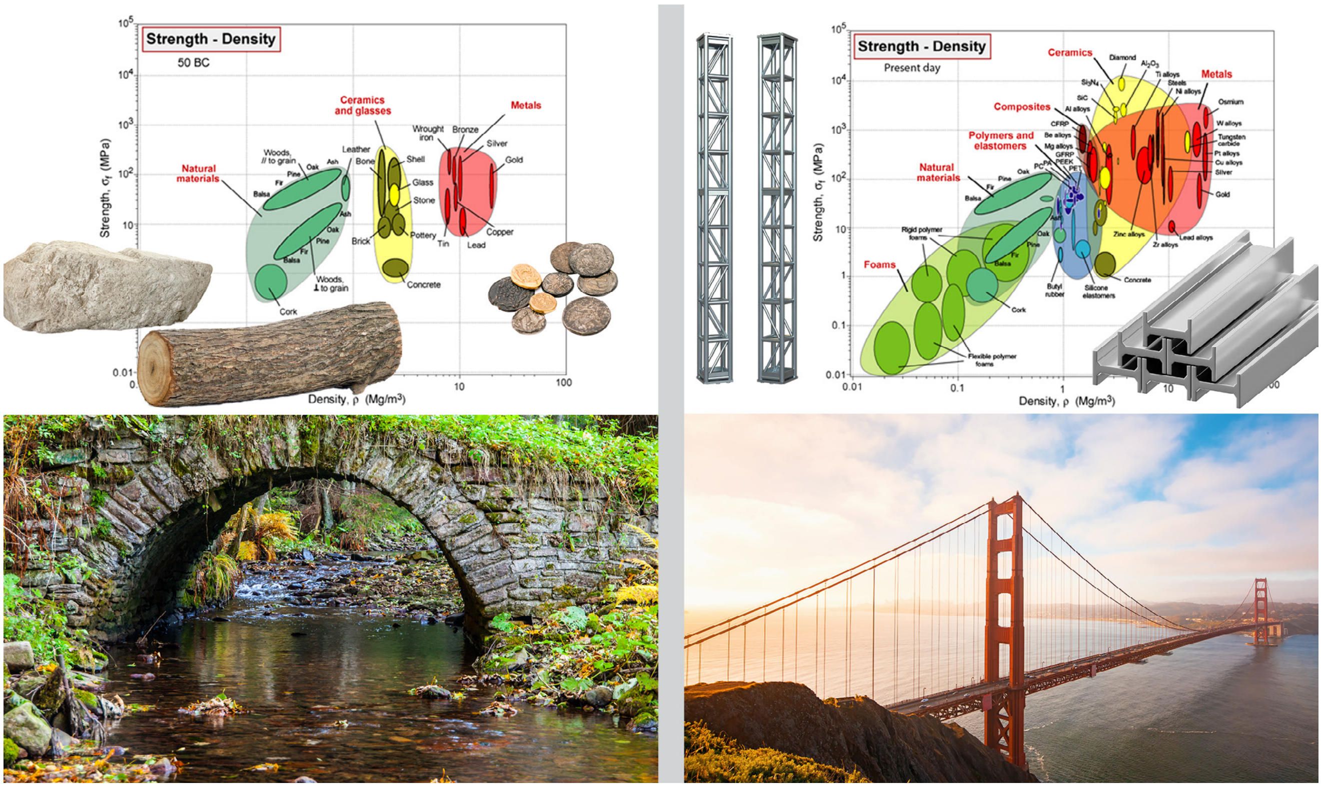


Figure 10: Comparison of materials available in 50 BC (left) and today (right), and the types of structures that could be built with them.

The shape of the arch and its individual pieces, called voussoirs, make use of the high compressive strength of stone. The voussoirs squeeze tightly against each other, holding the structure in place. You can find more information about the forces within an arch and why they are so stable in the second part of this case study linked here.

5. References:

[1] Britannica, The Editors of Encyclopaedia. "arch". Encyclopedia Britannica, 16 Feb. 2024, https://www.britannica.com/technology/arch-architecture. Accessed 20 March 2024.

[2] Hummel, R.E. (1998). The First Materials (Stone Age and Copper-Stone Age). In: Understanding Materials Science. Springer, New York, NY. https://doi.org/10.1007/978-1-4757-2972-6_1

[3] "Poster: the Evolution of Materials", 2021, Ansys Education Resources; https://www.ansys.com/content/dam/amp/2021/august/webpage-requests/education-resources-dam-upload-batch-1/evolution-of-materials-PSTEVLEN21.pdf

[4] Designing buildings, the construction wiki (2024, February 26); Arches; https://www.designingbuildings.co.uk/wiki/Arches

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