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Topic_101:

On the first page of David Billington's seminal book, "The Tower and the Bridge", he writes quote: “civilisation is civil works and insofar as these deteriorate so does society”.

Hello. I'm Maria Garlock, professor of civil engineering at Princeton University. This course is essentially about civil works, about civil engineering, and in particular about structural engineering.

In David Billington's quote, the meaning of deteriorate is not just a reference to the aging process but also the ideals and attitudes with which we design our civil works. If these deteriorate so does society. Although he wrote these words more than 30 years ago, they are more relevant today than ever.

This is a critical time for civil engineers since civilisation is facing a perfect storm of challenges. For example, over 70% of the world's population is expected to live in cities by the year 2050. In addition to increasing population densities, other challenges include:

1. Limited natural resources.
2. Aging infrastructure.
3. Increase in load demands such as intense and heavy traffic and extreme weather.
4. Natural and human induced hazards such as earthquakes and terrorist acts.

Engineers must design our civil works with these considerations and typically within the context of severe financial constraints. At the same time, in regards to buildings and bridges, elegance must be part of the fabric of design since these civil works visually dominate the landscape.

I have a question for you. What do you think a civil engineer does? This course illustrates how some of the best engineers of the past and present have faced challenges in their design of civil works. In this course, I will focus on bridges. In the future, I will speak of buildings and long span roof structures.

The foundation for this course is a scholarship with my colleague, Professor David P. Billington, who has defined post-Industrial Revolution structures that are efficient, economical and elegant as a new art form called structural art. Structural art has three ideals and each of these can be related to the ideals of the built urban environment.

Efficiency is the conservation of natural resources. Economy is the conservation of public resources. And elegance is the creation of an attractive urban environment. Efficiency and economy can be considered the ethic of the engineer and elegance the art of the engineer. Each of these three ideals can be matched to a dimension or perspective that can be used for measuring structural art.

The scientific dimension is measured by efficiency. It is based on calculations that reveal quantitatively the efficiency of form and the quantity of material used. This measurement is done with consideration of achieving adequate levels of safety. The social dimension is measured by economy. These large built works must be supported through public taxation or private commerce, both of which are influenced by the societal context including politics. And finally, the symbolic dimension is measured by elegance. Here the measure is mostly subjective. However, we can examine how artists such as painters and poets are stimulated by these large utilitarian objects. We can also examine how society embraces such works, many of which become not only an icon of the city but of the country.

Tell me what you think. Post a picture of a bridge that you consider to be structural art. After that, since I will next speak of engineering versus architecture, tell me what is the role of an engineer and the role of an architect in the design of bridges?

What do you think?

Topic_102:

In structural art, the forms for bridges, buildings, and long span restructures come from the imagination of the engineer. The structural artists that we will speak of -- engineers such as Roebling, Ammann, Maillart, Menn and others -- sought to integrate elegance into their forms.

Beauty wasn't an afterthought; it was a conscious decision embedded in the process of design. The elegance derived by the form is based on engineering principles, not decoration, and elegance can be achieved without compromising efficiency and economy. Despite the discussion of elegance, I'm not talking about works of architecture in this course; I'm talking about works of engineering.

There's a lot of confusion regarding the difference between engineering and architecture and the role in the design of structures. A perhaps too simplified way to explain the difference between structural engineers and architects is this; for engineers the form controls the forces whereas for architects, the form controls the spaces. Of course it's more complex than this but this difference is essential and it is in this selection of form that both architects and engineers have an opportunity to be creative.

For buildings where both the forces and spaces must be controlled, collaboration between engineers and architects is essential. The final design benefits from both complementary approaches and from the integration of both disciplines.

For bridges, however, the need to control the forces -- meaning the engineering task – becomes prevalent while the architectural contribution which is focused on aesthetic values must be subordinate to the structural concept. The bigger the bridge, the larger the forces to be controlled and, therefore, the more prevalent structural efficiency becomes.

I believe that both engineers and architects should be educated so that they are adept at rapidly finding approximate dimensions using simple formulas. Further, they should study the development of structural forms and construction methods from times past to the present and also learn to critique structures from both a technical and aesthetic point of view.

The study of history and criticism is not common in engineering education. There is little interest in the recent history of engineering; therefore, society tends to see engineering as a work of teams of technicians and committees of experts when in fact engineers are the heirs of centuries of technical progress achieved by outstanding minds.

In summary, the neglect of history and aesthetics in the education of the engineer has had the effect of dehumanising and discrediting modern engineering. The importance of civil engineering in today's world and my intention of crediting civil engineers for the value of their work and highlighting the role of structural engineers in the design of civil works are what have motivated me to teach this course.

Believe me when I say that I would be satisfied if through this course I could transmit to you just a minor fraction of the talent, passion, perseverance, and ingenuity embodied by all these structural artists; by these engineers that still today deserve our deepest admiration.

Just follow me and give me a chance to inspire you. I have a question for you; who designed the Millau viaduct; Michel Virlogeux, Norman Foster, both, or you have no idea?

Don't worry about getting the right answer. I'm not giving you credit on the right answer; I'm just giving you credit on answering.

Topic_103:

With a focus on bridges, I will illustrate:

1. How engineering is a creative discipline and can become art.
2. The influence of the economic and social context in bridge design.
3. The interplay between forces and form.

I will use examples of real bridges and real people to lead you through the fundamental principles of bridge engineering and examine the history and evolution of bridge design. In the short timeframe that I have, it's not possible to include all important bridges and important engineers in this course.

Please read "The Tower and the Bridge" by David Billington to gain a deeper historical perspective. This book was published in 1983. So to give you a more modern perspective, I end the course with modern bridges of Spain as just a small example of current times.

One major theme that runs through each lecture is that engineering is a creative discipline. Engineering creativity requires courage to try new things, discipline to stay within the boundaries of rational forms that lead to efficiency and economy, and creativity also requires play to search for proper form that is not only technically correct but also elegant.

The course has several learning objectives. By the end of this course you will be able to:

1. Recognise structural art and for the important structures studied in the course, be able to identify the name of the structure and engineer who designed it.
2. Solve for the efficiency of structures using appropriate formulas.
3. Evaluate the success or not of a structure within the measures of structural art, efficiency, economy, and elegance.
4. Illustrate how economic, social, and cultural contexts influence the design of bridges.

You will also learn about different bridges' structural forms including:

- Suspension bridges
- Beams, pre-stressed bridges
- Arch bridges
- Cable-stayed bridges
- Tied-arch bridges.

For each of these forms, you will develop an understanding of how the loads supported by the bridge travel through the different parts of the bridge to the foundations.

The course is designed for a general audience. No engineering background is needed. And the teaching consists of lectures, which focus on social and symbolic aspects, structural studies which focus on the scientific aspect and online questions.

The structural studies, which are about five pages long, will guide you through some fundamental equations of statics and equilibrium to calculate the forces imposed by the weight of traffic and the weight of the structure itself. Course participants with stronger technical training may find the calculations in the assignments too simplistic, but these formulas are not watered-down versions of what engineers use today. They are the fundamental equations used by every engineer to analyse and design bridges, in particular in the conceptual phase of design.

In the lectures, I will trace the development of outstanding bridges that arose with new materials that were developed after the industrial revolution such as:

- Industrialised iron
- Structural steel
- Reinforced concrete
- Pre-stressed concrete.

With each new material comes a new relationship between forces and form. For iron and steel, we have smaller members and therefore challenges of buckling or stability. With reinforced concrete, we have the relationship between the steel and concrete, and with pre-stressed concrete, we have the challenges of what's called creep that you learn about.

To start this historical perspective of form, we need to travel to Great Britain where one can argue that structural art began. Therefore, we begin our lecture series with Thomas Telford and British metal forms.

I hope you'll join us.

Topic_104:

Hello and welcome back.

To begin our study of structural art, we need to go to Great Britain and study the works of Thomas Telford, and also two other men, named Stephenson and Burnell.

I'm going to begin each lecture by defining some lecture goals, and in this lecture, the goals are:

1. To show how the definition and ideals of structural art began, and as I mentioned, they began in Great Britain.

2. Contrast the works of early iron bridges.

3. We're going to do that contrasting by critiquing structures through what we call a comparative critical analysis.

In these analyses, we critique both the technical and aesthetic aspects of the bridge design. So with these changes, from the scientific point of view, we have a new material that is born of the Industrial Revolution-iron.

From the social point of view, we have a new opportunity, industrialisation, and from the symbolic point of view, we have a new vision, a new form for structures which we define as structural art.

Let's start by comparing a pre-industrial revolution structure to a post-industrial revolution structure. One example of a pre-industrial revolution structure is Stonehenge, and I use this example to show essentially how far stone can span. In Stonehenge, the unsupported length of that beam, that horizontal member, is on the order of 3 m (10 feet).

Stone is not very strong in tension, and this beam on the bottom surface is experiencing tension. We're going to learn more about beams and tension in later lectures, but for now know that, again, stone does not carry very large tensile forces. It's not strong in tension.

In contrast, we have the iron bridge, the first bridge designed of iron. And iron is strong in both tension and compression. The iron bridge spans about 30 m (100 feet). Now, 30 m today is not very long, especially if you compare it to, for example, the Golden Gate Bridge at 1280 m (4,200 feet).

But back then, it was a very long span. It was designed in 1779 by Abraham Darby, the Third. It wasn't intended to be designed as a long span bridge, but really it was intended to be an advertisement for his company.

If you go to the bridge, which is still standing today, you'll see a plaque that says, “It was intended to be an advertisement for the skill of the Coalbrookdale Ironmakers.” The Darbys were in business for building pots, pans and weapons, and they used the iron bridge as a visible advertisement to show how iron can span 100 feet between supports.

Let's take a closer look at this new material iron, that came following the industrial revolution. Iron is stronger than wood and stone. For example, in compression, iron is about 10 times stronger than stone, and in tension, it is on the order of magnitude 100 times stronger than stone.

Iron is also more permanent than wood, but not necessarily more permanent than stone, because iron will corrode, and finally iron permits forms that are lighter than those of stone. Because it is stronger, you need less material to build it.

At closer look of the iron bridge, we see that it is comprised of five iron arches. It is, as I said, the first cast iron bridge, and is very light compared to others of the time. It is built in a way to make it look like a wooden structure, essentially carpentry in iron. We see mortise and tendon connections, for example.

Next, we're going to look at the social aspect of these British metal forms, but before we go there, I have a question for you:

The density of cast iron is about 450 pounds per cubic foot, and the density of stone is about 150 pounds per cubic foot. So which of the following is true?

1. A cast iron bridge will be heavier than a stone bridge.
2. A stone bridge will be heavier than the cast iron bridge.
3. A stone bridge will be just as heavy as a cast iron bridge?

The answer to the question is a stone bridge will be heavier than a cast iron bridge. Although cast iron is heavier than stone by volume, it's also much stronger than stone. Therefore, one can use much less material to build an arch. The resulting iron arch is much lighter than a stone arch.

For example, for the bridge built by Rowland Burdon Esquire over the River Wear at Sunderland, an iron arch was estimated to be 15x lighter than a stone arch of similar size.

Topic_105:

Now we're going to look at the social context of the Industrial Revolution and Great Britain. We see industrialisation happening in Great Britain in particular, and we're going to look at three reasons why this is happening.

1. One is we have Queen Elizabeth who outlaws wood cutting. The forests in Great Britain are getting diluted. So the Queen outlawed wood cutting. Wood was used for fuel and construction, and they needed to control this. They looked underground and found coal. Now they found a new material and need it for building and for fuel.

2. British Democracy encourages free enterprise. Britain wasn't really run from London. The transportation system in Great Britain was pretty bad. There was tendency for local freedom in what was done. London was far from the west midlands and so they left them alone. And that kind of democracy encouraged free enterprise. All didn't come from London. And finally, island isolation provides political stability.

3. Great Britain avoided wars on Continental Europe and they hadn't been invaded for about 700 years. Therefore, there was a sense of security.

So very briefly, that is the social context surrounding Great Britain and what allowed structural art to flourish in particular in Great Britain at that time. And the famous structural engineer of this era was Thomas Telford; born 1757, died 1834. Telford was brought up in poverty. He worked since he was eight years old, and began his career as a stonemason.

In 1782 at 25 years old, he left for London where he worked as a draftsman in an architect's office. And in 1787, he worked as a county surveyor. He designed his first bridge, a 3-stone arch span, completed in 1792. And at that time, he began to become recognised.

In 1795 there was a big flood over the Severn River where the Iron Bridge is. This flood took out all bridges except for the Iron Bridge. The stone bridges essentially acted as dams. The water pushed them over, and the wood bridges were lifted up by the water. The Iron Bridge was light enough so that water could go through it and it was anchored down.

When Telford saw this, he was impressed and he turned his attention from masonry to iron. There was an opportunity in Great Britain to build bridges and canals, because this was the infrastructure for the Industrial Revolution.

The Buildwas was the first bridge designed of iron. It wasn't a great work of structural art because it has two arches, and you don't know by looking at it which arch is carrying the load. So this is what we call an ambiguous form, meaning there is ambiguity in the way that we see the bridge because we don't understand how the loads are being carried. It was copied after wood arches. So it's essentially half engineered, half craftsman design. And it's also built over the Severn River.

If you look at Thomas Telford's early works, we're going to study three of them in this lecture. One is the Buildwas Bridge, 40 m (130-foot) arch that I just spoke about completed in 1795.

Next we're going to look at the Pontcysyllte Aqueduct which has short-span arches completed in 1805. And finally, the Bonar, a 46 m (150 foot) arch completed in 1810.

To be clear, Telford wasn't the only one building iron bridges at this time, nor were they the longest spanning ones. Telford's only bridge design rival, John Rennie, designed iron bridges on the order 61 m (200 feet) for example. But as David Billington writes in the Tower and the Bridge:

“What set Telford apart is his distinct personal style. His iron arches are more visually attractive and they are also technically superior. A compilation of cast-iron bridges built between 1779 and 1871 lists the bridges in order of their technical quality. Of the top 9 listed, 8 are Telford's. Of those 8, 5 are still standing today”

One of the bridges that no longer stands is the Bonar Bridge. It was taken down after 90 years because it was hard to maintain, not because of a defect. It's a cast-iron bridge spanning 46 m (150 feet). His design criteria for this bridge were essentially efficiency, economy, and elegance. He didn't use those words exactly, but he did use these words to describe the design criteria for Bonar Bridge:

“To improve the principles of constructing iron bridges, also their external appearance, and to save a very considerable portion of iron and consequently weight.”

So if you take apart that sentence, we see he writes, “To save a very considerable portion of iron and consequently weight." There he's talking about efficiency. When he speaks of, "To improve the principles of constructing iron bridges," there he is talking about economy, because economy is strongly linked to construction. And finally when he speaks about the external appearance, he is talking about elegance.

So in essence, the design criteria for the Bonar Bridge encompasses efficiency, economy, and elegance.

The Pontcysyllte Aqueduct carries the Llangollen Canal over the Valley of the River Dee in Northeast Wales. Completed in 1805, it's the longest and highest aqueduct in Britain. Viaducts were important to connect cities in Great Britain.

The Industrial Revolution required transportation. A pre-Industrial Revolution map of 1760 shows that there's not many rivers connecting the major cities. For example, Birmingham and Manchester were great industrial cities, but they were isolated. You couldn't go North or South via water, for example. Therefore, there's lots of canal building to connect these rivers. And a map just 30 years later in 1790 shows tremendous progress in connecting these cities via waterways.

The Barton Aqueduct of 1760 is an example of what was done prior to the Industrial Revolution. Everything has wind, human, and animal power. For example, you see the boat being pulled by horses.

The Barton is an arch form, a pre-Industrial Revolution stone bridge with Roman form. In contrast with the Barton Aqueduct, the Pontcysyllte Aqueduct is iron and it's much higher. The columns are also hollow. So Telford is beginning to think about minimum materials, efficiency. Not only are the columns higher, but they're much more slender than those of Barton. And if you see on the top this image, little tiny dots, those are people just to give you a sense of scale. This bridge is very tall and very large.

If we take a closer look at the structure, we see exceptionally slender arches. And this is a different aesthetic from the stone arches of the past. In the front there's a weathering plate, but the actual structure are the verticals and the arches.

In 1799 there's a huge competition for a London Bridge across the Thames River, and Telford proposes a single 183 m (600-foot) span to allow shipping to pass beneath unobstructed. This is way beyond what had been done before in any material. Nothing of the span had been done, not even close.

Telford's design impressed the committee the most. So the competition committee consulted many iron users, including university professors, to see if such a design was even feasible. Although the consensus was that the design could be built, Parliament never acted upon it and it was never built.

I have a question for you. How do you critique bridges? How do you measure the success or failure of a bridge?

Topic_106:

During Telford's time, James Watt was a leading critic of bridges, and he critiques Telford's design of a London bridge proposal. And Telford takes this critique very seriously.

Telford is then asked to write an article on Bridges for The Edinburgh Encyclopedia and when he writes this he critiques the Iron Bridge and others including his own, and in this critique he uses the ideals of structural art, although again, he's not using this terminology.

In this course we're going to critique bridges using the measures of structural art. We're going to look at it from the scientific perspective, looking at the materials, meaning efficiency. From the social perspective, minimum cost, meaning economy, and from the symbolic perspective where we have maximum personal expression where we measure the elegance.

We call these critiques, when we compare one bridge to another, a comparative critical analysis. So, from the scientific point of view we're going to compare the form and materials. Is it a suspension bridge? Is it an arch? Is it steel? Is it concrete?

From the social point of view we're going to look at costs and utility. What were the construction costs of these two comparisons? And, we're going to look at not only the construction costs, but the maintenance cost as well.

And, from the symbolic point of view we look at the appearance and the meaning. We look at the form, the details, and the ideas.

So let's do a comparative critical analysis using the Iron Bridge that we already looked at and The Craigellachie Bridge, one of Thomas Telford's later arch bridges made of iron. From the efficiency point of view, the Iron Bridge is a semi-circular form. The Craigellachie Bridge is “parabolic” and I put that in quotes because it's not really truly parabolic, it's really a very flat circle. It's a small slice of a circle.

The Iron Bridge is 30.5 m (100 foot) in span and the Craigellachie is 46 m (150 foot) in span, and despite being 50 percent longer, the Craigellachie has one third less material than the Iron Bridge. So, from that point of view, the Craigellachie Bridge is more efficient.

From the economy point of view we don't have numbers, but we could look at it and make guesses as to how it was constructed. So, the Iron Bridge we see it's constructed of many different parts with many connections versus the Craigellachie Bridge we see it is made in mass production.

The arch, you can see, it's separated in to seven segments. There's little vertical elements that show you where those connections of the segments are made, so it is mass produced, and we can assume that it was more economical to build.

From the elegance point of view, we see the semi-circular for the Iron Bridge versus again, “parabolic” for the Craigellachie. Both are arch bridges, so both are carrying the loads in compression. The shape of the Iron Bridge is what we define as mutilated, meaning if you look at those arches, the lower arch goes completely through from one abutment to the other uninterrupted, but the upper two arches are interrupted by the deck, so those upper two arches are what we call mutilated versus the Craigellachie Bridge has the arch that's unbroken. It goes from one abutment to the other uninterrupted by the deck.

The spandrel is what connects the deck to the arch, and in the Iron Bridge we see that they are circles. They are there for essentially decoration, whereas for the Craigellachie we have triangles, and those spandrel's are there for support.

Even though in this analysis we see that the Craigellachie Bridge essentially, say, wins in the context of measuring for structural art, it doesn't destroy the idea that the Iron Bridge is a great work, because it was so innovative using this material iron for the first time. It is a very important structural work.

Thomas Telford goes on to become the President of the first formal engineering society, The Institution of Civil Engineers which is still in existence today in Great Britain. He is the leading engineer of the modern world and he also considered himself an artist.

Telford is the first modern engineer to show that a concern for aesthetic does not compromise the technical quality that can improve it, and the people that we're going to talk about are the most accomplished and found engineers. Technically competent, but also artists.

That is one of the themes that runs through this course.

Topic_107:

Now let's take a look at Thomas Telford's later works. We started to look at the Craigellachie Bridge completed in 1814 spanning 46 m (150 feet).

Next we're going to look at the Mythe Bridge completed in 1824 at about the same span, 52 m (170 foot) span. And then finally the Menai Bridge completed in 1826. This is not an arch. This is a 177 m (580 foot) suspension bridge. With the design of the Craigellachie, Telford noticed that he made, what he would call, essentially a mistake. And he corrected this with the Mythe Bridge.

If we look at these two bridges we see that the landscape is different so you might notice they are different bridges by the landscape. But if you look at just the bridge itself, can you notice the difference between the two bridges? Because they are very similar to one another.

The difference between the Craigellachie Bridge and the Mythe Bridge is in the spandrels. It's in those diagonal members that connect the deck to the arch. If you look closely at those diagonal members you'll see that they're oriented differently in the Craigellachie versus the Mythe.

In the Craigellachie if you take the bisector of those diagonal pieces you'll see that that bisector is normal to the arch. It's coming perpendicular to the arch. Whereas in the Mythe Bridge the bisector of those diagonals is vertical.

It's completely straight up and down. In the Mythe Bridge this is a more efficient way of carrying the loads. The loads in those diagonals are more efficiently or more evenly distributed between those diagonal members, whereas in the Craigellachie Bridge in particular those diagonals that are leaning or more horizontal are carrying much less load than the diagonals that are more vertical.

Now we come to the Menai Bridge completed in 1826, a 177 m (580 foot) span suspension bridge designed by

Thomas Telford. Now there was a need to design this bridge and the need arose from the active union of 1800 which merged the Kingdom of Ireland with the Kingdom of Great Britain. They needed to connect London to Dublin and to do that you had to go through the Island of Anglesey all the way to the tip of Holyhead. And to get to Holyhead and even Anglesey you had to cross the Menai Straits.

If you look at the side spans of this bridge we see that it has both arches and suspenders. And this again is ambiguous. It doesn't tell you clearly how those loads are being carried. But Telford did this because he was concerned about wind. He wanted to make sure the back stands were heavy and anchored.

Just before the bridge opened, Telford's resident engineer noticed undulations from gusting winds so Telford added bracing, which cut down the movement. Ten years later, about two years after Telford's death, the bridge keeper reported large oscillations and unfortunately no action was taken and in 1839 a gale tore part of the roadway loose. Telford's writings in 1820s and his resident engineer's field observations showed how horizontal wind can cause extensive vertical motion in a suspension bridge. Unfortunately this lesson in history was lost in the bridge designs to come, as we will see.

In the Menai Bridge, although the towers look heavy, they're actually hollow, like in the Pontcysyllte Aqueduct Bridge. So Telford again is thinking about efficiency in his designs. Let's use the Menai Bridge to define some terms for you as related to suspension bridges.

The first term that we have to understand is span. When we talk about a span of a bridge we're talking about the longest unsupported length and for suspension bridges that distance is from one tower to the next. Next let's look at the cable. The cable goes from anchor to tower, to the next tower, to the next anchor, and it is in tension. And it's in tension due to the uniform loads imposed by the hanging suspenders. The suspenders are the vertical elements that suspend, or support, the deck.

The form of that cable is parabolic. I'm going to do a brief demonstration for you to show you the shape that these cables take when loaded and it will give you a better sense for why the form of a suspension bridge cable is parabolic.

In this demonstration this chain represents the cable of a suspension bridge. We know that the chain can only take tensile forces. It can't take any compression forces. It could be stretched but it can't be squeezed. So let's look at how the shape of this chain changes when we add loads.

So if I add one load right in the center we see the V shape that this chain takes. But if I — Now, I'm going to add continuously load along this whole chain, we're going to see it start to take the form of the cable of a suspension bridge, which is a parabolic form.

Now you start to see the shape change a little bit more… and more. So these weights represent essentially the load that's transferred from the suspender, which is the vertical elements of a suspension bridge, to the cable. And it's the load represented by the weight of the deck. And we see that as I add more and more of these loads along the chain, we're starting to see that parabolic form take shape, which is the shape of the cable in a suspension bridge.

Telford designed his bridges for carriage loads but the railroad age was approaching and that is where we move to next.

Topic_108

Telford designed his bridges before the railroad age. The Menai was not a railroad bridge. And railroad introduces new challenges. We have heavier loads due to the locomotive. And those locomotives, which are travelling very fast, also create impact loads.

To study the railroad bridges of Great Britain we need to now introduce Isambard Kingdom Brunel. Just some brief background on Brunel.

In 1824, he went to work with his father on the boring of a tunnel under the Thames River. During which time he was seriously injured when part of the tunnel collapsed. So his family sent him to Clifton to recuperate.

Shortly after arriving, there was a bridge competition in Clifton. Brunel had no experience designing bridges but he submitted 4 suspension bridge designs that spanned from 271 m (890 feet) to 279 m (916 feet).

Now remember that the Menai only expand 177 m (580 feet), to give you a sense of context.

The bridge commission felt uncertain about judging the 22 entries. So they asked Telford, who at that time was 72 years old, to be the judge.

I am going to show you some entries to that competition, to show you the state of the art at the time. None of these, however, are Brunel's entries.

One example is an underbelly type truss. So it's a truss that gets deeper towards the mid-span. Another shows a classical design that is essentially unbuildable. Or at least very expensive to build.

This one is an ambiguous form. It's an arch and a cable. The designer was, we're guessing, worried about wind. And therefore he is using the arch to stabilise the cable.

Telford who was the best bridge designer at the time thought that all the designs were bad. So he made one of his own, shown here with the large gothic towers. It's a bit of a strange design, putting huge gothic-like towers there, down near the water. He doesn't want to build longer spans than the Menai, because, remember, he is noticing that Menai is having trouble with the wind.

The idea of going from cliff edge to cliff edge with the towers would make the span too long for Telford. Brunel objects to Telford's design in a letter to the commission. He says that those 2 huge towers are not necessary, and the bridge should be able to span cliff to cliff.

So the commission essentially discards that competition and holds another one in 1831. And in this one Brunel enters and wins with a span of 702 feet.

Work for the Clifton Bridge began in 1831 but it was suspended when political riots in Bristol made it impossible to raise funds.

In 1831, there were revolutions in Western Europe and the British had to stop a lot of the building process. It wasn't until 1843 that both towers had been built. But the bridge wasn't complete until 1864, which is 5 years after Brunel died.

The Clifton Bridge still stands today. And as you look at it up close you'll see that the cables are made up of 3 independent rod iron chains.

Let's examine 2 other bridges by Isambard Kingdom Brunel. The Maidenhead Bridge completed in 1835 and the Saltash Bridge completed in 1859. Both were part of the Great Western Railway Project.

With bridge construction at a halt, Brunel turns to the railroad. And between 1833 and 1841, he directed the design, construction and operation of the longest rail line in the world, the great western railway that went between London and Bristol.

This line contained the world's longest standing brick arch bridge at Maidenhead expanding 128 feet.

Later in 1959, he designed the Saltash Bridge as an extension of this rail line. And I will come to that in a moment.

At the London end of this rail line is Paddington Station. If you look up Paddington Station, you see it's formed by a series of iron arches. Brunel designed the Paddington Station as well.

The Saltash Bridge of 1859 is an extension of this great Western rail line beyond Bristol. So it's built near Plymouth. And if you look at it, the form is what we call a lenticular truss. It is a combination of an arch and a cable.

And it forms the shape of a lens hence the name lenticular truss.

It is an ambiguous form because it's not clear how the loads are being carried. By tension through the cable? Or by compression through the arch?

At the tower, the horizontal components of the arch and the cable essentially cancel out so that the tower carries vertical load. An image of this bridge after the construction shows that the lenticular truss was lifted into place.

At that time, Brunel had a rival and his name is Robert Stephenson. They were rivals but also friends, because Stephenson was on site with Brunel during the construction, assisting him with the construction.

Stephenson is famous for the design of the Britannia Bridge, which is a railroad bridge also over the straits of Menai. He constructed tubes through which trains went. And it was constructed on shore and floated out and lifted into place.

Brunel was on site helping Stephenson during the construction of the Britannia, just like Stephenson was on site with Brunel helping with the construction of Saltash.

It is a little bit of a strange looking bridge, because it was supposed to be a suspension bridge. But the suspenders were too flexible for the railroad. Therefore they made the deck so stiff -- that hollow tube deck — that they realised they didn't need the suspension chains.

So the towers were built to contain cables but in the end, those cables were unnecessary. At that time, economy was less crucial than safety. Because unfortunately bridge failures were not uncommon. And it was a society that had grown wealthy.

Unfortunately, this Britannia Bridge as it was originally is no longer there. It was burnt down and something else was there put in its place. The towers are still the same. But it's no longer a tubed section. It's now an arch.

Let's do one of our comparative, critical analyses by comparing the Britannia and the Saltash.

From an efficiency point of view, the Britannia is a hollow box. Whereas the Saltash is a lenticular form. So these are different form for bridges.

The span is essentially the same, 140 m (460 feet) versus 139 m (455 feet). If we look at how much they weigh, the Britannia weighs 10.4 tonne / metre (7,000 pounds per foot). Whereas the Saltash weighs 7 tonne / metre (4,700 pounds per foot).

From an economy point of view, the Britannia cost 198 pounds per foot. Whereas the Saltash 102. So the Britannia is more expensive and it's also heavier.

But remember that the Britannia was designed to be a suspension bridge. And in the end ended up being a different form.

And from the elegance point of view, the Britannia is a closed form. It's unexpressive. It's not really expressive of the structure. Whereas the Saltash is opposite, in the sense it's an open form. But it is ambiguous as I mentioned earlier. It's not clear how the roads are being carried.

Both the Menai bridge by Telford and the Britannia Bridge are next to each other crossing the Menai straits, Telford's bridge carrying carriage loads, and the Britannia Bridge carrying railroad loads.

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These are iron structures. And the consequences of industrialised iron is that it's lighter than structures of stone, which now we have the portent for major failure.

At first, engineers didn't really understand this idea of how to design with iron, how to make those connections. And this concept of buckling and stability in members, was something new that was being studied by those engineers.

So, unfortunately, sometimes we did see failures happen with these bridges. And one of them was a bridge in Scotland called the Firth of Tay. This bridge collapsed in 1879, killing all aboard the rail line.

There were 2 great barriers to Scotland's east coast travel. They were the Firth of Forth and Firth of Tay, both stormy estuaries on the east coast of Scotland.

After the Firth of Tay Bridge collapsed, the next time the Scots had to build a bridge over a stormy estuary, they wanted to make sure it wouldn't fail. And so, they built the Firth of Forth Bridge, designed by Benjamin Baker.

And we see how massive this structure is and it's still standing today, spanning 521 m (1,710 feet). This was the longest spanning bridge in the world and it's also a railroad bridge. So, it was a great achievement by the engineer, Benjamin Baker.

To give you a sense of scale, as to how large the members of this bridge are, if you zoom in close to the supports, we see containers. We can see the relative size of those containers to the members of the bridge.

It is a massive structure. This close up image also gives you a sense of the different perspectives one can get from a bridge. So, close up, the Firth of Forth looks like a massive bridge full of clutter.

Whereas from far away, the bridge looks much lighter and you don't get that sense of heaviness.

Now let's look at this bridge and dissect it from a scientific point of view. The form for this bridge is called a horizontal cantilever. And to simplify the analysis, I'm only going to look at one span of the Firth of Forth.

The cantilever arm spans from the support towards the center. And the back span is called the anchor arm. It anchors that center support towards the anchors at the end.

And in the center, we have what we call a suspended span. We could think of this as essentially 2 seesaws. So, we've all been kids playing on seesaws and the seesaw has, let's say a center support, representing in this bridge, that center tower.

If we suspend a weight between these two seesaws, we know that it's not going to be stable. The seesaw will tend to rotate and it will no longer be horizontal.

To make those seesaws horizontal again, we know that the tips of them have to be pulled down. And that is what those anchors do. So, we can think of this Firth of Forth bridge as essentially 2 seesaws with a suspended rate between them.

Let's define the reaction at the anchor, that downwards reaction, as Ra. And let's define the suspended weight, a downwards reaction, W. So, will the reaction at the seesaw support be up or will it be down?

We need equilibrium. The sum of the forces in the vertical direction have to equal zero. Therefore, the reaction at the seesaw supports must be up.

Let's define this seesaw reaction Rs. Since the arms of the seesaw, meaning the size of the seesaw to the right and to the left of the support are of equal length, Rs of S, must equal W. Meaning, the seesaw support must equal that weight that's suspended.

In that case, what is the magnitude of the reaction at the anchor Ra, in terms of W?

Do you think that the reaction at the anchor Ra, is equal to W, W over 2, 2W or 2/3W? We can solve it in 1 of 2 ways.

The algebraic solution tells us that the forces in the upwards direction, equals the forces in a downwards direction. So, 2W is going up. And W plus 2Ra is going down.

And solving that, we get Ra, equals W over 2. Another way to look at it is to divide that system into 2 seesaws.

So that weight W, half of it is going to 1 seesaw and the other half is going to the other seesaw.

So that you know that if you're friend weighs W over 2, you must also weigh W over 2, to keep that seesaw horizontal. This double seesaw example is exactly how the Firth of Forth Bridge acts.

So, we have the suspended weight in the center W. And then we have the supports at those center towers, so to speak, is going up W. And then it's anchored down W over 2.

Now that we understand the reactions, let's look at the internal forces in the arms of the cantilever and anchor arm.

In this lecture, we're not going to try to solve for the magnitude of the stresses or forces in those arms. But we're going to try to define is it in tension or is it in compression?

Benjamin Baker did a physical demonstration to illustrate to the public how the Firth of Forth Bridge acts. So, he had 2 men sit on a chair. And they were holding another man in the center, who was the suspended weight. And then they had some bricks anchoring down. They acted like the anchors pulling down.

Just like in that seesaw example I just gave you. So, do you think that those men's arms are in tension or in compression?

And those wood pieces that they're holding between their fingers and the seat, are those wood pieces in tension or compression?

We did a similar example to this in my classroom, where I asked my students the same question. This is an easy experiment to do on your own and to build.

So, do you think that these students’ arms are in tension or in compression? After the experiment, I asked them, were your arms being stretched or compressed? And they knew for sure that their arms were being stretched. And that means that their arms were in tension.

Meaning, that the upper cord of this cantilever is in tension. And the bottom pieces of wood, the reason we used wood and not rope, is that that wood is in compression.

If we had used rope instead of wood, the experiment wouldn't have worked. So, the answer is the top cord of these horizontal cantilevers are in tension. And the bottom cords of these horizontal cantilevers are in compression.

So, in this lecture, we looked at some big metal bridges for railroads. We looked at the Britannia Bridge, made of iron. The Saltash Bridge, also made of iron and the Firth of Forth Bridge, which was actually made of steel.

What I didn't have time to talk about is the Eads Bridge in Saint Louis, which is also made of steel and the Garabit Bridge designed by Eiffel. Eiffel is famous for his tower, but Eiffel is also a famous bridge designer. And the Garabit is probably one of his most famous.

Next time, we cross the Atlantic and come to America, where we're going to see John Roebling is designing some magnificent bridges for railroads as well.

I hope you'll join us.