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00:30 [music]

00:50 HORIZON

00:55 [silence]

01:00 [music]

01:20 NARRATOR Without engineers none of this would ever have happened there would be no disasters. But also no achievement.

01:35 [music]

01:40 NARRATOR We depend on engineers for new constructions to provide us with safe shelter, safe transportation, and safe power.

01:45 [music]

01:55 NARRATOR We tend to take those successes for granted. But their failures are headline news.

02:00 [music]

02:10 TO ENGINEER IS HUMAN

02:20 HENRY Do engineers take excessive risks with human lives when they design bold new ways of doing things?

02:25 NARRATOR Because the shuttles had flown successfully 24 times before. The risk may have seen relatively low.

02:35 NARRATOR Those pictures show not just the horror but also contain clues. A tiny flame where there should be none. Then gas is leaking from the tank. And a sudden ball of fire near the shuttle itself, where seven men and women died.

02:55 PROFESSOR HENRY PETROSKI
Duke University
HENRY I am an engineer. And I look at such disasters also from an engineering point of view. Horrifying as that accident was, I immediately wanted to know, what can we learn from it. What can we discover to make future spacecraft that are safe. I believe that failure is the key both to understanding the engineering and to making new engineering advances. For that reason, I believe that failure should never be ignored or forgotten. But there is also this paradox. While failures lead to successes, successes also lead to failures. In the absence of something going wrong, successful designs are modified and changed until something does go wrong.

03:40 NARRATOR Or maybe we simply take them for granted.

03:45 HENRY And to understand how and why that cycle occurs, it is necessary to understand the nature of engineering design which like every other kind of design is a creative act.

03:55 NARRATOR Real engineering structures, whether they be large buildings or complicated spacecraft begin first in the imagination of the engineer. It's only after he can imagine what his structure looks like that he can hope to put down the detailed plans from which he can calculate the risk of failure from the equations of engineering science.

04:20 HENRY And he can calculate those failure risks only after he has imagined how the structure can fail.

04:25 NARRATOR And this uncertainty is as old as engineering itself. There's not much chance of this falling down, you might think. Even so the engineers of these ancient structures do face the problem of understanding how such a structure might collapse. How do they prevent that.

04:45 HENRY It's easy to imagine that the Egyptian engineers might have learned to build pyramids much as a child learns to play with sand.

04:55 [silence]

05:00 HENRY The impossibility of piling this sand to an angle any steeper than this, might have suggested to the Egyptian engineers that faced pyramids must not rise too steeply. But just how steep is too steep. Well, that may have been discovered not that sure.

05:20 NARRATOR At the foot, this early Egyptian pyramid rises at a steeper angle than any built before. But about halfway up, the angle changes from 54 degrees to 43 degrees. Around this bent pyramid, there's evidence of a structural failure that caused the engineer to lower his sides.

05:40 [silence]

05:45 NARRATOR And we find that at other sites in Egypt, all later pyramids were built at a less steep and less risky angle. A few thousand years later, the great Gothic cathedrals continued the process of structural evolution. Here, the aim was to build ever higher but at the same time to make more and more room for Windows. If one Cathedral was built without incident, another in a nearby city might be attempted with a higher vault or less massive walls. If a tower collapsed as the first did here at Eli, its replacement would again explore the engineering limits of Gothic structures. If cracks began to open up in the border between the stones, the master builder could order a redistribution of load by adding more weight through pinnacles. Or if a wall showed signs of bowing outwards, he could order that a buttress be erected. So successful was the Gothic style that its trappings have outlived their engineering need. At my own university in North Carolina, this 20th chapel could use steel as well as stone.

07:00 HENRY But we don't want to have to wait for centuries of structural evolution by trial and error, including massive failures as well as brilliant successes in order to learn how to build safe efficient structures. The essence of modern engineering is to use our knowledge and experience to anticipate as completely as possible how any new design might fail and then to take steps to avoid it. And preferably, here on the drawing board.

07:25 NARRATOR As soon as that design idea can be put down on paper, the process of analysis by the methods of engineering science can begin. That can involve a lot of complicated equations and detailed calculations.

07:40 HENRY But the engineer can calculate when failure will occur only if he knows what kind of failure to expect. Above all, he must know what kind of failure will strike first, the so-called governing mode of failure. Galileo in the 17th century was the first to consider the strength of materials from the modern point of view. This is his famous analysis of a cantilever beam. Let's try it.

08:05 [silence]

08:10 HENRY Galileo explained why a board placed upright in a wall like this can support more load. What he understood was that the depth here is important as opposed to the width. He explained it here. This is better than this. But even a genius like Galileo had trouble predicting how much load the beam could take before snapping at the wall. He was off by a factor of three, and he doesn't seem to have even worried about the fact that the beam could fail in ways other than by snapping. If I push down, it buckles. And here is another way it can buckle because it's too slender. No one ever accused the railway bridge across the Firth of Forth as being too slender. So buckling was never a problem with it. But that was not the case with a bridge planned to cross the St. Lawrence River in Quebec.

09:10 NARRATOR When its center section was being erected in 1097. Some great girders buckled. And seventy five men were killed in a tangle of steel. The ill-fated bridge was redesigned but suffered another setback when its center span fell during the erection. It was eventually completed and it still in use today. But the success of any complex structure depends on how well the engineer understands what may happen to each constituent part.

09:40 HENRY Let's imagine this piece of chalk is part of a machine or structure. It seems perfectly capable of resisting my pull or push. But if I bend it, it snaps very easily. Bending is a combination of a push and pull. Let's illustrate it with this piece of foam. If I bend it the cracks open. .If I bend it the other way, the cracks close. Bending is always a combination of a push and pull with one side being pulled and the other being pushed. The chalk breaks when I bend it because it can't take too much pulling. Look what happens when I twist this piece of foam. It's an entirely different action. If I twist a piece of chalk like that… look what happens. I get an entirely different failure mode. It's called failure by torsion. It's this failure mode that engineers overlooked when they were designing the Tacoma Narrows Bridge.

10:45 NARRATOR They were so concerned about making that bridge stiff against bending that they forgot to make it stiff against torsion.

10:50 NARRATOR Overlooking just one possible failure mode like that can lead to disaster. Dramatic new architectural designs can also lead to dramatic new modes of failure. And here again, it's up to the engineer to make sure that doesn't happen.

11:15 NARRATOR This hotel in Kansas City has bedrooms over there. And conference rooms back here. So the design objective was to connect the two, at several different levels in some way that would enhance the dramatic effect of this enclosed space. The solution was three skywalks, 120 feet long, suspended from the roof. This is what it looked like when it opened back in 1980. And in this new hotel they had tea dances. This is Friday July the 17th, 1981.

11:55 [music]

12:10 NARRATOR There were people watching from the walkways, others directly below. The cameramen recording the scene had to stop and change a battery. But the sound was also being recorded by a member of the band.

12:25 [silence]

13:00 NARRATOR Two of the Skywalks weighing over 70 tons had collapsed. One hundred and fourteen people were killed. Hundreds more were injured and thousands were marked by the tragedy.

13:15 [silence]

13:25 NARRATOR It emerged that the structural principles were not particularly complicated. The top walkway was to be hung from the ceiling by rods that would pass through its crossbeam to the bottom walkway and support the lower one as well. But somewhere between the initial design and construction, each single long rod was replaced by two shorter rods. As a result, the bolt under the top walkway had to support not only that but also the walkway hung from it, which doubled the force on that bolt. And in the end, the connection failed when the bolt was pulled through the box beam.

14:05 [silence]

14:20 NARRATOR How it had happened became clear within a few days. And then, there were suggestions galore about how the fatal detail could have been designed so that the accident need never have happened. But these proposals of alternative designs had the advantage of knowing what had caused the failure. They already knew the governing mode of failure.

14:40 HENRY But anyway, by that time there was a new design objective. To make the replacement walkways look as solid as a rock. During the multimillion dollar refurbishing after the accidents, those pillars were actually anchored in the rock beneath the hotel.

15:00 NARRATOR But that was too late for the victims who lost their lives in the accident and the engineers who lost their licenses. The challenge to engineering is to anticipate the fatal detail and to correct it in the design stage.

15:15 [silence]

15:20 NARRATOR Robert Stephenson had to face up to that kind of worry in the middle of the 19th century. He needed a bridge across the Menai Strait to complete the railway link from London to Holyhead on the way to Dublin. Since the tall ships of the day must not be impeded, any bridge would have to be a clear one hundred feet above the water with just one central support on the Britannia rock.

15:40 NARRATOR A suspension bridge like Thomas Telford's about a mile away was not believed to be rigid enough to carry the weight of railroad locomotives. So Stephenson conceived the bold new scheme of spanning the distance with wrought iron tubes through which the trains would run. But few equations were available to analyze the strength of such a bridge against failure. Besides who knew how it might fail. So models were used in which the tubes were loaded until they did fail. Then after each weakness was detected, the design was improved. But with the rail bridge act like the models… an expert on the strength of material still predicted failure. He calculated that the tubes would need to be supported by chains. And high towers were actually built to hold chains just in case. But Stephenson decided to trust the results of experiment and he was right. The bridge based on that design stood unchanged for well over a century. In fact until 1970 when two boys looking for bats in its timber roofed set it on fire.

16:55 HENRY Even today, when engineers design something new, they build and test models like these. Because it's only by anticipating every possible way in which a structure can fail that its safety can be assured. The engineer's dilemma is this, that he can never prove that he has considered every possible mode of failure. A bridge is like a scientific hypothesis, in that it can be tested and verified but it can never be proven absolutely. However, it can be easily disproven by a single counter example, a structural failure. And if such a disaster were to happen, it's far better that it happened here in the wind tunnel than after the actual bridge is built.

17:40 [silence]

17:50 HENRY Is that realistic? Well, the Tacoma Narrows did that and tore itself apart. After that disaster, engineers have studied wind tunnel models before building the actual bridge. But what if a bridge bottle survives the wind tunnel? Does that ensure its safety? Well, we've seen other things that can go, something that no one has thought about or seen before. And it's not just bridges, a roof could collapse killing everyone beneath it, or workmen could be killed during its construction. Anything could go wrong. Engineers lose a great deal of sleep trying to imagine what could possibly go wrong.

18:25 NARRATOR Robert Stephenson wrote, "Often at night I lie tossing about seeking sleep in vain." And when at last the first tube of his Britannia Bridge had been hoisted into place, he said, "Now I shall go to bed." And from another engineer, every shelf, and peg, and pivot of the British Museum reading room was thought of and determined in the wakeful hours of the night. So Antonio Panico, its builder was reported to have said. Herbert Hoover, the mining engineer who became president of the United States declared… "If his works do not work, the engineer is damned." This is the phantasmagoria that haunts his knights and daunts his days. He comes from the job at the end of the day resolved to calculate it again. He wakes in the night in a cold sweat and puts something on paper that looks silly in the morning. Such worries serve us well.

19:25 [silence]

19:30 HENRY But even if something survives construction and provide years of trouble free service, it still may hold surprises. Apparently, sound and identical bolts and girders need not be so sound or even identical on closer inspection.

19:40 [silence]

19:45 HENRY In my own home, I found an example of variability in common objects. We had been using these everyday knives for some years when one day I noticed that one of them had a rather large crack, here. I looked at some of the other knives. And I discovered that one of the others also had a crack. What if I were using this knife and cutting my steak. And what if it hit the bone and the blade flew off, flew through the window, through my neighbor's window, and killed her dog. I could imagine all sorts of nightmarish scenarios. I gathered the knives together. And I noticed what had been identical looking knives were really not identical at all. Some of the blades were longer than others. Some were shiner than others. Some had different words stamped on their blades. Some of the blades had cracked and others did not. Perhaps they had been made out of different materials, different batches of steel. Perhaps some of them had been stamped too hard. Perhaps some of them had been heat treated differently. What we did was we put the most badly cracked knife away and continue to use the other ones. In several years we noticed no significant changes. The cracked knife that we continued to use, didn't change. The uncracked knives never developed cracks. And as a result, these cracks that are there appear to be benign. Not all cracks behave that way. I once had a pair of plastic eyeglass frames that developed a crack. I watched the crack grow. After about a year the crack gave away and the frames were ruined. Those frames had replaced the same kind… that suffered the same fate in about the same amount of time. This was too much of a coincidence not to be a design flaw. The phenomenon of progressive cracking leading to total failure is known as fatigue. And it's a particularly sticky problem for engineers to deal with.

22:05 NARRATOR This failure mode is especially dangerous in airplanes that go through many cycles of large forces on takeoffs and landings. Cracks can grow with each flight. If they go unnoticed, they can lead to catastrophic failure. And that's what happened to the de Havilland comets of the early 1950s. The designers didn't think fatigue would be a problem, and that oversight cost Britain its advantage in capturing the post-war market, and commercial jet airliners.

22:35 [silence]

22:40 HENRY This action appears safe enough. I open the paper clip and close it. It's deformed but it hasn't broken and it still could be used. But if I repeat that action again and again, eventually I find that something happens. The paper clip breaks. So what was a safe load when applied once becomes unsafe when repeated again and again. This is another example of failure by fatigue.

23:10 NARRATOR In the tower that holds Big Ben, the timing mechanism of the great clock failed explosively in 1976. And that disaster was traced to failure by torsional fatigue of a shaft that had been twisted back and forth millions of times since it was installed in 1859. But even if they understand fatigue, how can engineers predict accurately when such a failure will occur.

23:35 HENRY Well, let's try a small experiment to see that it's not trivial.

23:40 UNKNOWN Ten.

UNKNOWN Seven.

23:45 HENRY These students are bending paperclips back and forth… to see how many times they can flex them before they break.

23:50 UNKNOWN Five.

UNKNOWN Seven.

23:55 UNKNOWN Six.

HENRY Okay, hold it. What this little experiment shows us is that there is no one answer to how many times it takes to bend a paperclip to failure. Although the average appears to be 7, some clips lasted as long as 13 bends, others failed at only a single bend. This is a problem that engineers must face all the time. There is so much variability in the strength of materials that it is impossible for us to predict exactly how many bends the next paperclip out of the box will take.

24:30 NARRATOR Or for that matter, when concrete might eventually break in a test.

24:35 [silence]

24:40 HENRY If there is so much uncertainty in failure predictions and if the safety of design is impossible to prove, then how can engineers be sure they are not taking undue risks. Careful experiments can be performed with modern test equipment to better understand not only the reliability of theories but also the strength and variability of materials. And a further practical measure is to introduce a factor of safety. It works like this. If an engineer is expected to design a beam to carry a 10 ton load. He will design it to carry 20 tons. That would be a factor of safety of two against load.

25:20 [silence]

25:30 HENRY And if a material strength were rated at so many tons per square inch, the engineer might only trust it to one third that strength. This would be a further factor of safety of three against material variability and uncertainty. The beam's total factor of safety would then be two times three. Most would regard six as an adequate factor of safety for most ordinary structures around us.

25:55 NARRATOR After those Kansas City skywalks collapsed, it was discovered that they had a factor of safety of just over one and nobody had spotted that. It could have been prevented by a simple well-established test. It's called a proof test. London's Tower Bridge was constructed in the early 1990s. The guests invited to its ceremonial opening could rest assured that the bridge was not going to collapse because it had been tested in advance with 150 tons of steamrollers and trucks full of metal, resulting in a trivial deflection of just one and a half inches. The bridge was declared to be safe. Such a test may also play a role in restoring public confidence after some structural failure.

26:45 HENRY Here a few miles upstream, another of the bridges across the Thames recently began to show its age and had to be closed to traffic. It was reopened to light traffic and to London buses only after six of them were piled on it all at once. That's twice the maximum that would subsequently be allowed at any given time. In practice, there would even be fewer. Such ways of assuring safety and minimizing risk have served the engineering profession well. Let's take a look at a spectacular success also here in London in 1851.

27:30 NARRATOR The Crystal Palace built to house the Great Exhibition, the first World's Fair. It was constructed in record time but without sacrificing safety. Its designer Joseph Paxton was an erstwhile gardener who had an amazing eye for detail. Two hundred and forty five other designs had already been rejected and the building committee had come up with an awkward compromise when Paxton suggested a radically new kind of structure. It was developed from his work on greenhouses such as the giant Loevy house at Chatsworth in Derbyshire. He based its design on the structure of the lily pad itself. Paxton sketched the germ of his idea on a blotter and produced a detailed design within a week. He offered it not only to the building committee but also leaked it to the public in The Illustrated London News in July 1850. It was an immediate success. And construction began within weeks. The only major problem was how to deal with several large trees that conservationists insisted must not be destroyed. But Paxton obligingly adopted his design to include a transept which would enclose them.

28:40 [music]

28:50 NARRATOR His interchangeable standard parts fitted smoothly and efficiently together. He designed the ridge and ferro roof with special gutters to catch not only rainwater but also condensation from inside the glass and iron building and channel it to drain pipes within the supporting columns.

29:05 [music]

29:10 NARRATOR He designed special machinery to make the miles of Paxton gutters that were needed. And special trolleys to help glaze the roof. But speed did not imply lack of care. All cast iron girders were tested. Wrought iron girders on the other hand were only spot checked to verify the design because experience had shown that material to be more uniform and so more dependable. To test the galleries that overlooked the main avenue, burly workmen jumped up and down and soldiers trooped over a trial section.

29:45 [music]

29:50 NARRATOR And all under the approving eye of Queen Victoria. She opened the Great Exhibition on schedule on May 1st, 1851. Up to one hundred thousand visitors a day would leave a lot of rubbish. So Paxton designed a wooden floor with gaps between the boards so that litter could be swept into the space below by a specially designed machine. However that turned out to be unnecessary because Victorian skirts did all the sweeping anyone could need. Then each night boys crawl beneath those floors to collect any trash that might feed a fire.

30:25 [music]

30:30 NARRATOR And all this was designed to be dismantled when the Great Exhibition closed. So Hyde Park could be restored to its original state. But the parts were designed for reuse. And then enlarged crystal palace was erected at Sedona, where it stood for over 80 years. The Crystal Palace did eventually burn down in 1936. But that was hardly a design failure, since the building had served long and well far beyond its originally intended life.

31:00 [silence]

31:05 NARRATOR There are plenty of other examples of innovative designs that have succeeded to become symbols of engineering excellence. The first iron bridge still stands in the valley that cradled the industrial revolution. In New York, the Brooklyn Bridge, once the world's longest recently celebrated its centennial. And the Empire State Building which was erected in the astonishingly short period of 14 months, long remained the highest building in the world.

31:35 [silence]

31:40 NARRATOR The good news is that the world is full of structures that are successful, that have stood the test of time.

31:45 [silence]

31:50 NARRATOR Structures that have not fallen down because their designers correctly anticipated what could go wrong. And they designed against it or included factors of safety large enough to handle the unexpected.

32:05 HENRY So why should we have any design failures. Why not simply copy the successes of the past and make our future almost entirely free of risk. Well, we see one reason all about us in building such as this. It's not at all clear what this structure is used for. In fact it's a pharmaceutical research laboratory. And this… What do you think this is? One answer is a medical insurance office building.

32:40 NARRATOR Another is an innovative and surprisingly well balanced piece of modern engineering. Large cities and successful companies want bold distinctive structures that are also symbols. Just as the cathedrals were sometimes built with more than structural safety in mind, some modern buildings are often constructed with more than mere function in mind.

33:05 [silence]

33:10 NARRATOR Or there may be more practical reasons for change, just as the stone on a great monument may have been changed partway through construction as finances got pinched. There are pressures today to use less expensive materials. Here's a case in point.

33:25 HENRY Who could imagine using stone to construct this high speed inner ring road around Cardiff in South Wales? It's made of chunks of reinforced concrete and glue. New materials are not only cheaper, they may promise more. And new construction techniques open up all sorts of new possibilities.

33:45 [silence]

33:50 NARRATOR At this point over a railway line, they have to work by night. This is the only time they can stop the trains to swing the new segments into close.

34:00 [silence]

34:05 NARRATOR Each segment is 30 feet wide but only 10 feet long. And the glue goes on the faces between the segments of country. That clue is not just a stick the segments together. It will carry the forces smoothly through from one to the next.

34:25 [silence]

34:35 NARRATOR Here in Britain not so long ago concrete got a bad name when a few years after construction some concrete structures began to fall apart. But as ever, engineers have learned from that failure and when it's finished, this new concrete structure is not expected to crack or require a great deal of maintenance. For Maintenance also has to be considered in any engineering design. Will a structure continue to function as it did when it was new? Painting a great bridge to protect it against a corrosive sea air is a never ending task. But when maintenance is not carried out properly and otherwise sound structure can fail.

35:20 HENRY In 1979, a DC10 crashed in Chicago. Because an engine had fallen off during takeoff. This crash was ultimately traced to faulty maintenance. Instead of following the manufacturer's instructions for removing engines for repair and maintenance, the work crews were using a forklift to shortcut the procedure. This caused excessive forces to be exerted on the engine mountings and large cracks began to develop. Since designers never expected these kinds of cracks to appear, well this mode of failure was never anticipated. When the engine fell off, it ripped out some vital hydraulic lines and the plane lost control killing 273 people.

36:00 NARRATOR In 1983, a bridge carrying the Interstate 95 highway over the Mianus River in Connecticut fell apart in the night. Neglected maintenance was again blamed. The traffic was light but even so, three people were killed. In all such accidents, the immediate response of engineers is to suspect all similar designs. Other bridges like this one were inspected after it collapsed and were also found to be defective.

36:30 HENRY But these accidents also had one thing in common. They all lead to safer structures, more careful maintenance, and closer inspection of improved designs.

36:40 NARRATOR But even if they have no problems, some successful design seemed to be dead ends. They don't fail but they're not copied either, perhaps because there are cheaper ways of achieving the same result. Robert Stephenson's Britannia Bridge and Benjamin Baker's fourth bridge have been called over designed by other engineers.

37:00 [silence]

37:05 NARRATOR Does it use too much material? Is it a structural freak? The Empire State Building too was built very strongly. And that turned out to be no disadvantage in 1945 when it survived the impact of a B25 bomber and suffered only minor structural damage. But if the tallest building in the world could stand up to that, why not make lighter skyscrapers with less steel.

37:30 HENRY Extend that argument stage by stage and gradually a safe design would evolve into an unsafe one. That not only can happen, it does.

37:40 NARRATOR The history of suspension bridges illustrates the cycle of failure and success. Thomas Telford's Menai Suspension Bridge was a bold advance in 1826. But its debt was notoriously shaky and susceptible to being flung about in the wind. The deck collapsed in what the site engineers report described as a hurricane in 1839.

38:05 [silence]

38:10 NARRATOR And at the wheeling bridge across the Ohio River from West Virginia, we have an eyewitness report from 1854.

38:20 HENRY About three o'clock yesterday, after enjoying the cool breeze and related motion of the bridge, we heading off and only two minutes when we saw the whole structure heaving dashing, lunging like a ship in a storm until at last down went the immense structure from its dizzy height to the stream below with an appalling crash and roar.

38:40 NARRATOR But the following year, a new bridge over the Niagara Gorge proved that a suspension bridge could be built with a deck stiff enough to carry even railroad traffic.

38:50 [silence]

38:55 NARRATOR Engineer John Roebling had learned from the earlier failures.

39:00 [silence]

39:05 NARRATOR And his Brooklyn Bridge opened in 1883 took the suspension bridge to new lengths.

39:10 [silence]

39:15 NARRATOR The George Washington Bridge whose steel towers were never encased in the stone they were designed to carry, could safely be made longer still and also more slender than any other when it opened in 1931. Engineers continued to plan and build ever longer and more slender suspension bridges until 1940. And here, they overstepped the limit. The Tacoma Narrows Bridge was only two lanes wide and its deck was supported on shallow steel girders rather than the open truss work of earlier bridges.

39:50 [music]

39:55 NARRATOR The Tacoma Narrows soon came to be known as "Galloping Gertie". And for some people, driving over it was regarded as great fun. It was also an object of study to the engineers at the University of Washington, who measured and also filmed these wild oscillations. Aerodynamic stability had been less important for the heavy stiffer bridges. But here it became the limiting factor.

40:20 [music]

40:25 NARRATOR On November 7th 1940, the wind rose to 42 miles per hour. Gale force but in a region where gales are not uncommon.

40:35 [music]

40:50 NARRATOR By 1940, engineers had forgotten the Menai and Wheeling collapses. Economy of material and slenderness of form had been evolving from the earlier, more over designed bridges. So it was back to the drawing board.

41:05 [music]

41:10 NARRATOR New York's elegant Bronx Whitestone Bridge which was completed before 1940 had also been lifting in the wind. Its deck had already been modified to reduce the effects of the wind. But after the Tacoma Narrows collapse, the misbehaving Bronx Whitestone was hastily stiffened with ugly steel trusses. They obstruct what can be a splendid view of the Manhattan skyline to the west and also spoil the slender silhouette that had once made the original design of the bridge so attractive. And Bridges still on the drawing board in 1940 were redesigned with much larger factors of safety. The Mackinac Bridge connecting the upper and lower peninsulas of Michigan and the replacements across the Tacoma Narrows, both went back to deep open trust deck structures. And so did the Forth Road Bridge just like the older more conservative designs.

42:00 [silence]

42:15 HENRY During wind tunnel testing of the Forth Road Bridge there was an accident. The model was blown adrift and smashed to pieces. Since they had some spare wind tunnel time, they decided to try something new. It's a deck with an aerodynamic cross section. And a narrow edge to slice through the wind. This walkway had another one like it on the other side. Our wing like structures connected to the hollow steel box beneath the main roadway. And they tried something else, angled suspension cables to help stiffen the deck further. But that turned out to be not such a good idea. Some of the first lot (inaudible) had to be replaced. But the bridge was never in danger of collapse. There are obvious difficulties with winds in an area like this but that's not a structural problem. The main structural problem with this bridge is that it was never designed to carry such heavy traffic nor such heavy trucks. The basic design principle of this bridge however is sound and it is being adopted for other bridges of this generation elsewhere. The next great leap into the unknown will take place with a new generation of bridges that are expected to be twice as long as this one. One such proposed span is across the Straits of Messina between Italy and Sicily, a distance of about two miles. The history of suspension bridges illustrates the cycles of success and failure that are encountered in the evolution of all engineering designs. We tend to take our successful designs and gradually evolve them into failures. But then we learn quickly from those failures how to succeed a new.

43:55 NARRATOR Of course, such great swings are not limited to engineering design. They're seen in all forms of human activity, as each new generation looks for new ways to solve old problems.

44:10 HENRY Old time engineers, which here means many of us over the age of 40 once used a slide rule to calculate the loads and deflections on our structures. I bought this with a great deal of pride and care when I was a young engineering student and I fully expected it to last a lifetime. But it was soon made obsolete by the far greater power of the computer. In comparison with those, my slide rule did have obvious disadvantages. But I like every other engineer soon learned how far I could rely upon it. In particular, when I calculated with this I could only determine an answer to three significant figures. But that was enough for most engineering applications of the time. Far more importantly, this never gave me a decimal point. This meant that I and other engineers always had to know how large or small to expect our answer to be. But this helped us develop a sense of scale, in the slide rule age also. Because calculations took so long to carry out and were so difficult to check. Engineers were reluctant to attempt designs for which they had little field.

45:10 NARRATOR Today, there's a temptation to design by computer, what sluggard engineers would never have attempted. Too often, the computer gives us more information than we are able to assimilate. It gives the illusion of looking at everything. It also gives more apparent precision than can be meaningful. And longer strings of figures than you'd ever get with this.

45:35 [silence]

45:40 NARRATOR But whatever the degree of expertness that can be programmed into a computer, I believe that we should never rely entirely on the computer to anticipate failure. In particular, we should not expect it to think of failure modes that human engineers and programmers haven't already thought of. Human engineers worry and lose sleep while their designs are evolving. And that minimizes the risks for all of us.

46:05 HENRY Computers don't worry about failure. Instead, they can generate a false sense of security, as they did in Hartford, Connecticut in 1978.

46:15 NARRATOR The Hartford Civic Center roof had an ambitious design, a three dimensional assemblage of metal rods that covered two and a half acres while resting on only four columns. It gave unobstructed views of the basketball court on a cold January evening. But just hours after thousands of fans had left the game that roof totally collapsed under the snow and ice that had accumulated on it. The roof failed because some of its 30 foot long rods had buckled, a failure mode completely unanticipated by the computer or its users. The design would have been impossibly tedious for the slide rule engineer.

46:50 HENRY That daring roof might have never been attempted had the computer not promised to be so efficient and reliable a calculator. What was to be a dream arena turned out to be among the first computer assisted nightmares. So it seems that along with all the electronic help, we have developed what amounts to a new mode of failure. The computer aided catastrophe.

47:15 NARRATOR Careful engineers today maintain a healthy skepticism. For the gates of the Thames Barrier, computer models were used in their design. But physical scale models were also constructed to study the failure modes and to check the computer results to make sure the computer solution did not miss anything crucial. And the higher the risk, the less many would trust the computer's reassurance. This is a shipping container for nuclear fuel being tipped on its side. Will it really survive a head on collision as the computer predicts? There's one way to find out. The container in this test is pressurized to see if one full of fuel would leak.

47:55 [silence]

48:15 NARRATOR And it seems there was no leak.

48:20 HENRY But accidents will no doubt continue to happen and for reasons more than just lapses in engineering. Sometimes the non-technical side of human nature can ignore or overrule the engineering side. Perhaps because the engineer is believed to be too pessimistic… or overly cautious. But engineers know that they're dealing with human lives and they must be cautious. And they also know that they must continue to worry and loose a great deal of sleep over real and imagined failures. Because after all that's what engineering is all about.

49:00 [credits]