Sue Nelson
Hello, I'm Sue Nelson and thanks for joining me on Create the Future, a podcast brought to you by the Queen Elizabeth Prize for Engineering.

My guest this week literally aims high, extremely high in fact, because he's the structural engineer behind the Burj Khalifa the tallest building in the world. This stunning silver skyscraper in Dubai famously played centre stage alongside Tom Cruise in a Mission Impossible film, and its Y-shaped reinforced concrete tower required a new buttressed core structural system in order to stand a staggering 828 metres high. But there's more to Bill Baker than this engineering marvel. Around the world his buildings and bridges are impressive and distinctive additions to the landscape made possible by Skidmore, Owings and Merrill, or SOM, where Bill has worked for over 20 years. After studying civil engineering in Missouri, he gained a master's in Illinois and today he travels around the world, lectures at the University of Cambridge as an Honorary Professor and is also an International Fellow of the Royal Academy of Engineering. Bill is based with SOM in Chicago, and since the United States is famous for its skyscrapers, I began by asking Bill what his favourite tall building was when growing up.

Bill Baker
I grew up in a small town in the middle of Missouri so there weren't many tall buildings around. Growing up no, can't say I was particularly aware of them. I think the tallest thing in my town was probably three stories, which I did like. I have to say one of my favourite buildings of all time that I did see when I was young, maybe didn't appreciate quite as much was the John Hancock Tower here in Chicago, which is that X-braced tall tower that my firm had done in the late 60s, early 70s.

Sue Nelson
Chicago is a beautiful city though architecturally.

Bill Baker
Yeah, it's actually considered to be, in America, the capital of American architecture. And it's interesting because there was the first Chicago School. You know, the first skyscrapers were done here in Chicago, which was basically a combination of different technology, structural engineering technology, vertical transportation, the elevators were coming in. But also, the way that changing the skin of the building from load bearing to what we call a curtain wall, something that was hung from the structure rather than being the structure itself. And then there was the second Chicago School if you will, that happened in the late 30s and 40s. You know, Mies van der Rohe left Germany, came to Chicago, Todd at IIT. So, this was really the capital of this new modern architecture that came out. And part of it was because unlike cities, say, like London, or New York, or Hong Kong, where there's a great deal of money and the land is very valuable. In Chicago, the rents aren't so high and so the buildings have to be very rational and disciplined. If you wanted to have enough money left over to have a nice lobby you had to have very efficient systems and very efficient structures. So that's one of the things with economic pressures that led to the kind of the, the very clean, stripped down architecture of Chicago.

Sue Nelson
And in a way you've described one of the qualities that an engineer has to have really, which is not just an eye for the design and the technical skills, but also the practicalities, isn't it in terms of budget?

Bill Baker
Yeah, a lot of times, design is a search for constraints, the most impossible project is a building on a green field with no known use constraints. And so, as you layer on the constraints, you define the design problem. And within reason the right constraints can make you have to be more clever. And actually, having a tight budget doesn't necessarily limit the design, but it does force more creativity to do something that's interesting.

Sue Nelson
So growing up in a relatively small town and you were also at a university in Illinois. Did you have any indication when you were younger, that you were interested in how things were being built? Did you play with construction bricks or build huge towers in a sort of Steven Spielberg sort of close encounters kind of way?

Bill Baker
Certainly, I grew up with the erector set child's toy for building things, you know, we all did that. Kind of an interesting thing. You know, I'm from a small town, Fulton, Missouri. Actually, in our hometown, we have a church by Sir Christopher Wren, believe it or not. There's a small college there called Westminster College. That's where Winston Churchill gave the Iron Curtain speech. When I was growing up, they took a bombed-out church from London, and, and rebuilt it block by block on campus. And I used to crawl through the construction when I was a kid, you know, as all kids do, to kind of get around the construction fence and get into the get into construction site. But you know, growing up, you know, yeah, we would build things but actually, you know, small town America, we spent a lot of time working on cars, you know, playing with cars and engines, and back in those days, it was not electronic, it was either mechanical or electrical, and you could actually figure out how to fix it. So, it was it was actually kind of rewarding to take a car that wasn't working and make it make it work.

Sue Nelson
So, what made you then decide on studying structural engineering rather than say mechanical or electrical engineering?

Bill Baker
Part of it is, in a small town I didn't know much about engineering and so when I was in high school, I took the, you know, the guidance counsellor gives you these aptitude tests. I took an aptitude test and it indicated that I had a propensity towards engineering. So, I went home and asked my mother, what an engineer was. Well, turns out both my grandfather's had been engineers, structural engineers, so I guess it's in my genes. But not knowing that at that time, I looked around at what engineers did, and I was really impressed with the physical representation, like a bridge or a building that, you know, just how tangible it is and how monumental and seemingly permanent it is are the things that structural engineers built. So, looking back part of it maybe is a little search for immortality, you're trying to make something that will be there longer than you. And so, you know, that's certainly part of it. Before I went to graduate school after I graduated my first degree, I worked for an oil company. And I worked in various aspects of it, some mechanical design stuff, some chemical engineering, duties, and reservoir, petroleum engineering duties. And a lot of those were very challenging mathematically, you can do these incredibly beautiful processes, where you change the temperature and pressure and all these amazing things that you predict actually happen. And so, it was actually very, very rewarding and challenging. But it wasn't what I wanted to do. I wanted to make things physical things like buildings or bridges. And so that's what I decided to go back to graduate school at Illinois.

Sue Nelson
I've seen a couple of your talks and you talk about the importance of maths and the work that you do. And you call it the geometry being this intersection of architecture and structure.

Bill Baker
Geometry is just absolutely fundamental. The space I'm in here you would describe it in geometrical terms, you know, you use geometrical terms you're describing the works of the Greeks or the Romans you know, and I would be describing the architecture, you would also be describing the structure. Or if you started to try to describe the structure, you would at the same time be describing the architecture. They meet in the geometric

intersection. But also, geometry, I also find very fascinating. When I look at, say, a bridge, I see the geometry of the structure, you know, it maybe has cables or hangers or trusses or whatever. But I also see the geometry of the equilibrium as equally real, but you don't see it, like every node of a truss, you know, there's, there's a closed a polygon that represents equilibrium of that joint. And so we've been doing a lot of research on the work of James Clark Maxwell, who was the founder of reciprocal diagrams and shall we say graphic statics, where you can you see not only the geometry of the structure, but you see the geometry of the forces. And one of the things I like to do is, is maybe design the forces first and then see what the structure looks like. Of course, what you do is you go back and forth between the two, maybe you guess a structure, you see how the forces are, then you then you design the forces and see what that does to the structural geometry. So, it's an incredibly important part of our life, mathematical life and an engineering life is to understand geometry. And quite frankly, geometry is not taught as much as it should be. We've actually been doing deep dives on projective geometry, which was the red-hot mathematics of the 19th century. It's what Rankin and Maxwell and all the great engineers of the 19th century knew was projective geometry which actually allows you to see things differently. If I look at say a bridge, a three-dimensional object that's in equilibrium, if I take a photograph of it, I have a two-dimensional representation of a three dimensional structure. Guess what? That two-dimensional structure is also an equilibrium. Because as you look at it, you know, the projection of the forces and the projection of the geometry follow the same mathematical rules. And so, a lot of times it's interesting to look at the three-dimensional structure as a series of two dimensional structures. Say you have a roof, a grid roof, or a shell or something, if you look straight down, you see a two dimensional structure. And what's more interesting you no longer see gravity, you only see the horizontal reactions to gravity and so looking at our designs geometrically and understanding the geometry of both the structure and the geometry of equilibrium is a great design tool.

Sue Nelson
It sounds as though you've got a very good feel for not just the forces that the maths, the engineering, the practical side, the design, but also sort of seeing it as, I hate to use the word holistic, but it does sound like you use a very holistic approach in order to sort of envisage what you're doing.

Bill Baker
I think a lot of structural engineers and architects are visual people. So, a lot of times what I try to do is I try to look at the problem and I actually tried to solve it visually, or intellectually, or heuristically, if you will. I'm a pretty decent mathematician, also I can I can get in there and do and do the differential equations. But I actually got my insight by trying to understand it in a visual nature. And I think that comes to the part you know, where we're, you know, structural engineers are often very, very visual people. And the more you look at things, the more you study them, the deeper and richer your intuition becomes. And you can imagine, you know, how you might design something or change an idea and make it something different or better.

Sue Nelson
Well, visual is definitely something that I think people associate with your work. I have been to Chicago but I've not seen the Millennium Park, pedestrian bridge that you've built. And when I saw a picture of it, I loved it because it was so curvy, and it looked like a mobius strip across the road. It almost looked fluid.

Bill Baker
Yes, it's another case where a design constraint becomes a design opportunity. This was done with the architect, Frank Gehry. And so if, if you're trying to abridge over a roadway and you want to make it accessible to handicapped people, well, you could put in an elevator or something and you get up and go over. Or what you can do is you can make the slope so gentle, that anyone can negotiate it. Generally a slope of one to 20% is considered gentle enough that a handicapped person or a wheelchair or walking aid can handle that very mild

slope. But if you have to get up a certain distance and you have to get down a certain distance with a gentle slope you need a long distance to do it, so how do you take that required length and then make it something that makes it an experience. This is, you know, a lot but Frank Gehry and his crew brought to the practice is creating this experience where you walk back and forth and you obviously are on the bridge, but you see the bridge that you're on as you're walking on it. And so you're creating vistas of the city, but vistas of the bridge itself as you as you walk along here.

Sue Nelson
It's really quiet something. I mean, one of the things about it did have in the same way of some of your buildings, it has the wow factor. Do you always approach something with the thought of "I've got to make people go wow, now?".

Bill Baker
No, actually, I try to make it honest and tell the story of the of the structure or the building and try to make it as clean and as honest as I can in such a way that the story the building will come through and that's really important things of architecture and structural engineering, where they come together is how do you take a building and tell the story of the building through the way you express it and the like. In London, I did a building there at Liverpool Street Station called exchange house, which spans 78 metres over the tracks going north out of Liverpool Street Station. And it's a building but it's also a bridge, how do we tell the story of the flow of loads through the structure, you know, from the from the floor plates to, you know, to the columns or hangers up to the arch or down to the arch and then how the ties work, and how the building sits on its bearings up there, nine metres in the air. You can see the entire resolution of the forces. And then we also wanted to leave remnants of the construction process so that you know, the building was originally assembled on falsework. And so the hangers below the arch during the construction phase were actually columns with very little load on it. So columns on the less and so we know we left part of that to show just in a subtle way which you know, probably is not understood explicitly but is still felt you know, how this building was built or how was put together and how it was expressed.

Sue Nelson
You mentioned about it fitting in I mean, that's I was in Dubai last year for the for the first time, and it's quite an astonishing city it feels as though it's a permanent construction site anyway with buildings just going up everywhere that you look, but wow factor is definitely at the Burj Khalifa, I thought it was stunning, beautiful to look at, you couldn't take your eyes off it. In a way I didn't want to go inside it because I only wanted to just look at it. It's very futuristic. And I wondered before we get onto this, you know, structure that you had to do in order to make the world's tallest building. Are you inspired by science fiction, because when I saw it all I thought of was a city of the future.

Bill Baker
I enjoy science fiction, a lot of our influences are so subtle, we don't know they're there. Do I love the movie Metropolis by Fritz Lang from the 20s which is about the future which we still haven't quite gotten to. I mean, all that stuff is there I don't know about if it is exclusively, but it is all there parked back in my brain somewhere. So, you're never quite sure where these references come from. The Burj Khalifa was actually, you know, a highly technical issue. And so, what you see there is his response to the technical demands and also the you know, the desires of the client and the use of the building.

Sue Nelson
What would you say was the most technical demand of that building?

Bill Baker
It's true of all, not all, most tall buildings is that they're dominated by how they resist the wind. And so, one of the things that we wanted to do is we wanted to design a building that would respond to and actually try to negate the forces of wind. So, what we did is we shaped the building in such a way that the wind forces wouldn't build up. Whenever the wind goes past an object. I don't care if it's a lamppost or a mountain. It happens at all scales. As the wind goes past some bluff object first, you know, the air will go to the left and the right as it does is it creates these vortices, these vortex streams that come off the building and every time this happens, it'll create like a pressure differential across the building which will make it want to rock from side to side. If you have if you have a building which has sharp corners, and is the same size from top to bottom, you will have fairly organised vortices that are all happening in unison. And so what we what we did on the Burj Khalifa and it took us quite a while to get there, we spent a lot of time in the wind tunnel with this building, we would keep reshaping the building so that these vertices would not get organised because the rate of the vertices is related to the wind speed, which you can't change. Wind speed does change as you go up and down the building. That's right to the wind speed, and then the width of the building and the shape. And so playing with the width and the shape, we were able to get the wind forces very, very low. They never got organised and one of the interesting things was when we won the competition we based our initial scheme on some ideas, we had from wonderful projects and things we'd learnt on a project in Korea. And immediately after we'd won the competition, I wanted to go into the wind tunnel. And we did. And it turns out the building didn't work. The motions were too big, and the forces were too big. And it kind of reminded me of the Adams book, Hitchhiker's Guide to the Galaxy. On the cover of this, of the guide mentioned in the title of the book, it's says, in bright letters, don't panic. So that's the advice we took, we did not panic, but we worked the problem as engineers should. And in the process of understanding why the wind forces were so big, we were able to change the building so much, that we were able to go much taller than where we started because our initial design was only around 518 metres tall, and we ended up at 828. So just the change in the height of the building during the design process was taller than the Shard in London.

Sue Nelson
I'd read about this, that the height of the building remained a secret while you were actually building it. Why was that?

Bill Baker
Well, at the time, there was a red-hot competition in the world there to do the world's tallest building by various developers. So, you know, it was it was it was this big secret and you know, there was a lot to this. And a couple of things came out of that. One is I kept on noting other competitors that had announced their buildings around and I'd look at them and one by one, they all stopped for various reasons. They didn't go forward. And so one of the things I study is how do buildings get built but also why buildings don't get built? And a lot of the buildings that were proposed were never realised, in my mind weren't realised because they didn't understand issues of scale in both the real estate market and structural sense. A lot of times they were they were based on an engineer making an architectural sketch not fall over. As opposed to having a design that was where the architecture and engineering ideas were developed as one. It wasn't, you know, the engineer coming in later to make something or like I say, not fall over. And so, those are very, very important things that I learned from looking at what the other proposed ones which were never realised, I remember on January 4 2010, which was the grand opening of the Burj Khalifa. I was in Dubai and, you know, I was sitting off with this group of, you know, all the engineers and architects and contractors, all the big shots were over in another area. And I was sitting there feeling very smug because I knew the height of the building. What I did not know and so they decided to change the name of the building. Until the day of their grand opening was called the Burj Dubai. So I asked my friend next to me what is this about? He saw “ah they've named it after Shaikh Khalifa”, who is the

head of the entire Emirates. He's also in charge of Abu Dhabi. The design was driven by, I would have to say it was driven by practical considerations and physics.

Sue Nelson
And part of those practical considerations was this now famous buttressed core structural system. Obviously, you try everything out beforehand, you know, using models of the building and the wind tunnels and what have you. What gave you the idea for this particular structure? Maybe you could just describe it first.

Bill Baker
We just finished on a project in Korea and it became quite obvious to us that some variation of that idea could go quite high. And so, we started out with a system very much like what we had done in Korea, but after while it became clear that it just wasn't right for this. And so what happened is, you know, the system morphed and you know, it became more and more pure. You know, a building coming out of the ground is really just a giant beam coming out of the ground. And it, if you think of like an I-beam, you'll have, you know, a web that carries the shear, a flange that takes the overturning moment. And so instead of being an I, with two flanges, it's kind of a Y with three flanges, then one of the very, very important things is twist. You do not want to have a tall building that is torsionally soft. It needs to be very stiff tortionally stiff. There's a lot of experience out there with buildings that were not torsionally stiff having issues. And so you need something to keep it from twisting. So we use this core in the middle of going like a big axle. It's a hexagonal shape, which is torsionally very, very stiff that goes up but it was not stiff enough, it was good for torsion and not enough to take the lateral loads. And so it was then buttressed if you will, by the three wings of webs going down the corridors and then connected into flanges, if you will, or cross walls that were in the walls between the residential units. And because this was primarily a residential building, but the process I like is, when you're starting your design, keep it very open, ideas flowing all the time. And then after a while when you think you're close to it, when you think you're onto something, can you describe it in words? Okay. And if it takes a lot of words to describe what you have, maybe you're not done. I think Mark Twain once said, “letters can be very long because I had not time to make it shorter”. Or I think Winston Churchill once said “I'm going to give a long speech because I have not had time to prepare a short one”. And making something simple takes a lot of time. To reduce something to the essence, you know, like editing your design down to its essence is a very important thing. And it's not easy, you know, making something simple is not easy. Anyway, but at some point, when you think you're there, describe it in words. And as I said, if it takes too many words to describe, maybe you're not there. But sometimes you can get down to perhaps two words, a noun plus an adjective. And if I look at the work of some of my predecessors at SOM and so on, like Fazlur Rahman Khan, who didn't know the Sears Tower when are called the Willis Tower. You know, he described it as a bundled tube. And the Hancock building which is the X-brace building here in Chicago, he described as a trussed tube. Those two words, carefully selected, describe the essence of the system, and so when we looked at what we had created, it appeared to me that the essence of it was a core in the centre, which is essential for doing the tourism, that was buttressed by these three wings coming out of it. And so that that was the name that I gave it. And it's very important because, it's also very useful because, if your ideas can be that clear, you can then describe it to your team, and they know what you're doing. You describe it to the other disciplines, to the owner to the contractor. And very importantly, when you resolve conflicts, it tells you who gets the right of way, tall buildings are all about conflicts, very, very complex things to build, you know, all kinds of mechanical, electrical, plumbing systems and circulation, vertical circulation and maintenance things and, you know, amazing number of things have to go in those buildings and so you're forever resolving conflicts and a lot of times the initial design for tall buildings like a train wreck, they're just so many things going on and they're all in conflict. And as you resolve these conflicts, you have to decide what's going to go through and what gets out of the way. And so, for the [unclear], you know, shall we say the structure got the right of way most of the time. In fact, all the time and the rest was coordinated with, I mean

obviously, the functionality has to work, everything has to work, but you know, the buttressed core was the essence that was not to be compromised.

Sue Nelson
The Burj Khalifa, that began in 2004. But just a couple of years later, you also started work on another building in Dubai, the Cayan Tower, which is this wonderful sort of helix shape. So were you working on both buildings at the same time?

Bill Baker
Oh, yes. I work on multiple buildings at a time. Certainly one building may take more time than others, but no, I had several designs going at the same time. I think in 2009 I had three buildings that were at that time, in the tallest buildings in the world open or top out. So yeah, you're working on multiple buildings at a time. The Cayan Tower, that one was, can you do a building where the shape of the building changes as you go up. If you're in London and say you're taking the above ground on the train, you look out there all the time you see chimneys, and chimneys will have what's called a strike, you'll have a wire that goes around the chimney in a helical manner that there to break up the vortex I spoke about earlier. And this building essentially had this helical shape. It wasn't like a rectangle per se but it was you know, close to a rectangular shape that rotated through 90 degrees as it goes from bottom to top. And on that building it greatly reduces the wind forces, but also could make the construction a bit complex. A lot of a lot of the innovation there was how to make the construction simple. And so basically, we had the same set of formwork from top to bottom, every lift, you go up and you kind of essentially rotate it 1.3 degrees. And then by the time we got to the top, you had your 90 degree rotation. So that was the structure was interesting and took a lot of work. but the plumbing was also interesting. Every time you get off the elevator the floor plates are essentially identical. But you have to walk farther down the hall. So say unit B, okay, you have to walk further down the public corridor to get to unit B because every floor it's moved a little bit from where it was from the floor below. And one thing that civil engineers know is that you have to respect gravity, okay, and so you have to get your plumbing to work out. So that was one of the challenges we had, eventually we were able to solve that problem.

Sue Nelson
You've designed so many buildings, including a Trump Tower, and you know, you travel across the world. You're an international fellow for the Royal Academy of Engineering as well. And you're often at Cambridge. What would you say has been, so far, your favourite building?

Bill Baker
Hmm, that's a dangerous one. For many years I worked with a man named Myron Goldsmith, who was one of my mentors. He was an architect engineer. He studied architecture under Mies van der Rohe, and engineering under Luigi Nervi. That's kind of like an amazing combination there. And he started as a chief structural engineer but eventually went back into architecture. And when I knew him, he was an architectural design partner. And he would always have these slideshows, and he'd always show the same slides. And one of my friends asked him, I said, Myron, how can we show you the same slides? Well, he said, they're the only good ones, you know. And so one of my goals in life was by the end of my career, I would like to have five slides, five buildings, five ideas. And I'm still working on the list quite frankly, there's a few that I'm pretty sure are going to be on the list of the five. The Burj Khalifa certainly is one, the London Exchange House, which I'm very, very pleased with near Liverpool Street Station, you know, we detailed every connection there. I remember working on that one, we had a debate about how it should be detailed, should have a machine aesthetic, kind of like Lloyd's of London or something. But we decided, in fact this was Bush Graham’s idea, to have more of a structural aesthetic, like you would see the true structural application. So it's all exposed steel except for some of the some critical elements. But in general, everything you see out there is you're looking strictly at the steel.

Others on the list today, I did a very nice little pedestrian bridge up in Calgary Canada, is at least on the list of five for the moment and there's a few other contenders. There's a little bandshell I did on an island in the Mississippi River in St. Paul, Minnesota, which I liked quite a bit. So my five slides are still changing, but I do have a lot of buildings that are so important. But the Burj and Exchange House are going to be on that final list.

Sue Nelson
And you've had a you know, 20 years at SOM you've obviously enjoyed it. You've obviously got to, you know, be part of some amazing constructions for budding structural engineers. What would be your best piece of advice?

Bill Baker
Well part of it is, when an architect gives you a sketch do not take it as something that you can go out and just immediately engineer, take it as a problem statement. I need a building or I need a canopy or I need a skylight. As engineers too often we are we are trying to solve the problem given us when in reality, maybe we should change the problem. And we know many things that other people on the design team don't know. And we should, we should exercise that knowledge to make the project much bigger. So that's certainly one. And don't spend your career making a bad idea not follower, which I try to come up with collaborators, you know architects and other disciplines that you collaborate with, where you develop the ideas together, that you end up with designs with buildings where they're holistic, you know, you can't separate structure from the architecture because it's truly one but one idea when building. Another thing is, don't get lost in linear thinking. And the other thing is, look into designing the forces and not the structure. Can you design the forces you want the equilibrium you want and see what the structure is that helps you achieve that. Turn the problem on its head. Do most of your preliminary calculations by hand. I do almost all my all my major buildings, preliminary calculations use it makes me make the problem simple. I get down to the essence of what it is I'm designing. Of course, we always go to the computer and maybe the computer will get a little different answer than you expect. And that's okay because you will now learn something that you would not have learned if you hadn't done the preliminary design by hand. I probably have a very long list. The other thing is, here's another one, if you are student, this is one for students, take as many theoretical classes as you as you can, theory is practical. When you're on a job, you can learn about the practical things in life, but you're not going to be able to teach yourself some of the higher mathematics or some of the other things, because you might say today we live in a computational age. But soon I think we'll be in the post computational age. The value of engineer is not the ability to be able to manipulate the computer or the box but understand what is coming out of the box and why it is and that's the stuff that that will have very long shelf life, is just your fundamental knowledge, your knowledge of fundamentals.

Sue Nelson
That's great. I think you've given really interesting advice there. Although I did notice you forgotten one to add to your list, which is of course, don't panic. Oh, yes.

Bill Baker
Panic does not help. Okay.

Sue Nelson
Bill Baker, thank you very much indeed for joining me on the Create the Future podcast.

Bill Baker
Thanks for having me. I enjoyed it very much.