Brian Kane — Arboricultural Biomechanics

[00:00:12] **Rebekah Holtzclaw:** Hello and welcome to the ISA Conference Rewind video series. I'm Rebekah Holtzclaw, Editorial Assistant with the International Society of Arboriculture. Today, we are excited to bring you a presentation by Brian Kane on Arboricultural Biomechanics and determining likelihood of failure. This presentation was originally given at the 2023 ISA Virtual Conference, so the views seen here are those of the presenters. If you are interested in gaining a general understanding of tree biomechanics or learning about how to identify the likelihood of failure, this presentation is for you. Sit back and enjoy.

Brian Kane: Hi, everybody. I'd like to spend some time today talking about arboricultural biomechanics, and this is a presentation that I have worked on [00:01:00] for a little bit of time. It's paired down quite a bit from the normal length because of the virtual medium that we're in right now, but hopefully it'll be a good opportunity for all of us to learn a little bit. I'm really excited to be here and thank ISA for giving me this opportunity. Before I get started, I'd just like to acknowledge in particular the funding sources that have made this presentation possible. First of all, the Florida Chapter of the ISA and the Tree Fund and, last but not least, the Massachusetts Arborists Association, which endows my position at UMass Amherst.

When we think of arboricultural biomechanics, normally considering how it relates to the likelihood of tree failure, [00:02:00] and in particular, that relates to doing tree risk assessments or doing pre-climb inspections. So, anytime we're concerned about the likelihood of a tree or part of a tree failing, whether we're doing an assessment for a client or about to do the work on a particular tree and want to make sure it's safe enough to work in, we need to understand these important mechanical concepts that relate to the likelihood of failure.

There's a couple of definitions on the screen here that are the fundamental things or concepts we need to think about when we're trying to understand likelihood of failure. The one definition states failure occurs when the loads exceed the load-bearing capacity. The other definition then is failure occurs when the stress exceeds the strength. [00:03:00] Both of these definitions apply, not just to trees but pretty much any structure that you're interested in, or if you were an engineer, that an engineer would be interested in trying to understand likelihood of failure. It's helpful to put ourselves in the shoes of someone who similarly would be assessing likelihood of failure, whether it's a bridge that may need to be repaired or a building that has survived an earthquake, but people are unsure whether it's structurally stable. We need to think about these same sorts of questions when we're stood in whether a tree is safe to climb or how likely a particular tree is to fail when we're doing a risk assessment.

[00:04:00] I'm going to spend today mostly focusing on the definitions of the mechanical concepts, terms that you see on the screen here. Of course, we just mentioned loads, load-bearing capacity, stress, and strength, and then if we go in a little bit deeper, then we have these other components of loads and stress and load-bearing capacity which were things like force and bending moment, lever and static, dynamic, etc. It would normally be several semesters of college level engineering and physics classes to understand all of these in a sophisticated way, and we obviously don't have time to do that. Most arborists don't have the time to take extra classes at a local university. So, we're going to try to keep this pretty simple, and even if you don't fully understand every last detail [00:05:00] about each of these concepts, just understanding them from a conceptual standpoint, like the definitions I mentioned earlier, that will give you a better sense of how you can better apply your experience as an arborist when you're thinking about likelihood of failure.

Let's go back to this definition of failure. Failure occurs when the loads exceed the load-bearing capacity. What is a load? A load is a general term—kind of a catch-all phrase—that, for our purposes, we're thinking mostly about forces and what are called bending moments. Force, if you see on the left-hand image, is, for example, the force of gravity, which is shown here as a [00:06:00] downward arrow in yellow. So, that's gravity pulling down on that tree, and that's basically what gives that tree its weight. Another force in that same image is the force of the ground pushing back up against the force of gravity, and that holds the tree in place. This is a pair of forces that are acting on the tree. They're acting with the same amount or the same magnitude because the tree is not moving upwards or downwards, and they're acting in opposite direction. And again, we know that because the tree is not moving; it's stationary in place. A force is a push or a pull. Gravity is pulling down on the tree and the ground is pushing back up on the tree.

Sometimes, and in fact with trees pretty commonly, the forces that act on a tree still are equal in magnitude [00:07:00] or the same amount and they're in opposite directions, but they might not be lined up with one another. So, if we compare the picture on the left-hand side showing gravity pulling down and the ground pushing back up, those forces again, they're equal in amount. They're in opposite directions, and they're also lined up with one another. We can draw a straight line right between them. In the picture on the right, we've got another force here. This is the force of the wind and that's called drag. In reality, there would be a whole bunch of little, tiny arrows on every leaf and every twig, etc., but we're going to keep it straightforward and just have one big arrow that represents the force of the wind. Again, this force is called drag.

We know that the tree is also being held in place by the ground, because it's not moving through the ground. It's not sliding across the surface [00:08:00] of the Earth. There are forces that the ground exerts on each root and each little square inch of root area that are pushing back, opposing this force of drag. Once again, forces share the same magnitude, they're the same amount, and they are in opposite directions, because they're pushing on the tree in different directions. In order to draw a line between them, we have to draw this yellow line here, which is designated as what we call a lever. The lever is literally just this distance—this measured distance here between where the force in the crown of the tree is acting (force of the wind, that is) and where the force of the ground pushing back against that drag is acting. So, this distance now [00:09:00] (and you can see that the lever is at a right angle), it's perpendicular to both of these—the applied forces to the tree. That creates what's called bending moment, and a bending moment is quite literally just the amount of the force multiplied by the length of that lever.

This would be, for example, if you were using English units, then it would be force would be measured in something like pounds and the lever would probably be measured in either inches or, more likely in this case, it would be feet. You would get foot pounds of bending. If you were using SI units (metric units), then it would be Newtons of force or maybe kilonewtons of force, and the lever distance would be in meters. It would be kilonewton meters of bending or newton meters of bending. So, loads are forces and bending moments. For our purposes, that's basically what we're interested in, [00:10:00] and the forces you see illustrated on the page here are precisely the ones that we're normally going to be thinking about. The forces of gravity and drag.

When we need to convert a force or a bending moment into a stress, we take whatever that load is, either the force or the bending moment. It's not quite so simple, but we basically divide that load by whatever the cross-sectional area is. The illustration here is one showing a cylinder that's representing the weight of the tree. The other smaller [illustration] is representing the weight of a branch that's in that same tree. They're both oriented parallel in the same direction of one another. These large arrows on the outside of the cylinder [00:11:00] represent on the top the force of gravity pulling down, and on bottom that large arrow just represents either the ground pushing back up on the trunk, or in the case of the branch it would be whatever the lower part of the tree that's supporting that branch pushing up to hold it in place.

The load, whether it's a force or a bending moment, is going to get distributed inside the tree. Inside the cross section, it gets divided up over all of the square inches or all over the square meters or square millimeters of area that are in the cross section. So, here's the small arrows now inside of the cylinder on both of those drawings that are just representing how the force or the load gets distributed [00:12:00] across the entire cross section. The tree, the weight of the tree obviously, is going to be a lot more than the weight of the branch.

I've just put some simple numbers on here. A 10,000-pound tree or 100-kilonewton tree weight. The branch shouldn't be 10,000 pounds. The branch should be more like 100 pounds or maybe a single kilonewton. Now that trunk area in the tree is going to be a lot greater. We're just making up the numbers here to make the math easy. This is 100 square inches of cross-sectional area, or let's say a square meter of cross-sectional area in the trunk. In the branch, it's going to be less than that obviously, because it's a lot smaller. So, just making up numbers again to keep the math pretty straightforward. This is 1 square inch of area or 10 square centimeters of area. [00:13:00] So, if we divide these numbers 10,000 pounds by 100 square inches or 100 kilonewtons by a square meter, we get 100 pounds per square inch—that's just 10,000 divided by 100—or 100 kilopascals. Kilopascal is just another name for a newton divided by a square meter. Since it's 100 kilonewton, then it becomes 100 kilopascals, because we're dividing 100 kilonewtons by a square meter. The same stress will occur in the branch because, even though I'm just going to change this here to make this 100 pounds or one kilonewton, if we take this same number here and divide by either a square inch [00:14:00] or 10 square centimeters, we end up with the same stress in both of these cross-sections.

So, even though the force (the weight of the tree) is very much greater than the force in the branch (the weight of the branch), because the cross-sectional area is greater in the tree, in the trunk, the stress is actually the same. Stress is a really good concept, because once we have identified its value—either 100 pounds per square inch or 100 kilopascals that we're showing here—once we've identified that, then we match it up to the strength of the material, and that would be the strength of the wood either in the trunk or the strength of the wood in the branch. If those strengths values were the same, then the likelihood of failure of the trunk or the branch would be the same, [00:15:00] because both of them have the same wood strength and both of them experience the same amount of stress due to their weight. The load-bearing capacity as we mentioned earlier is matched up with the loads that the tree experiences.

Whether it's a force or a bending moment, those are the loads we're considering when we're trying to estimate likelihood of failure, and now we need to figure out, what is the load-bearing capacity of this tree or part of the tree? How much of a force can it actually take or how much of a bending moment can it actually take before it fails? There's basically three different things that influence the load-bearing capacity of the tree. The first is how big it is. So, what's the diameter? The second thing is a little bit less important, because most of the time we're going to consider [00:16:00] the tree shape as a circle or an ellipse. In reality, if you really want it to do this, you need to take very careful measurements to see how irregular the shape was, but for our purposes we're going to assume everything is just circular in shape or elliptical in shape.

The other thing that you need to understand is the wood strength itself (so the inherent strength of the wood that is in whatever part of the tree you are trying to estimate its load-bearing capacity). Now with wood strength, the most important thing to remember is that it's pretty variable, much more than we normally think of. For example, it varies by species, which I think most people probably understand, but even if the species is the same, it can vary by the growing conditions. So, two individual trees of the same species [00:17:00] still might not have the same wood strength if they come from places where the growing conditions are different, the amount of precipitation, the climate, the temperature, the soil properties, etc. And even different parts of the same tree—so, whether that means older wood or younger wood or wood that's taken from the branches versus wood that's taken from the trunk or wood that's taken from the roots—that can also influence how strong the wood is. It's not so simple as to say all the wood of, you know, this particular red maple or this particular white pine is going to have the same strength properties. It can be quite variable even in the same exact tree. It also depends on the strength of the wood that is.

It also depends on the type of stress [00:18:00] that the cross section experiences. I'm going to show a slide in a little bit that illustrates that, but before I go to that, I just want to point out a couple of things about size and shape. We already mentioned that the shape we're normally just going to think of as a simple geometric shape like a circle or an ellipse, and we acknowledged that that's not always going to be perfectly accurate. But for right now we're going to just go with that. The important thing to remember about the size of the cross section is that small changes in the diameter can lead to big changes in either the increase in load-bearing capacity or decrease in load-bearing capacity.

The change that occurs in load-bearing capacity is related to the cube of the diameter. [00:19:00] What that means is that if you were to double the diameter of a trunk or double the diameter of a branch, then you have to cube that doubling, which means it's 2 × 2 × 2 (doubled doubled doubled three times basically). That gives you 2 × 2 × 2 is 8 times the load-bearing capacity. By that same measure, if you triple the diameter, so from you know, 10 inches or 10 centimeters in diameter to 30 inches or 30 centimeters in diameter, you're increasing load-bearing capacity 3 × 3 × 3 which is 3 cubed, 27 times. So, there's a huge increase if you have a doubling or a tripling of diameter.

Another way to think about how important the diameter [00:20:00] or the size of the cross section is is by imagining a weak-wooded tree—whatever the most decayed piece of wood you can imagine— but make it, you know, three times the diameter of another piece of wood that is the strongest wood you could possibly imagine. So, if you try to bend that piece of wood, even if it's really weak wood, if it's three times as big in diameter as another piece of wood, it's going to be much harder to bend. Even the strongest wood is usually only going to be about five or six times stronger than the weakest wood, and like we just saw, tripling the diameter, you get 27 times the load-bearing capacity. So, there's a really [00:21:00] disproportionate effect of the size of a branch or trunk relative to a factor like wood strength. Not to say that wood strength isn't important, but it can be relatively unimportant if you're talking about big changes in diameter.

Now getting back to this idea of the strength of the wood and how it relates to the stress that is applied to the tree, when we looked at this image over here from an earlier slide, we were basically measuring what's called compressive stress. So, the forces are pushing together and that causes a compressive stress. We're trying to make each of those cylinders smaller by compressing it. Well, wood in general [00:22:00] is going to be twice as strong if we were to try to pull it apart as if we are trying to push it together. So, the type of stress can play a big role in likelihood of failure, depending on what stress is actually building up in the cross section. And wood, if you try to bend a branch, has about eight times the strength as if the wood were being sheared or sliding next to one another.

You've probably seen both of these types of failures in your in your travels and in your daily work. This failure here is a shear failure. The branch split right along the middle where the shear stress is the greatest. The branch that failed on the right-hand side is kind of the more classic failure in bending, [00:23:00] where the branch broke off because it bent and then the wood fractured. So, even though the image on the left, that branch hasn't failed in bending and it hasn't broken and landed on the ground, it still has failed in the sense that the shear stress that the branch experienced was greater than the shear strength of the wood in that branch. The bending stress did not exceed the bending strength of the wood, but the shear stress exceeded the shear strength of the wood.

Defects or something that we commonly assess, whether we're doing risk assessments or whether we're doing a pre-climb inspection, everyone recognizes that depending on the magnitude of the severity of that defect, the likelihood of failure can increase. [00:24:00] In the particular example here showing a hollowed-out cross section of this tree that has obviously been cut down, a hollow stem, just to point out the obvious, has less wood. As a result, the cross-sectional area is going to be less, and because stress is equal to the load divided by the area, the stress is going to be greater. When you have a hollow cross section like this, the reason there's a greater likelihood of failure is because there is greater stress, since there's less wood. It's also possible to have a decayed cross section that is not hollow. You can see inside here, as I'm kind of tracing this out with the laser pointer, all of this wood in here is pretty decayed. The outer wood (the sapwood) has not decayed. [00:25:00] That's all pretty intact, but all of this wood in the center is very well decayed. In this case, the stress is going to be the same, because there's the same amount of wood. Stress equals load divided by area. So, the area hasn't changed, but the decayed wood doesn't have the
same strength. The likelihood of failure has increased here, because the stress, even though it's the same, is more likely to cause failure because the wood is not as strong.

When we think about a tree that has defects and try to reduce the likelihood of failure, then there are things we can do from an arboricultural standpoint that can change either the force or the lever or maybe even both of them. [00:26:00] We'll use the easy example of the wind here. Again, the force of the wind is called drag. This picture is the same one we saw earlier where the drag is acting on a lever, and that gives us a bending moment. Well, in this case we could reduce the drag, and we could also reduce the lever. In order to reduce the lever, we would have to shorten this crown a little bit to remove however much height is between these lines like this. That would make this lever a little bit shorter. Even if we didn't change the drag, now the lever is a little bit shorter, and so the bending moment will be less. As we remove these distal parts, the exterior of the crown of the tree—we obviously [00:27:00] want to make good reduction cuts on this to make it shorter—but if we were to do that, we are obviously going to reduce the drag as well.

I just put this equation over here to give you an idea for the drag that a tree experiences. It's related to the air density, the frontal area of the crown, something called the drag coefficient, which for our purposes just is a measure of how easy it is for the wind to kind of pass around or pass through the crown. And then the last thing is the velocity of the wind, the square of the velocity. If we are reducing the crown area by pruning this exterior foliage out, then we're obviously going to reduce the drag in addition to reducing the lever. Even if a defect increases the likelihood of failure because there's less wood or [00:28:00] because the wood is not as strong in the case of decay or a hollow tree, we can address that by pruning the tree and reducing the loads that it experiences. Therefore, the stress might not increase, because if the decayed cross section or the hollow cross section has increased the likelihood of failure, reducing the drag or reducing the bending moment that's caused by the drag can similarly reduce the amount of stress and therefore reduce the likelihood of failure.

There are obviously other examples of this (installing cables to reduce the likelihood of failure, weak stems), and in each case, there would need to be a matching of how much of an increase in [00:29:00] likelihood failure you expect because of a defect or because of a certain set of conditions. Commensurately, how do we address that by reducing the load that the tree experiences or, in the case of the cable, increasing the load-bearing capacity of the tree? We've been thinking about loads from a kind of simple standpoint of forces and bending moments, and I haven't really addressed what's a pretty important concept obviously when we think about the loads associated with the wind or the loads associated with rigging or even climbing for that matter. That's the difference between what we call static and dynamic loads.

A static load is one that doesn't change very quickly in a short period of time. [00:30:00] So, for example, the weight of the tree, even if you include the weight of snow or ice or just rain that accumulates on the foliage and on the branches, that tends to occur over a long period of time. You can watch branches for example as they start bending slowly when snow accumulates or ice accumulates. And again, even rain, liquid precipitation. You know branches will bend a little bit. That occurs over a long period of time, so we can think of those as static loads. They're technically quasi-static, because they are changing but we're going to think of them as static loads for our purposes today.

On the other hand, dynamic loads like a gust of wind or when you rig a piece of wood and it shock loads the tree, or even if you were to you know ascend into a tree and maybe [00:31:00] had to stop abruptly. All of those changes in the magnitude or the amount of the load, they occur in a very short period of time. Instead of an hour or multiple hours, those changes in a dynamic load occur in a matter of seconds. Gusts of wind can change within to 3 to 5 seconds. Then the shock load of rigging occurs you know in less than a second sometimes. The dynamic load is one that changes in a very short period of time. Think about the order of seconds rather than the order of minutes or hours. When a tree experiences a dynamic load, it tends to sway back and forth or parts of it tend to sway back and forth.

There's two important concepts to understand that describe the swaying motion. [00:32:00] One is called the frequency and the other is called the damping. The frequency is just a measure of how quickly the tree is moving back and forth as it swaying. We think of this in terms of the number of sways per unit time. Normally that's thought of in terms of seconds. So, how many times does a tree sway in one second? Or how many times does a tree sway in 10 seconds? Damping is the other important concept that describes sway motion, and it's basically how quickly the tree stops moving after a force acts on it. If you've ever been in a tree and you take the top out or you take a big piece of wood and you know that you're going to experience a shock load because you have to stop, the rigging has to stop the piece quickly, there's going to be some pretty violent swinging back and forth, [00:33:00] but eventually the tree will slow down and stop moving. How quickly that occurs reflects this concept of damping. How many times the tree sways back and forth in 10 seconds or one second, that's what the frequency is.

There's an important difference between simple sway motion and complex sway motion. So, we're going to play the simple sway motion video first. This is more common in trees that don't have a lot of branches. They get a kind of nice pendulum-like, swaying back and forth motion. And again, you can count the number of sways. If you had a stopwatch, you could measure the time it takes to do those sways and how quickly the tree stops. In a tree that has lots of branches, where the crown structure is much more complex, you can see that [00:34:00] the trunk basically stops swaying almost immediately, even though the branches continue to sway for a much longer period of time. If we were to think about this these concepts of frequency and damping, we have to think also on a complex structure like this tree with a lot of branches. We would have to think about it from the perspective of well, are we measuring the whole tree? Are we measuring the trunk or are we measuring individual branches? Because the values of frequency and damping will probably be different when there's a lot of moving parts as in this open-grown, you know, sugar maple.

This graph is just illustrating what we saw in that video of the simple sway motion. This is just a motion—this yellow highlighted line here—this is just a motion of a tree swaying back and forth. And you can see [00:35:00] it sways forward. This is its maximum forward position. Then it sways backwards in the opposite direction. So, it's going now backwards. And then it sways forwards again. That's coming back, forward, back, etc. This is just charting the motion of a tree going back and forth over a certain amount of time. If we know the number of sways that the tree has made during a certain amount of time, then we can calculate that frequency that we talked about earlier.

Here's a different tree showing a slightly different motion. This is the more complex motion that we saw in that open-grown tree. So, the highlighted black line here is showing the tree as it first comes forward. That's this big peak here. Then it goes back in the other direction. [00:36:00] Then it goes forward again, backwards, etc. And then after these kind of initial two seconds where it's kind of wobbling a little bit, then it settles into this more kind of up and down motion which looks a little bit closer to this simple tree. If we trace this out from the starting point at 0 seconds when the tree first starts to move forward, we can see that in about 13 seconds the motion has essentially stopped. This is what we would use the number of sways that are in this particular graph as well as that elapsed time, and that would help us calculate or measure the amount of damping. Just as we said before that practices like pruning and cabling [00:37:00] can help reduce the likelihood of failure, either by reducing the load or increasing load-bearing capacity, the same thing is true for swaying motion. Things like cabling and pruning, depending on how severe they are and depending on the tree itself, you can change the frequency and perhaps even the damping ratio. It's a little bit harder to change the damping ratio than the frequency, but it's certainly possible under certain circumstances.

The keys that studies have shown with frequency and pruning, for example, if you shorten the lever and decrease the amount of mass that's in the crown (so, pruning obviously is going to decrease the amount of mass in the crown) that tends to increase the sway frequency. So, instead of a tree swaying at this frequency, it might sway at a much faster or higher frequency. [00:38:00] If, on the other hand, you increase the lever by pruning lower branches and leaving higher branches, that might slow the frequency down, given the way the mass is distributed in the crown. This can have competing effects on likelihood of failure. Even though you may have decreased the load that the tree experiences in the wind, if you change the frequency so that it coincides with the wind frequency—so, how gusts of wind hit the tree—that actually can increase the likelihood of failure. This gets complicated pretty quickly, and we don't have time to go through this in great detail, but it is important to understand that the likelihood of failure can relate not just to the amount of a load, [00:39:00] not to the magnitude of drag or the magnitude of the bending moment, but it can also relate to these dynamic properties, these sway motion characteristics of the tree. It's also important to note that when trees are leafless—so, when deciduous trees drop their leaves—they tend to have a much higher sway frequency than if they have a full set of leaves on them. The exact opposite is true with damping when a tree has a full complement of leaves, it tends to have a much higher damping ability than a tree that is leafless.

And the other effects of arboricultural practices like pruning and cabling, tend to have much less of an effect on damping, mostly because the leaves play such an important role there. [00:40:00] So, studies have kind of consistently shown that you'd have to prune a lot of foliage out of the tree or you'd have to really cable the tree very tightly, and both of those things are not really advisable from a practical standpoint in order to change the damping of a tree. These are very kind of general, broad statements. This is a much more complicated topic than we can cover safely in this short amount of time.

We're now just quickly revisiting these topics, these concepts, that engineers use all the time when they are evaluating structures and trying to understand likelihoods of failure. Failure occurs when the loads exceed the load-bearing capacity or failure occurs when the stress exceeds the strength. [00:41:00] To understand both of those things, we need to understand things like forces and how forces become bending moments through levers, and then also understanding that a force or a bending moment gets distributed over a cross-sectional area, which gives us a stress. That can be influenced by the presence of defects. The stress can increase or the defect could decrease the strength of the wood, even if the stress stays the same. Both of those things can increase the likelihood of failure. To decrease the likelihood of failure, there are practices, either pruning or cabling that can help us reduce the likelihood of failure when a defect is present. [00:42:00] We also want to make sure we recall that a static load is very different than a dynamic load. For trees which tend to sway back and forth after being loaded, dynamic loads are pretty important. To describe those dynamic loads and how the tree responds, we need to understand the frequency, the sway frequency, or the gust frequency of the wind, as well as the trees damping, its ability to stop moving after a force has acted on it.

I know there is a lot of material that we've covered. Hopefully, this is kind of just a quick introduction to some important mechanical concepts, and this overall kind of broad topic of arboricultural biomechanics, and why it's important for arborist to understand these things when they are considering aspects of likelihood a failure. Thank you very much.