Hello, ladies and gentlemen. Just wanted to make sure that you guys can hear me. Can everybody hear me? Okay, I see some head shaking. Thank you. Welcome back. Obviously the homework set was just do. I hope everybody got it turned in without any trouble today's lecture is gonna pick up where we left off.

At the end of Tuesday that's in the historical perspectives portion of lecture 2.

Wanna make sure that everybody is able to. See me and also see the slides it looks like that should be working. Good, thank you. David. Just as a comment, there are a number of you who are logging in using something besides your western Michigan University email address as your Google username.

Well, that's not a huge problem. It does require then that I am able to admit you to the meeting rather than just having you come in as a meeting inviteee. So if you hear the noise that comes through every once in a while. You know, functionally that's what's going on.

There's a little ding that occurs and and then I have to look over and admit you. So be easier for everybody if you just used your Western Michigan University email address as your login. I'll try and remind you guys as we go throughout the semester, but that's what I'm requesting.

Again, also it's nice to see your faces if possible. If not if you have a technological limitation, that's fine, but would appreciate seeing your faces if I could.

But I'm on the wrong page here. That's the next lecture let's start instead start this lecture.

Okay, so you know last time when we ended we were talking about the scaling laws this sort of adverse law of the length versus area versus volume. Really first discussed in the literature by Galileo, but still very relevant and a challenging to this day. And what that amounts to is that the mass of something tends to scale as it's volume whereas the strength of something tends to scale as it's area and so one goes as length squared one goes as length cubed and so that can cause some challenges we looked at how this applies to animals and how it applies in in some sense also to aerospace engineering of vehicles.

Of course the caveat that we put on it is often an aerospace vehicle tends to have a lot of empty space within it. Something scale is volume like fuel storage some things scale some masses scale as areas like the skins of the aircraft and then I mentioned just sort of offhand that.

You know later in the semester we're gonna get into things like beam bending and torsion where we now recognize that there's some other geometric scaling factors that come into play so that was a quick summary of last lecture today's lecture we're gonna instead look at how aircraft structures have developed over the years, we're not gonna go back too far, we're gonna start with this image right here.

This is of course a very famous image.

It's a very famous image from a 1903 it's an image of the Wright brothers and they're very first flight you've probably seen it a million times so this flight took place December 17th 1903, the the flight distance was a hundred and twenty feet in a total of twelve seconds now it's worth looking at the aircraft and thinking about what it's principal features are.

Now let me go back to that slide for just a moment as we stare at this aircraft, what do we see what is perhaps similar or what is different from what we're seeing in a modern aircraft now if we are all in lecture. I'd let you stare at this for a little while.

I'd ask you guys to chime in so feel free to do that if you're willing in the chat window.

If I don't know how well that's going to go in the chat window, so I'll just go ahead and give you a moment and then I'll move ahead to the next slide where I'll give my thoughts.

So looking at that photo the principal features of that aircraft, well, first of all, it's structurally what it is it made out of it's made out of wood it was made out of primarily spruce and bamboo. It had fabric as the wing skins for the aircraft it did have ribbed wings, of course, we still have ribbed wings today, although the ribs look very different than they did back then it did have some steel in it it had piano wire it had some rods it had some metal fittings and of course it had an engine that was very much made out of metal, but most of the structure of the aircraft was made out of wood.

So how were the right brothers successful where others behind them failed a few of the items that made them successful were structurally related some of them were not we're not going to spend a lot of time on aerodynamics or really much time beyond today's lecture on aerodynamics in this class, however, I will mention that one of the things that the Wright brothers did really well that others had not done as well before them was to look at the airfoil and really study it in a wind tunnel.

They did extensive wind tunnel testing and by doing so they were able to improve their airfoil for their wing also the air foil for their propellers the Wright brothers though, they were bicycle mechanics had a reasonably a good understanding at least for its time of aerodynamics. And certainly rudimentary by a modern standard but it is you know compared to their predecessors it was a big advancement another very important enabling technology that allowed the Wright brothers to be successful where others before them had failed was their improvements in their flight control system the right brothers developed wing warping techniques.

In order to to control ultimately the role of the aircraft they used a canard to control both pitch and to some degree yeah, of course as you guys probably are aware from intro to aerospace engineering yeah and roll tend to be coupled together that was true then as it is now but they were nevertheless able to control this.

With the control systems that they had in place. I'm going to pause for just a moment. I've got a door that's open in my house and that's making it kind of loud in my office, so I'm going to go back and close that door.

All right, hopefully that's a little bit better.

Another really critical improvement that the rights had over their predecessors were the improvements that were going on at that time in internal combustion engines. Internal combustion engines are still in broad use today not only in aircraft but also an automobiles things like lawn mowers and other mechanical devices this era this arrow around 1903 early 1900's was a time of great advancement in internal combustion engines, it's no coincidence that Henry Ford and the assembly line and the mass production of automobiles coincided with this flight of.

The Wright brothers this first flight so this internal combustion engine was an enabling technology for both automobiles and aircraft and and primarily this was because a specific power advantages. These enabling technologies briefly discussed here will largely be ignored throughout the rest of the course, we're going to look solely at structural mechanics advantages.

Now, another thing that you may have observed in that right brother's aircraft was the use of what we would call today a trust structure. And this structure. I've got a couple of images here one's a bridge. So civil engineers, we're using trusses very widely at the time and the Wright brothers also used trusts a trust-like structure in their aircraft wing.

What does a truss structure allow that the predecessors to the rights didn't necessarily have in their aircraft design? Perhaps most importantly this trust-like structure had a very high stiffness to weight racial. The wing itself could withstand relatively high loads with relatively small deformations. At reasonable weights. So that that metrics stiffness the weight ratio was quite critical to the right brothers to be successful.

So their work was largely based on civil engineering structures of the time as I mentioned bridges were in common a trust bridges were in common use even in this early era. Now you you probably are quite aware that we're not using biplane trust-like structures and most of our aircraft today and so you might you know, sort of in the back of your mind wonder well if that was true for the rights, why isn't it true today?

Well, in fact, it is still true today, of course. You know biplane trusts like structures are still structurally very efficient, however the aircraft engines that we have now are much more powerful, especially on a specific power basis. That's the amount of power. Generated per mass of the engine. And so therefore the aerodynamic penalties associated with the trust-like structure as we've increased our speeds have have essentially outweighed the structural benefits, once you get past a certain airspeed.

So, you know, as I had mentioned their predecessors many of them had been modeling their wings after birds or bats, and so they had single wings which presented some very unique structural challenges.

I see that Ethan and someone. Using some handle. I don't recognize said had chimed into my question earlier about the Wright brothers. So Ethan had mentioned propellers aren't a pusher configuration and there are no dedicated ailerons so that's absolutely true of the right brothers and that actually brings to mind something that's a little bit interesting.

The you know, as as I mentioned in my prior discussion the Wright brothers were using a canard that's essentially they're they're using instead of a what we would now call a conventional tale, which is after the main wing. Instead they had a canard which you know, sort of amounts to a tail in the front of the main wing and the challenge with one of the challenges associated with the right brothers aircraft it was actually aerodynamically unstable which made it quite difficult to fly the other comment that was in the chat room, of course that they were rectangular wings and and that's that was a largely for simplicity of manufacturing.

Okay so a few more comments on the right brothers, so the biplane configuration in addition to having structural advantages that is separating the load carrying surfaces allowing the the truss structure to carry bending moments more efficiently, it also provided for additional lifting surface area. Consequently because it was a larger area you.

You all probably remember the lift equation lift is equal to the dynamic pressure q times the wing reference area times the lift coefficient so if you double the area at the same dynamic pressure, you can fly with a half the lift coefficient now lift coefficient, of course, when you're talking about drag ultimately is a squared quantity that's called induced drag.

So having a larger surface area dramatically, in fact the biplane configuration has a dramatically reduced induced drag and sort of for the same plan form area and as you probably are aware this this is the dominant drag at high lift coefficients that are typically employed at low air speeds so going to a biplane actually was another enabling technology in terms of the power to weight ratio the aircraft you can fly at a much lower powered aircraft with the biplane configuration.

You know, as I had mentioned the control ability control ability was through varying the tension of the bracing wires, this is what Ethan was alluding to in the comment section no dedicated ailerons, in fact there were no Iran's at all instead the right brothers employed wing warping they actually actively warped the wings with cables applying tension in the cables to change the shape of the wing in order to do their roll control.

Note this trust like structure is useful not only for the wings, but also for the fuselage we really only discussed it in terms of the wings, but many fuselages of that era were also configured with trust like structures. I mentioned the wings were covered with fabric now in this case wing fabric was actually structural.

Okay, you might not think of it that way it's membranous recall, we talked about structural classification last lecture we said cloth tends to be membranous it can carry tension well in some certain circumstances it can carry shear and sheer intention or related to each other in a in a very direct way as I will teach you a little bit later in this class.

So the right brothers were able to use lightweight cotton cloth in a plain weave configuration, they actually oriented that cloth so that the bias of the cloth that's you can think of that as being the aligned fibers were oriented 45 degrees relative to the spar that's relative to the span-wise direction and because of that orientation on the 45 degree a relative to the spar that ultimately helped to carry the drag and inertial loads of the aircraft sort of inattention.

Arrangement it was it's because of the way shear and normal are coupled together sheer on one plane is ultimately manifests itself as tension on another plane, again, we'll get to that later in the semester as previously mentioned the primary structures were made primarily out of wood and this arrangement seen in the Wright brothers 1903 flyer became the standard that is wood structures fabric a biplane configuration.

With trust like structures.

Now stepping forward a few years in aerospace engineering development. One of the things that came next in terms of significant structural change was the early monoplane. So I had mentioned some of the advantages of flying in a biplane or in fact tri-plane or multi-planar aircraft configuration the biggest of which is a decrease in the induced drag again induced drag is at high lift coefficients and slow air speeds so as pilots wanted to fly faster, of course now the parasitic drag which is dominant at higher air speeds became something that they were quite concerned about the biplane configuration has substantial parasitic drag.

Because of all the bracing wires because of the more frontal surface area, that's exposed and because of the overall increase in wetted area of the aircraft. So moving on designers wanted to get back to having one wing as long as they could structurally carry the load a second development that's seen here in this photo was the fuselage itself.

The right brothers if we went back and looked at that photo were actually not laying down on top of the wing and so they didn't have much protective structure around them as occupants of the aircraft so the fuselage development of the fuselage was actually a structural advantage from the perspective of the engineer of the pilot ultimately this is the pilot and is his or her accessories no longer needed to sit right on the wing could be located somewhere else besides the wing.

And another thing that was actually quite important structurally as an innovation of the fuselage is that it would absorb energy the structure below the pilot if you happen to get into a crash event the the structure of the fuselage could absorb the energy rather than pass energy onto the occupant and so therefore it made for a safer aircraft.

Now it's interesting the challenges associated with flying monoplanes. I'm going to take just a moment to let you think about what would be structurally challenging about that feel free to pop into the chat window or unmute your mic if you'd like to address some of those challenges. I'll go over to the chat window and answer Jeremy's question, so we're the fabric wings covered in a sealant material like a dope we'd see in a fabric wings today the answer to that is I believe so of course.

I'm not an expert on the Wright brothers aircraft, but it did have a sealant as my understanding so some comments coming in for my question. Joel says supporting the wing so obviously supporting the wing. I guess a little bit more specificity is what I was looking for in that jewel so as you look at this aircraft on the screen right now, you see it is a monoplane, but it still has that same characteristic airfoil that the Wright brothers had that's a very thin airflow that's a hint to what I'm looking for.

So David says not exceeding the bending limit to the materials, yes, we're getting at that. I'll get back to that one in just a second. Steve says lack of lift relative to the biplane so you're you're you're right in a sense a lack of lifting surface. Steve it's comparatively left less lifting surface, although of course that means ultimately you're either flying at higher dynamic pressures or flying with.

Light larger lift coefficients and and in each of those cases it has drag implications. Joel says supporting the bending moments from the CG being away from the wing mounting point, that's an interesting point in will or address. You know, what does that mean that ultimately you've referenced some keywords bending moments these are forces times distances from a reference absolutely that becomes part of the challenge so we'll get back to that in a little bit, so whoever is identifying themselves as RC girl.

383 says doesn't look like there is a spar. So it not a spar in a conventional modern sense, certainly although they did have a span-wise support it turned out that that's bandwides support that that you know. I don't know what you would call it. I guess a. I'm not finding another word beside spars very thin spar, very thin spar to be able to maintain that airflow shape.

I'm gonna give you a hint to look at the wires that you're seeing on top and below the aircraft as you're thinking about structure. Garrett says fuel capacity so fuel capacity, of course the they weren't flying these aircraft terribly far and and obviously they wanted to fly further would want to carry more fuel that is a weight challenge and all of the structural challenges of the aircraft are tied into its weight so okay, so it's Ashley Ashley is the one who was referenced as RC girl 383.

Thanks Ashley, so Jeremy says wing external bracing was necessary, so let's move on to that slide, so here's a. Sort of a schematic view of what these early monoplanes looked like so they did have a spar very thin spar in the span wise direction but in order to carry the bending moments that you guys as students have referenced several times, in fact, it's quite difficult to carry bending moments with such a thin spar so instead they used bracing wires to balance.

Or offset or react the lifting loads now. I'm going to try my best to add some. Sort of chalkboard like markings on this image, so you can get a full picture of what I am trying to do, so obviously we're generating lift in this direction. Now that creates a bending moment with respect to the wing root.

In order to offset that bending moment there is lift being. I'm sorry there is these bracing wires that are generating down forces. Now note. I only drew one component of the downforce. Okay, but obviously because these are tension wires. Really that overall force should be drawn like so.

Now this in fact presents one of the big challenges, okay, anybody want to take a pass at what that challenge is, why is is this why does this arrangement where we have a component of lift? Where a component in the lift direction of an overall tensile wire have impact on the design of the aircraft.

While your digesting that on the right hand side of this image. I will instead look at the left hand side of the image and mention that as there is lift. It's obviously the down wires on the downward side that are pulling the opposite direction don't forget also that we have gravity that pulls the wing down when this thing is sitting on the ground or when there's a dynamic load, for example when you're landing so in addition to having the downforce that we're showing on the right hand side we also have these cables that are creating the same sort of.

Vector components of force. In the so-called landing wires, so we have landing wires and we have lifting wires. Okay so cadence has no flexibility. Josh says the structure in the fuselage will have a lot of force on it that it has to withstand. Joel says the fuselage has to support compressive forces coming in from the spar so that those those statements especially those last two statements are true obviously there is going to be a compressive force coming into words the fuselage now whether that is something the fuselage can handle actually, it wasn't the fuselage that was limiting.

Ultimately in large part the forces that are on the right hand side coming inwards are roughly equivalent to the forces coming in from the left hand side so it is squishing the fuselage but it's in relative equilibrium the forces are relatively balanced really what the challenge was was not so much in the fuselage but was rather in the fact that the wing itself and the wing spar were very thin.

And you can think of that wingspar in this context as if it were a piece of spaghetti now if you're pushing axially a compressive load on a piece of spaghetti, it doesn't take much to break it it does something that's called buckling so these early monoplane designs structurally were limited very much so by the fact that the compressive loads generated from the lifting and landing wires created compressive loads down the length of the spar which would cause them to buckle and structurally fail.

So anyway this slide here that I'm showing is there a downside to wire bracing, of course, we've already dealt with that yes compression and buckling failure due to the load component, that is parallel to the wing. Parallel to the wing. And of course, another sort of unmentioned in that prior discussion downside to having the wire bracing having wire creates drag each one of those wires, of course created an additional amount of drag and so although you went to a monoplane design and decrease the overall wedded aircraft surface area, which that results in a drag reduction still having the bracing wires external to the fuselage did still ultimately relative to the monoplane without the wire.

S increase the drag. So because they were trying to get away from the the drag that was present because of that external wire bracing aircraft designers of the time did attempt to and successfully divide develop some internal wire bracing. However, that didn't solve this compression buckling problem that was associated with a wire bracing to begin with and in fact it could make it worse because it didn't permit you to create larger angles that would decrease the component for the same amount of lifting force.

So internal wire bracing was not a solution.

So the next big structural innovation in aircraft structures was the so-called cantilever wing. Now, this particular aircraft is perhaps not the best example of a modern cantilevered wing. This of course is a try try plane aircraft multi-plane aircraft instead of a biplane to try plane. However, it didn't have the same relative amount of bracing wire as those original.

Wright brothers biplanes. Rather it actually had what is notable a larger cantilevered spar and when I say larger here in this context, you see the airfoils begin to get. Thicker because they are thicker they actually can contain internally a much larger spar and by doing so they reduce the drag associated with bracing.

So there really was no longer any bracing it was just a much structural much more structurally sound internal spar rather than internal external wire bracing. So the aircraft that you see here is the focker DR1 which was built 1912, it's principal feature was that it had. Or I'd say.

One of its principal features was that it had this spar box. It was still largely made out of wood. It was made out of plywood with a spruce stringer.

Here's an image that represents that VR1 spar. So it had plywood walls as you can see going all around the exterior portion of the spar.

But it also had stringers concentrated areas. Of a material far comparatively far from the reference or neutral axis of bending of the aircraft. So this starts to look much more like a modern beam. So here I'm going to draw what is the neutral axis of this aircraft in bending about one particular axis.

So the further that material is from this reference area, the more efficient that material is at carrying bending load. So this image that you see here now employs all the features of a modern structural. Spar box that is it has a at least one spar and then it has this box where you have thin walled?

Structural load carry members, so these carry torsion as we'll see later in the semester these thin walls carry torsion, whereas the beam spars these stringers ultimately carry most of the bending. Now the walls themselves these vertical portions are called the web. Okay and they're called the web because they carry sheer load for reasons which we will get into much more detail in about week five or six of this class, but for now just accept that the thin plywood walls carried shear and the bending was largely carried by the stringers.

That's worth noting that structural skins were used on the wing and the fuselage so that that plywood skin that I was showing you that was also true of the fuselage. At this time the planes were still multi-wing to increase surface area ultimately so this was a combination of increasing surface area and decreasing the bending moment associated with the wing.

So by having again this biplane or tri-plane arrangement your decrease in the overall length that the lift is generated at relative to the fuselage, so the bending moments go down because the moment arms are decreased.

The next major structural innovation and aircraft technology are at least the next that I will highlight is the move to metallic aircraft. Now metallic aircraft the Ford trimeter shown here is one of the relatively early metallic aircraft that we're designed. Part of there were a number of reasons why they moved to metal at this point which I will deal with in the next slide or to however I will mention that despite the fact they were moving to these metallic designs, they nevertheless designed them.

Quite similarly to how they were designing wood truss like structures. So moving to metal was a change structurally it was a great structural innovation, but in many ways, they didn't take great advantage of that improvement in material properties. Just a moment, folks. I've my son has shown up in my office.

I've got to send them out for just a minute. Hold on. Andrew I'm in lecture could you please go? Thank you. Sorry about that. The challenges of of teaching at home. He's a great kid. He loves to listen to this stuff too, although maybe not as much as you guys do.

Anyway, so the wing and fuselage coverings at this point did not carry much load. They were still largely made out of either that plywood or or even fabric. And they still were trust-like structures internal to the aircraft so they weren't structurally as efficient as a modern aircraft.

Now the first practical all metal aircraft was the junkers J-1 monoplane that was built in 1915, but all the way into the 30s is when metallic skins began to be used quite frequently. It's notable that at the time they actually used corrugated skin. Corrugated is you can think of corrugated as being like plywood.

I'm sorry like. A cardboard like cardboard it had that wavy pattern to it that you can now see in this image.

It was vent into this wavy pattern that wavy pattern is called corrugation cardboard boxes are still to this day using corrugation quite extensively a cardboard box structurally has corrugation internally and then face sheets that are glued to it. And that's how you get to have a relatively strong cardboard box or at a relatively lightweight and comparatively low cost.

Now, why did you chore it? Why would you corrugate this? Ultimately well, it would look we're gonna find out for reasons later we'll study the math of this later but this allowed it to be stiffer against loads that were applied. So for one thing point loads would not be as likely to damage the skin.

And ultimately, it made it more stiff in bending. However, the skins were not designed to carry much loads, so they were still at that point largely braced.

So there are a number of arguments in favor of metallic structures. Over what was previously there that is wood. One of the reasons to move at that time was that automobiles were beginning to be manufactured out of metals. Whereas previously they had also been made largely from wood structures, so an extensive amount of work had gone into developing manufacturing techniques for metallic structures.

These you can think of these things as things like stamping metal bending were becoming quite efficient because of the large production of automobiles and so therefore it was relatively easy to do the same thing for aircraft in argument and favor of using metal. Relative to wood. Does that metal was considered to be fire resistant?

And you know, that argument is reasonably good argument. However, it's a bit of a flawed argument. It's pretty clear as we've gone forward from the 1930s to today that the primary source of fuel in an aircraft fire is rarely the skin of the aircraft. Of course, they're made out of aluminum now.

There's plenty of fuel around that's not made out of metal. So fire resistance, although being a relative. Benefit did not prevent aircraft from catching on fire. A really important argument favor of metal was the fact that there the properties of metal alloys were much more consistent and predictable than equivalent wood properties would being a natural fiber has a fairly large variation in its stiffness and strength perhaps most importantly in its strength, whereas metallic materials metals have a much more predictable if you go into the laboratory and test the strength.

Of an aluminum alloy you're likely to get a very similar strength from batch to batch from manufacturing facility to manufacturing facilities, so long as you're using truly the same alloy. I guess the last argument in favor of switching over to metal aircraft compared to to wood aircraft was that after World War one there had been a lot of spruce which was the primary wood that was used in aircraft.

A lot of spruce had been used up during World War. One, so it was much harder to get ahold of spruce, of course metals were much more available through the mining efficiencies that were being developed at the time so metal become became quite comparatively inexpensive.

Sorry, I'm trying to get this video started.

So the point of this video, of course is just to show that metal aircraft can still burn, you know fuel being probably the largest source of combustible material in an aircraft but certainly aircraft interior components also can burn quite extensively and so just moving to metal aircraft didn't make them fireproof.

The next major I'll say okay so looking over at the chat window. David asks was that recent you know, to be honest. I don't know the date of that crash. I know it was a Russian aircraft. I think it was in the last decade but I don't know David I can pull that from the video source and answer that question later.

So the the next big advantage that began to occur and this is relative to the trimeter where the skins of the aircraft were not designed to carry much load was the structural innovation to what is called a Monaco structure or perhaps assembly Monaco structure. Now some examples of early aircraft that took advantage of this feature, the DC-3 is one of those aircraft.

Okay, that's what's shown up here in the top left. In fact, schematically, it's structure as shown in the bottom left. And this image taken. This image taken that's in the top right was an image of paratroopers in a DC-3 which can you can actually see internally the structure of the aircraft exhibiting the semimonacoque structure.

So what does that mean? What does that word mean? So in this case, it was smooth metallic skins flush riveted with multiple spars arranged into cells. And then with local reinforcement in the form of localized stringers.

You can sort of see that here in the lower left corner with the the you know, schematic of the structure of the DC three the next slide actually contains. I think something that'll be a little bit easier. To visualize.

As you look at this image what we have and these are from the textbook. CT Sun's textbook on the left top left is a monocoque structure. We have two spars.

One here one here. We have stressed skin, of course, that's this thin walled structure that goes around it's enclosing essentially empty space, although in most aircraft wings today, we're putting fuel in the wing. But structurally speaking of course the fuel doesn't contribute anything so this is what would be called a Monaco structure whereas a semi-monoclook structure is then something that is also locally reinforced so here in this image of this is quite a modern image of what a torque box would look like in a modern aircraft, so again, we have the spars which have concentrated area and the spark caps that's far from the neutral axis of bending.

There's the spark caps you have localized reinforcements. That's these here that those are essentially little little mini beams that take the pressure from the skin and help carry that pressure the load associated with that pressure ultimately towards a rib and then from the rib to the main spar and this this aircraft now can have a pretty highly stressed skin in terms of the torque that it can carry can carry to work very efficiently, it can carry bending very efficiently.

And these structural elements of this semi monocoque structure now are employed in an essentially all modern metallic and composite structures modern aircraft.

So here on this slide we're seeing a two what I would classify as modern transport aircraft. Of the Boeing 707, which is the aircraft on the left the Boeing 787, which is the aircraft on the right. Now you might laugh a little bit when I say that the Boeing 707 where it was developed in the 50s and delivered to customers first in 1958, so now well over 60 years old, why would I call that a modern transport aircraft well in this sense what I'm talking about is structurally modern the, Design features of that aircraft that is stress skin semi monocult structures reinforcing spars thin skins all are pretty much mirrored very similar now not identical but similar from the left picture to the right picture now there are some substantial differences as well, so the aircraft on the left was made out of largely aircraft aluminum with steel the aircraft on the right is made out of carbon fiber, you know about 50% structural mass of carbon fiber rather than aluminum.

But the overall structural arrangement nevertheless still quite similar it's also worth noting that aerodynamically these aircraft are quite similar, you know, the same type of tail same type of wing mounted engines. The same type of tube and wing arrow overall aerodynamic configuration. So we've we've continued to refine the modern transport aircraft over the last 60 years but by the late 50s we had most of the features of what I would call a modern transport aircraft in place.

So what are some of those features more specifically? Perhaps quite critically, in fact one of those features is a pressurized fuselage. So aerodynamically speaking and for a number of other reasons we like to fly at about 35 to 40,000 feet of altitude. And allows us to fly fast and efficiently, however human beings, of course don't like to sit in the open air at 30,000 feet there are people who climb Mount Everest without supplemental oxygen, but that's just a few and far number in between relative to the human population so by having a fuselage that could be pressurized essentially when you're riding in a modern transport aircraft you're riding in something where it feels like you're at about 8,000 feet the little higher than being in Denver.

Kind of around the veil altitude is as the air pressure that you have inside the cabin. Now I should also mention that a modern transport aircraft that's the 787 is actually designed to have a 6,000 foot cabin pressure rather than 8,000 feet so 2,000 feet actually makes a big difference in terms of passionate passenger comfort, you'll feel less fatigued you'll feel less dehydrated, you know fatigue and dehydration are common experiences from flying at in commercial airliners with the cabin pressure at 8,000 feet far more comfortable to be at 6,000 feet so some of them modern materials and modern design methods.

Have. Allowed us to to carry a 6,000 foot pressure cabin instead of an 8,000 foot. Now, why is that structurally relevant? Of course we get a larger delta p a larger pressure differential internal to external and so therefore those aircraft skins in the fuselage are carrying much higher loads.

Another feature of those aircraft is that the fuselage was more or less circular IE it's a pretty efficient pressure vessel. Again for that purpose of maintaining the cabin pressure cut outs in that fuselage such as windows and doors in the early aircraft the pre-modern aircraft they were in fact square.

There was some very famous aircraft incidents resulting from square windows of pressurized aircraft. Those square windows cause stress concentrations and fatigracks and then ultimately catastrophic failures and loss of life in the aircraft. So a modern structural aircraft will have rounded corners if it has a pressurized fuselage. The the aircraft that I was referencing was the devil and comment and.

Ultimately these features of the aircraft all have caused. Us to be our primary concern because we are doing exceptionally well on overall structural design fatigue now has become the dominant concern of the structural aircraft designer the fuselage itself and and and the wings and many of those components in order to make them structurally efficient we have to make them carry relatively high internal stresses and because they are relatively high internal stresses loaded cyclically either through.

Repeated pressurization climbs and dissents as in the case of the fuselage or just a repeated flexion of the wing. It's now cyclic loading and the associated fatigue that are the dominant concerns of the modern structural engineer.

Okay. So we've kind of gone through many of the features structural features, especially that are present in modern aircraft as well as given some historical perspective on how we got there. Let me mention some challenges that are present in a modern aerostructures environment. So what are we doing today to advance this discipline?

It's still quite a fast fascinating fast-moving fascinating discipline. And therefore I'm going to just highlight a few things that we have structural engineers are really focused on right now. One thing that you're going to see as a common theme is a move towards composite materials. I showed that 787 the 787 is over 50% by mass structurally composite rather than aluminum or steel.

Now that is a massive change and that change really this is the next generation of aircraft that are being brought into service. Now where does composite material fit in comparison to aluminum and other structural metals? A composite structures tend to tend to be designed to have very high stiffnesses with very low weights.

Now that's true just in and of themselves but it becomes even more so when we begin to take advantage of things like sandwich structures, the sandwich structures are the images that I'm showing you now. In a sandwich structure. We have a core material. Which I'm kind of highlighting here.

And schematically is this lighter gray material here. A core material that is sandwiched between face sheets now the face sheets, obviously are these materials here. And represented in this context by this darker gray material. Now with this arrangement what you're doing is you're taking a very strong and stiff material and you're concentrating its area far from the bending axis of the composite structure.

So, I'm going to draw a dotted line loosely representing the bending axis. And by moving the strong material far from that bending axis, we can have very stiff very strong structures. Whereas the material in between this lighter gray material here represented actually in this image. It's it's like a.

It's almost it's corrugated in some sense it's vertically corrugated it's in some ways a foamy structure in the middle in some cases, it actually is a structural foam like a polystyrene foam or a polyester foam. I should say that ends up being quite light, so it's got a lot of air trapped in it or it could be a metallic foam as shown in the image on the left.

So that foam that core material then acts just to primarily to separate the face sheets. But it does it with a very lightweight material and that lightweight material carries some shear loads, so it needs to have the ability to carry that shear load. But the face sheets ultimately carry the tensile and compressive loads associated with bending.

So very strong and stiff materials on the outside very lightweight materials on the inside and the net result of this is a panel a composite panel that has a very high stiffness relative to its weight ratio. So one of the early examples of that was the devil in mosquito which had balls of course and which between spruce face sheets bolts, of course is a very lightweight wood bolsters a great aerospace material.

However, not nearly as good as some of these modern materials that we have in aerospace structures.

You guys are awful quiet out there. I'm not seeing any questions coming across a feel free to interrupt me if something is confusing or if I'm I've lacked clarity in the way. I've described it. In these modern composite structures, you're typically going to see carbon and boron as as fibers that are in frequent use carbon fiber famously quite performant.

They have very high specific stiffnesses and specific strengths. As I mentioned, the core is often constructed of foam that has a high compressive strength, you can buy aerospace grade foams. Or else you can buy more of these corrugated or hex cell almost like honeycomb structures that are ultimately the the core material.

The cornflake phase tend to be adhesively bonded together, although they can be molded in place. You could use corrugated metal in between you could use metallic foam those probably more commonly used in high temperature applications where the various plastics don't survive as well. Now, one of the early composite aircraft that was brought into service was the the beach starship.

It was a burger tan designed Raytheon Raytheon and built manufactured aircraft that was put out in 1986 and then fighter jets began to use carbon fiber as their principal structure it it came in, you know, it was a much more expensive material from a manufacturing perspective so it didn't really hit the commercial airline space until many of the challenges associated with it began to be worked out with essentially fighter jets and, Military.

Very aircraft and then as the technology matured then it was eventually brought into a light aircraft generally aviation aircraft the serous SR 20 and 22 aircraft are examples of moving to a primary composite structure in a modern general aviation aircraft and then thereafter it became something that was brought into service and large commercial airliners like the 787 Boeing 787 and the Airbus A350.

I I may have mentioned if forgive me if I failed to that in this image on the left, that's a honeycomb structure core. In that composite.

That's worth noting that we can now at this point manufacture metallic foam, that's quite an interesting advancement of the last say decade and a half you can see in the image on the left. A a low density porous metallic structure on the interior which prevents this particular tubular structure from being crushed nevertheless, it's simultaneously allows a flow of a coolant such as air or a liquid coolant through that structure and this is the beginning of what I would call a multifunctional structure.

So that metallic foam serves both a structural purpose. And a thermodynamic purpose. So this is one of the challenges that modern aircraft designers are faced with how do we develop multifunctional structures?

Another thing that is relatively common. I shouldn't say relatively common is I should say is of relative interest to us as aerospace structural engineers now is the idea of tailoring our stiffnesses in our composites. Tailoring them to meet a certain need and that may be beyond just strength it may actually be purposefully designing a deformation mode into a structure.

The example of that that is perhaps most famous is this idea of arrow elastic tailoring.

Soil what is ilera arrow elastic tailoring it was a method by which you design using composite materials directional differences. In stiffness such that as for example the wing deformed. As the wing bent up due to aerodynamic load lifting force it also twisted forward instead of backward, so pitch down rather than pitch up in order to contain or decrease the risk of wing divergence.

The aircraft that is perhaps most famous for that is the grooming X29A it was a forward swept wing with arrow elastic tailoring you probably remember from some past discussions in this class that when you have a forward swept wing it has the tendency to be a divergent wing which can lead to a catastrophic failure, but it was designed this particular aircraft was designed with air elastic tailoring so that as the wing bent it actually pitched it had a relative pitch down of the leading edge.

In order to prevent or decrease the likelihood of wing side a winged divergence.

I'm going to look over here. I saw a couple of questions flash into the the chat. Joel says air is compressible and wouldn't support the skin of the sandwich structure effectively separating the skin into two separate structures.

Yeah, so that that was an answer to David's question. David was why is foam used in the middle of the sandwich instead of air? So that's a good question. Really. I'm gonna expand on Joel's answer just a little bit. And that's to say that the amount of relative heat transfer scales with the surface area that the airflow is over so by in by putting foam in the middle not only do you get the structural support that Joel alluded to from the foam but you also increase the surface area that the heat can transfer convectively into the air that's flowing through it so you get this sort of a two purposes your double dipping there multipurpose multifunction device.

Question thanks.

Another interesting area today in aircraft design. You know what's the next generation of aircraft's gonna look like we talked about how we have the modern transport aircraft which is largely been quite similar for the last 60 to 65 years maybe even you know, depending on when you started that revolution you could even include the DC3 as having most of the structural features that a modern transport aircraft has so that's like 80 or 90 years to get to the next generation of perform an aircraft one thing that may be an enabling technology is this idea of wing warping.

So this little video just demonstrates wing warping for you essentially we're going back a hundred and twenty years to the right brothers. There are some real advantages to being able to work the wing, especially if you can work it to a quite a large degree. Okay so with modern control systems modern actuators, modern materials modern design processes, we can go to a wing warping system, this is a demonstration of that at the RC scale and therefore decreased drag penalties associated with things like ailerons.

So that is one example of a enabling technology of the future so if that gets us a few more percent decrease in drag of the aircraft that obviously increases the performance of that aircraft. Another challenge that is sort of an extension of that idea of wing warping is to to making very large structural configuration changes of the aircraft.

This instead would be called morphing so it's a morphing aircraft rather than a warping aircraft, you know, and this ultimately the goal is to resolve the differences between low speed demands that's for takeoff and landing where you want to have a large wing area, very high aspect ratio, very little sweep you want to resolve that with high speed demands where you want to have a relatively small wing you want to have a high degree of sweep, you want to have a comparatively low aspect ratio.

So there are a number of developments going on in the aerospace world right now with regard to wing morphing it's a modern challenge really an exciting design opportunity if you happen to get into that area professionally some of the challenges that you face in doing this is that we have large changes in configuration that has both aerodynamic challenges and structural challenges, so in order to accomplish.

This you know, the load paths become very different than they were previously the actuators add weight or can add substantial weight and of course we need to be structurally sound in each of these configurations independently and also during the transition from one to the other and of course we get large shifts in CG location when this occurs and so we have a control systems challenge as well.

So Jeremy asked does wing morphing have benefits over variable wing sweep designs. The short answer is yes, there's of course a much larger answer as well, you know wing sweep tends to not allow you to decrease the wing area. Which means ultimately that you're you you become constrained with your lift coefficients and you're not necessarily able to fly it optimal lift coefficients in all regimes of flight, if you're able to morph the wing and sort of resize the wing in real time then that allows you to find better lift coefficients, of course, if you have optimal lift coefficients, then you are improving your efficiency, there's probably some other arguments in favor of wing morphing certainly it doesn't come without costs, so there's a cost of complexity.

There's a weight penalty associated with a wing morphing and so I you know, that that could be an entirely separate lecture great question, but the answer the short answer is yes, it has benefits.

Some other things that are going on in modern aircraft, so at least from a structural perspective one of the challenges that we face is the idea of fail-safe design we like to have redundant load paths in the aircraft in the event of a failure of one structure the load can be carried through another structural element or along a different load path.

This allows us to limp home to get the aircraft down the ground safely, even after some sort of structural failure, another concept is the idea of safe life structures, we recognize that as materials age as they are cyclically loaded we can't entirely prevent cracks from occurring. About what we can prevent is to have those cracks propagate sufficiently to cause a catastrophic failure and hopefully we can prevent them from growing even to the point where there needs to be a repair, although that's not always practical and sometimes has weight penalties associated that we can't accept but bottom line a safe life structure is a structure that's designed so that fatigue cracks never grow large enough to have catastrophic failure over the design life of the airframe.

And then the last thing I'll say with regard to modern safety innovations is this concept of system optimization. I mentioned the five subdisciplines of aerospace engineering used to be you know, is recently is a few decades ago probably we would have only listed four subspecialties now we conclude system optimization and that's the idea of looking at multiple features and functions of the aircraft tied together, how does the impact of a change in one area impact the other?

Aspects of the aircraft the rest of the aircraft system.

So those are overall structural things that have gone on. I'll mention some material innovations. Now, this is not a class of material science. There is an excellent class at Western in that discipline. In many ways, we are treating our materials as linear elastic materials, very simple approach in this class.

However, materials have allowed innovation that's quite important to us as structural engineers. So, for example, we have aluminum alloys and other alloys other metals that are constantly being improved by material scientists. So we have higher strength materials or more fatigue resistant materials all coming in different aluminum and titanium magnesium and steel alloys.

If you go to a higher strength steel, if it has the same a resistance to fatigue obviously, you can decrease the mass of the steel part. So material innovations quite. Important we've gotten better at welding we've gotten much better at adhesive bonding over the last two or three decades and in both cases what we're doing is eliminating rivets and other fasteners that can cause stress concentrations and points of failure in a modern composite aircraft there's a lot of adhesives and there's not nearly as many parts as a result.

And so that has both weight benefits part count benefits and cost advantages, although it's not without its challenges. I've mentioned composites a little bit composites really are an ongoing and continuous material innovation. I'll say that composite material is compared to metals have a naturally high fatigue resistance, so their fatigue life at the same load level tends to be much better.

Composite materials tend to have natural crack blunting properties in the fibers so that it's harder for cracks to propagate through the material. However, unlike many of the engineered alloys that we use now composite materials are not as easily predictable for their fatigue lives. So we've gotten pretty good at predicting the fatigue life at a certain load level and most metallic alloys that we use however we're less capable of doing that in composite materials a composite materials also tend to be more difficult to inspect than metals.

There are additional repair techniques that not only need to be developed but also then propagated into the workforce we need to teach our aircraft mechanics how to properly repair composites repair a composite repair may or may not have. A similar strength to what it previously had. Most of our composite repairs we can get to near equivalent strengths, but sometimes it may be superior or sometimes it might may be inferior relative to comparable metal repair techniques.

And oh, by the way, most of the composite materials that we have are not naturally conductive. So a lightning strike is one of the challenges of designing a composite airframe whereas in aluminum airframe basically a lightning. Bolt will pass right through an airplane on its outer skins as if it were a Faraday cage with a composite airframe.

We need to be more attentive to the fact that lightning can cause damage and not conduct as well. Another material innovation is temperature resistant materials. This is true very much in supersonic and hypersonic airframes, of course, supersonic and hypersonic airframes are in constant development and have been for many decades.

One example of a supersonic aircraft and its use of innovative materials is the SR-71 Blackbird which was 85% titanium. And that aircraft quite an interesting aircraft extremely performance still probably the fastest air breathing aircraft in existence. Of course, we've gone hypersonic with rockets, but not with air breathing propulsion systems.

There's the SR-71. In fact, I believe that this is the SR-71 that we have at the air zoo now after it retired it came out of Kalamazoo and now lives at the Irv Zoo.

A few more comments that we as structural engineers need to be a paying attention to things that are ongoing that cause challenge in our job of course fuel economy always being an important consideration in aircraft design. We want to admit, you know, mitigate greenhouse gases and and one way of direct mitigation is improving our fuel economy that's by making lightweight structures.

So all the structural innovations that improve our ultimately decrease our weight are having a very positive impact on the environment in a relative sense. A big challenge today is aircraft noise and other aircraft residential conflicts. You may have noticed that when an airport is built typically there's not a lot around it then as a city grows, you know, the the property around the airport becomes quite popular both from an industrial perspective, but then also periodically residential neighborhoods tend to creep in and then after moving next to the airport, they tend to want to decrease the airport noise and so this is one of the challenges that, We've.

Face and then another environmental impact aspect of aircraft design is the recyclability of aircraft the ability to manufacture aircraft in a clean setting without negative environmental impacts and then of course we want to consider the life cycle of an aircraft manufacturing process not just a fuel economy as it impacts the environment recyclability is actually quite challenging from the perspective of composite materials as we move to composite airframes away from aluminum.

You know aluminum is essentially nearly infinitely recyclable, of course you're changing the alloy composition and so it may not be used in airframes anymore but it can certainly be used in aluminum cans however a composite airframe as it reaches end of life, we're still developing techniques for mitigating the environmental impact of that aircraft.

Here's a little video of an interesting.

Interesting new concept as you guys are probably aware 3d printing is becoming quite popular our capabilities of 3d printing are advancing exponentially not only can we 3d print in plastics we can also 3d print in carbon fiber reinforced materials, we can also now 3d print in metallic structures and so by 3d printing we can really take advantage of some new structural concepts.

Here's an image. Of a 3d printed aircraft this one was printed at a university actually it'd be a great senior design project it exhibits some interesting characteristics that wouldn't be possible in a or at least wouldn't be as practical in a large a manufacturing setting you can see the ribs of this wing are offset at 45 degrees.

Much like the Wright brothers did with their fabric so that makes them more efficient at carrying the drag loads the sheer loads associated with a lift generation and further we also have the the fuselage has this helical wrap to it and that allows the the fuselage to be much more stiff with regard to torsion than it was previously and and that again would not be very practical in a, You know, a larger manufacturing setting but it's something that 3d printing can enable of course, we're also 3d printing things like rocket nozzles a number of other aerospace components that go into engines and other structures in an airframe.

It's an active area of research of the aerospace structures community.

I think the last thing I'll mention before we wrap up for the days that international politics actually plays a role in aerospace engineering and aerospace structural mechanics. So some things to think about is you know trade subsidy. Technology transfer gross domestic product, all of these things are things that impact us as aerospace engineers quite directly.

What I mean by trade subsidy, you know, the largest airframe manufacturers are Airbus, which is a European consortium of air aerospace manufacturers, and then of course Boeing. And you know, there's constantly political strife. I will call it over whether or not those are government subsidized so are the contracts fair and equitable are they getting governmental support to run those facilities, and if so how does that impact trade trade politics?

It's it's actually has a pretty substantial impact on the employment of aerospace engineer, so that's why I mention it. There's the idea of technology transfer those are things that are developed in one country and then moved from one country to another country, so the defense industry aerospace is obviously quite tied to the defense industry and techniques that we develop here.

We are very careful about which of our international partners we want to be able to get access to that that technology. So hopefully allies only not adversaries and that plays a huge role in engineering in the aerospace sector and then lastly gross domestic product, let me just show you a slide regarding gross domestic product.

This this guy here his name is Norm Augustine. It was a CEO. I believe that Lockheed for a number of years and he put forth a whole bunch of what he calls laws, they were observations that he made about the aerospace engine industry. There were on the order of a hundred of them of which perhaps the 16th is the most famous.

It's the one that I want to mention to you right now and that is that defense budgets grow linearly but the cost of military aircraft grow exponentially. If you look at this plot from 1920 all the way up to the year 2000. A different aircraft plotted on the price per unit.

So, for example, the P51 Mustang as manufactured in about 1945 was you know, less than a hundred thousand dollars today's F-35 lightning is over a hundred million dollars per aircraft if you plot those it turns out it grows exponentially it's a log linear plot versus time. However, of course the growth of the budget grows, what is probably more closely approximated as linearly?

Now, why is that a challenge to us as a as a country? That is that because aircraft are more expensive we end up having to buy fewer of them. So in the year 2050 for this is following his projection in the year 2050 for the entire defense budget will purchase just one aircraft the aircraft will be shared by the Air Force and the Navy three days each per week except for leap year when it will be made of available to the Marines for the extra day.

So he made that claim in 1986, and if you look at this his prediction going forth into about the year 2010 with the F-35 Lightning, You know, it's still holding true even to this day. We're not we're not buying nearly as many F-35 lightnings as we did P-51 Mustangs.

In fact, the F-22 Raptor, I think the entire production run was less than 200 units of that aircraft. Caden asks does this account for inflation? You know, honestly, I don't remember if this particular plot has accounted for inflation the overall concept holds pretty well though. You know, we're talking of orders of magnitude on the left ten thousand hundred thousand million ten million, you know all the way up to a billion whereas inflation over that time frame, you know, it may have relative prices may have doubled or tripled in that time, but it hasn't gone six orders of magnitude.

So the concept is is pretty sound. So that's it for today's lecture. Thank you for your attention. Thanks for the questions that are being asked all hang on the line here for a few more minutes and take any more questions that come in. Otherwise do look out for the next homework assignment which should go out pretty soon.

I would encourage you to try your best to communicate to me in office hours or of course to Xander Sereni the TA in office hours asking those questions. Questions that come in over email are quite difficult to answer. So much of providing homework help is subtle hints rather than direct statements of what you need to do and so that's hard to do over email appreciate if I could have the opportunity to interact with you a little bit to give you a subtle hint to push in the right direction.

Nicole asks, what is an aileron a great question? Nicole thanks for asking if I remember correctly from last lecture you're our mechanical engineer or one of the mechanical engineers in the class. So the aileron is the little plain flap that's on the outboard section of the wing. I'll see if I can find an image of a,

Well, let's see here.

I guess I'll use.

I'll use this image here. So you can't see it very well, but there are little plain flaps out here.

And what happens is as one goes, you know, as you're trying to roll the aircraft one of those deflects up one of those deflects down it changes the lift on one side, so the side that goes up actually decreases the lift it creates a downforce on that side on the opposite side where the aileron goes down it creates a force up increasing lift and that's what roles the aircraft that's how most modern aircraft control role of the aircraft, so that's turning left or right in the aircraft.

That's what an aileron is and and wing warping of course the Wright brothers did not have ailerons that was actually something that was developed by. Oh now you're testing my memory Curtis were developed by Curtis and then actually Curtis in the rights fought over that in regard to patents but ultimately turned out that the aileron was more efficient and effective in the short term, although it may be that when warping is more effective in the long term.

Okay, I'm not seeing any more questions come in over the chat window not hearing anymore questions come in over the audio, therefore. I'm gonna assume that no one else has questions for the day thanks again for your attention. I will see you guys next week have a great weekend.