MSE-440 Composite Applications Lecture Transcript

Dr. M.D. Wakeman

Good afternoon everybody. Thank you for showing up physically and also for those on line.

This afternoon we've got three lectures.

The first one is looking at where composites are today, particularly with regards to sustainability and those kinds of technologies. The second lecture will be on sustainability strategies and the economy. And doesn't really mention composites at all, it's a very general lecture. Then the third lecture will be towards sustainable composites, looking at recycling biobased materials. Some emerging sectors, hydrogen tanks, e.g. Some of these guys can come and give the lecture because they now know more than I do. And we'll look at a bit at 3D printing.

The first lecture will be around 40 min, Take a ten minute break, and then we'll do the next, 10 minute break and then do the next one.

Particularly in the second lecture, I'll ask you questions. Just just put your hand up if you've heard of things, if you haven't, helps me to know what you already know. Again, you may know more about some of the topics than I do because we're all learning together.

Okay, so to the **first lecture around composite applications.**

Composite Applications Lecture Transcript

Now we will look at how composites are used today. And what I'd like to see is two main categories, mass adoption of composites and mass production. Mass adoption means there's lots of tonnes of it being used. It doesn't necessarily mean there are hundreds of thousands of parts being made. If you look at aerospace, it's mass adoption. Not very many aeroplanes per type are made, but there's a large amount of composite being used. You can look at wind turbine blades. They're very large structures, but we're not talking about 200,000 Mercedes C class per year. We're talking about relatively lower numbers of blades. The second way we can look at composites being used today is in mass production. This is not supercars, that's more mass adoption, but starting to look at where Bmw have gone with their i3, we start to see composites in consumer electronics. We see composites being used in compressed natural gas and in the future hydrogen type tanks and also an automotive in higher volumes. Two ways of looking at this as we go on to look at the circular economy and sustainability strategies, we need to think about how we can apply these ways of thinking to these two classes of material.

I want to give you a little bit of industry landscaping. This is a Mekko chart which looks at basically dollars by different material types across the top and different industrial sectors. What I want you to look for is the big areas, okay? That's where we can make the biggest impact as you go forward.

Looking at composites in terms of dollar value, commercial aerospace is very big. Wind is here with epoxy and a bit of carbon and glass. They're dominated by mainly aerospace in this picture. Okay, so that's where composites are mainly used today on a $ basis. It's important that we look at the aerospace industry.

Another way of looking, looking at some more of the constituent material types. Here you can see a big dominance of resin. That's mainly because it's very hard to separate where epoxies are sold for coatings versus composites. You can see all the injection molding materials, and automotive sheet molding compounds. Carbon fiber is growing the fastest. This data shows growth rates and indicative gross profits.

That's where composites are used, which is why I've chosen Aerospace, Automotive and Wind for a quick look, starting with aerospace. This is the Airbus A350 fuselage section made in carbon fiber. And what I want to do now is to show you a video from Airbus, because they describe how they see composites in their company and it makes it a bit more real for you. This is supposed to be an industrial lecture looking at the more applied side of things.

Aerospace, mass adoption

Okay, we use composites in aerospace. Yes. To make it lighter, which reduces lifecycle costs. It's grown from military into civil aviation. Now it's in primary structure. It's important because aviation today contributes 4% towards global warming. But in the future, it could consume a six of the remaining temperature budget to limit global warming to the Paris Treaty target of 1.5oC because it's going to grow considerably. Still what we've seen is increased automation in aerospace, and you'll see this in the video. And composites can reduce the number of parts counts in an aircraft, so you can make the aircraft with less pieces in composite than in aluminium. It also increases the service life of the aircraft, less maintenance, and that's also important in the circular economy, is to make parts last longer. Carbon composites have excellent fatigue and better corrosion resistance, and you can see 6-12 years. There's real reasons behind why they use composites, not only just to make it light weight, it's a more robust structure. I'm now going to play the video and you can just sit back for 4 min and listen to this lady talk.

https://www.youtube.com/watch?v=JkFAkoCrmT0

"Carbon fiber production was launched at this Airbus factory. Gas just outside Madrid Five. It was the start of a groundbreaking investment in Compass material obligation, but industrial innovation in carbon fiber use, resemblance to 30 days, has made a multi million dollar investment in new technology. We're going to have to do that every time carbon fiber production was launched at this Ebus factory, Inoles Gas just outside Madrid 25 years ago and it was the start of a groundbreaking investment. Encompass material in civil aviation, industrial innovation in carbon fiber use bears little resemblance to the early days. AirBus has made a multi million dollar investment in new technology, turning the facility into a world leader composite industrial manufacturing, 700 highly skilled staff work here. Theresa Booster is the plant director. In my opinion, this is one of the more important effects that composite that we have. We have the experts work, we have more or less the patents for use in the 50 program las patterns. We consider that we are on the top of the pain when the balls frozen carbon fiber like this arrived at the Les gas plant are just 200 H before the raw material perishes have been treated very rapidly. First, the machine build up two really meter credit layers. The composite material. The most advanced machinery exists anywhere in the world to take the exact shape of the aircraft structure. In this case, the carbon file will be used to make the rear fuselage section of the 80. After that, it's heated or cured with a resin mix in massive pressurized ovens known as autoclaves. When they emerge, the large sections are turned into light but strong composite parts. In the beginning on the 320 program, under 10% of all the aircraft structure was made from carbon file. It rose to 25% on the A 380 and it's now around 53% on the 350 XWB. 25 years ago, we produced parts by hand, but by hand usually the person is able to lay up three kilos per hour, more or less. The restriction for that was unbelievable. We were not able to produce part more at 20 or 5 m, 6 m long. Today we are some means that are able to lay 33, 34 kilos per hour. You can imagine the size of the parts are bigger and we can produce more complex parts. Five weighs significantly less than a minium, which of course means the aircraft carry more passengers without adding to the weight. On top of that, the maintenance costs come down to basically the main advantage is the weight weight saving. Making parts of carbon fiber we can save compared with aluminum, up to around 20% of weight. It is also another advantage that there is no corrosion, there is no fatigue. Okay? This is a main advantage for the customer, for their liners because they can minimize the level of effect in the life of the aircraft nowadays, the process of turning the carbon fiber into a composite part into little days, a maximum at 80, but innovation. Never ends the way to speed up the process and bring the weight of the composite parts down even further. These water jets, E.g. pattern parts without the wear and tear risks from traditional machinery. We consider Airbus the work leader for different things. First, material development, second, tooling, innovation and composite parts processing. Okay, thank you for you a little look inside an Airbus plant to see the scale of the operation, the investment in the operation, size of the equipment, what goes on beyond the fracture mechanics lecture, which is fundamental to all this, okay? “

This is what's really happening today and this is the bit of the history where you can see very early use of composites, mainly on the tail area areas, up to the A350, which is pretty much the highest use of composites at around 55% of the structural weight. And here you can see a change in the processes being used from the '70s and '80s, which was a wet layout, then shifting to pre-preg, then going from hand lay up to automation, starting to look at out of autoclave processes. You saw that huge chamber. Yeah, that machine is very expensive and the cycle times are very slow. So they're trying to get away from this and it's a major thrust of composites research.

Increases in advanced fiber placement, which was that machine you saw placing the UD material. It gets rid of waste, it gets rid of the labor. It's very precise. The fibers are carefully aligned so you can see the advanced fiber placement (AFP) and the advanced tape placement (ATP) percentages going up and the hand lay out process down with time in the future. The big discussion is around the replacement for the Airbus A 320 which is an aluminium fuselage aircraft, but it's made at high volumes. So this is the number of units of single is aircraft compared to the number of units of large aircraft. And the big discussion is how much composite will be used in the replacement of the A 320? The composite companies like Toray and Hexcel are trying to capture this business and it will drive up the manufacturing volume of carbon fiber in aerospace. And that has big questions also for composite engineers to be able to make aircraft more sustainable. We'll see that in the third lecture, it's really increasing.

Here are just a few pictures that just show you where composites are used on the A 380, you can see again, the tail is very popular part of the wing structures, a whole range of processes, some Rtm hand layups and thermoplastic parts. On the Jnose of the wing, resin infusion torsion box. You've got the central wing box that goes between the wings. It's an enormous composite structure. Gains the width of the fuselage. Gigantic piece of composite, really enormous, A350 which is even higher percentage composites. You can see the whole barrel of the aircraft is made. It's a challenge for composites because you get impact from stones and debris on the runway on the lower part of the aircraft. And it took them a lot of work to get this to actually work, but now it's a very automated and very precise process. Okay.

I wanted you to really see what they've got to, which I think is very impressive. Boeing has done the same thing there as advanced as Airbus 787. You can see again, the fuselage section and you can see some of the different companies involved.

A global industry, military is the same. You can see percentage of composites going up. This is the F-35 fighter and the entire skin is from composites. This is to save weight. It's also for stealth reasons. They didn't actually make the inside of the aircraft from composites because they're actually making it quite high volumes. But you can just see the trends with time, increasing use of composites.

Same thing with helicopters, but even higher percentages because they're obviously hovering and they hold less aerodynamic lift. They need to be even lighter per unit thrust, almost entirely made of carbon fiber. Okay. Just gives you some ideas.

You can look at these videos which just show you UD tape being placed onto a flat structure. Here it's being placed onto a curvi-linear surface, which is more complicated. This is now possible with thermoset composites and thermoplastic composites. It shows you the complexity of the heads that they've developed. The mechanical engineering in here is really impressive, to make this robust to work day after day is quite an achievement. Again, you see the A 380 structure going into this enormous autoclave that costs millions of dollars. That's why autoclaves are not allowed in American Cup boats because you'd have two teams, Boeing and Airbus (and their suppliers), because they're the only ones who could make a boats in such a large autoclave. We use resin fusion and other techniques in LPAC that I talked about including out of autoclave and this is an example. Airbus have a big program called the Wing of Tomorrow and here they carbon epoxy prepreg tapes deposited using automated fiber placement machines like on the last slide. And it applies this material over a male mold. And that is then cured out of auto clave under a vacuum bag. And they can get 0.1% void content, which is a very low void and needed to give you the high mechanical and fatigue properties that you need. So that's process they can use to place the fibers and that's the part that they're making out of autoclave. They choose pre Preg versus liquid resin because you get very precise fiber contents in a pre-preg.

If you're doing resin infusion with a vacuum bag, you can get some variation, but maybe they solve this, but that's how the aerospace guys see this. But going on to look at liquid resin infusion, people are working on out of autoclave cure. You can cure different parts onto each other. With this process you can get higher volumes and get rid of the autoclave. It's very nice. There is one aircraft which has the wing skins already made by liquid resin infusion, Russian aircraft that is actually already commercial, which I find very interesting. You can read a few more articles in your own time about how they're trying to go out of autoclave using liquid resin fusion techniques to make aircraft structures. Also using thermoplastic composites for increased inter-laminar fracture toughness. You can see some composites sitting at the back for drone structures. This is made of UD carbon PEEK tape. It has a 5x increase in interlaminar fracture toughness, doubled fatigue resistance, and 2x increase in compression after impact versus carbon epoxy. It is extremely tough, very good for impact type structures. Here they lay down the tapes using a similar plastic variant of what you saw. And then they stamp form these in oppressed by compression molding them. And you can make these structures and use water jet cutting to remove pieces out afterwards. That's a really quick tour of aerospace, the things that they're looking at, getting rid of labor, going to automation, using these UD materials out of autoclave processes, interest in thermoplastics. Okay, we'll look at the recycling issues in the third lecture and we'll see that's very embryonic.

Automotive – mass production

So going from mass adoption to mass production. This is the BMW i3 safety cage or life cage as they call it. It is made by several processes including resin transfer molding. So back in the 1970s, I know the guys at Ford very well. They made a vehicle made of carbon fiber epoxy. Okay. It's been done for a long time. You might not like the aero dynamics, but the weight saving was still there. The manufacturing techniques weren't ready for high volume production. This is basically a rolling aircraft or a rolling military jet.

Carbon fiber is also used in supercars here. It's not for weight saving, it's for performance, it's for acceleration, it's for stiffness and handling, okay? It's not to save fuel because this has a 720 Hp supercharged V eight, it uses huge amounts of fuel.

Okay, So the most interesting area I think is going towards high volume use, and we had a visit once from Bmw and the manager there said that to get to the status of the i3, they spent about 3 billion euros on composites R&D in Bmw. That included supply chain consolidation and investment including using hydropower to make the carbon fiber. In their joint venture with SGL, they use high speed resins, they use automation. They ticked all these boxes to produce this structure, and we're going to look at it in a bit more detail in the moment.

But if you speak to automotive companies about saving weight, they all have different strategies. Okay? Some say aluminium is really great. Some say high strength steel. And basically, they're all correct because their aim is to save weight. Okay, so you can have more than one correct solution. You can both be right. This just shows you some breakdowns of percentage material for conventional light weighting, moderate light weighting. And that's what we're seeing today, really lots of use of aluminium. It's the primary go to material to save weight. I'm saying this in the composite lecture, but it is a reality then. Extreme light weighting and you can go to higher percentages that's been done on the Bmw. But if Aldi, and Ford, and Volkswagen and Toyota all decide to make an i3, what's the problem? There's not enough supply base for carbon fiber. They can't buy it. It can't be made. There are not enough carbon companies with capacity to supply it. Has to be solved if you want to see wider the use of these materials. So we're going to look a little bit at some of these materials in a bit more detail, but just to make a point, because many people don't understand this. When I worked in Dupont, the senior managers there, did not understand that. If you assume one kiloton of aluminium sheet is equivalent to a kiloton composites. Just roughly speaking, in 2020, there were 2000 kilotons of aluminium sheet used in the automotive industry. Well, there were 20 kilotons composites used in automotive, out of a total 110kT of CF made in 2022, and you divide the two numbers together and you can see the issue. If you want to scale up the industry to replace aluminium, which is what the composite guys like to dream about, you go to the JEC and they say composites will change the world. Well, this is a major issue on the supply base. Okay. So that's the current worldwide demand of carbon fiber, industrial, wind consumer, aviation. Automotive. Okay. If you have one part on four mainstream vehicles, one body and white at 100,000 per year, you double the automotive demand. If you go to four parts on eight vehicles, you double the world demand.

One thing we need going forward into a sustainable economy is people need to put in place infrastructure. That's an issue for carbon fiber to be quite honest with you. That was looking a bit at the supply issues of carbon fiber. Now we're going to look at which composites are used today in automotive.

The most widely used this sheet molding compound. It's been used for a long time. It's got a big supply base. It's a cheap material. You can paint it, it can go through e-coat, it's stable dimensionally with temperature. It's a great material, very established. And you can see here you can have some structural parts. That's part of the Ford Transit van being torsion tested, take some loads and like I say, you can paint it. It's the most mature automotive composite manufacturing process, but it's chopped random fiber glass. It doesn't have the mechanical properties of the carbon tapes we just saw. It doesn't give you the same weight savings but it's very stable. It's widely known. People have gone on to use carbon fibers SMC, where they've made some UD material with some random fiber inside which can be placed into near net shape preforms. And then you can compress mold these in under a minute, 90 S cycle time. You can push these out at high volume, you can make lots and lots of. So they're good for mass adoption.

And this gives you a lot more weight saving than the glass material, and you can use slightly better resins, vinyl-esters, epoxies rather than polyesters. Okay, very interesting material, and I think we'll see more of it in automotive. That was thermoset.

Now looking at the thermoplastic equivalent, which is a glass mat thermoplastics, again, a random glass mat that's impregnated with a resin polypropylene or polyamide in a double belt press. It's made into a sheet. And then you heat it up in an infrared oven and you put it in a big press and you compression mold parts. And these are made in around 30-50s, so under a minute, because the cycle time is only limited by heat transfer. You just got to cool down this hot sheet. There's no chemistry going on really. It's basically heat transfer, crystallization and final consolidation. It's a very tough material because it's so plastic, it's very good in crash, someone drives into the back of your Mercedes, it helps absorb lots of energy because of the way it deforms and it gives you the weight saving. But you have to assemble it after the electrophoresis treatment because of its melt temperature. When you normally dip a body and white to protect it against corrosion, temperatures go up to 200 degrees C and polypropylene that's long melted. Okay. So it affects your logistics chain and how you assemble the car.

In our lab we worked for many years on the enabling science and the early applications looking at how we combine injection molding with composite, cheap materials?

So we take a woven textile or thermoplastic and we can injection mold material on top. Or we can take UD material and place that with a robot injection mold around the top. And this research started about 20 years ago and it ran through some different projects in our lab. Going from generic parts that we talked about, simple robotic systems, cost modeling, structural analysis, to making some demonstrators. That's the early stage research project. This is a story, you'll see in a minute that I'm going to bring it to commercialization.

Second project where we did a more advanced robotics with some consortium of companies that you see here and we made these generic pieces. We also looked at a seat structure that we will talk about in the cost lecture. We did the structural analysis and started to take it further.

One of my jobs in Du Pont was to help run this project where we again made a thermoplastic composite sheets using a double belt press in glass or carbon or UD tape that we would heat up and stamp form. It's a very fast process, it's a very thin sheet, 20-30s cycle time, and it's very tough. Then we over-inject

them, it's in red to make it look nice and pretty. And we installed automated equipment, that was a demonstration facility.
Other people were working on taking carbon tapes here, carbon nylon tapes. And they worked out how to make a net shape pre-form from a plastic tape that could then be heated up and stamped. That gets rid of all your waste and gives you very nice fiber directions.

There are now two companies who have made industrial cells that can convert tapes into pre-forms which can then be compression molded. These are very interesting because there's no labor, very little scrap. The very fast cycle times enable the scaling up of composites to high volume manufacturing. As you will see in the cost modelling lecture, if you want to make 200,000 parts per year, you need cycle times of below a minute. That means you can't be cutting out the tapes by hand. You need automated equipment and to implement this technology you need a supply base. There is now a whole range of suppliers who are supplying the machines for over-molding equipment. There are turn key cells, you can call up Engel and you can buy an over-molding cell which is equipped with everything you need to do this. There are different material companies that you can buy laminates and tape from. Companies have developed finite element approaches, to simulate these materials and to include the tough failure modes of the thermoplastic resins because they are different to epoxy materials. Very good in crash. We see now this is gone all the way through to early OEM developments. Glove box, which has what they call an organo sheet, this is a part from Porsche which is a central tunnel of a vehicle. This is a B pillar from a vehicle, multi material system steel and a composite mixed together. This is a door module that has UD tape inside it. These are early applications that are now coming out of these kinds of materials. So you can see it's gone all the way from early research to commercialization and you can now make composite parts. Very short cycle times for automotive type applications.

Going on to look at body and white structures for vehicles, it's more demanding than glove box housings. And you have to consider these kinds of questions. One of the key ones is that aluminum and steel are very nice materials because their properties don't change across automotive operational temperature ranges for example -40 to +90 or 120 oC - and composites do, depending on which polymer you use. It has to withstand the e-coat, temperature and the chemicals that the vehicle see. Nylon 66 you can't use on the outside of the vehicle because road salt affects polymer different limitations.

We've had some other projects in the lab looking at a steel vehicle, going to a composite vehicle. This was sponsored by European Union working with Volkswagen. You can see here we've gone from 28 parts in steel to one part with carbon, epoxy RTM, and you get massive integration potential. Huge reduction in parts counts, big savings in weight, and you get rid of that huge automated assembly line that you need for metal, and that's one of the biggest advantages. Bmw, as I talked about, they've invested in automation for RTM and they've also looked at high speed resins and we will talk in the cost lecture about the effect of the resin cure kinetics on the cycle time and hence part cost.

Ten years ago, 15 years ago we were at 10 min cure, now we're down to 90 S less than 2 min, 1 min. Hexcel M77 pre-preg compression molding used on the BMW 7 series is now under 2 min. It's got really fast which means you can make more parts per year from one tool. This is the chemistry that's enabled composites here, some of them you have to watch the thermal exotherm, others are design for thick parts. You cannot make a wind turbine black, but for thin pieces, you can go really quick. This is a quick look at the Bmw. We'll quickly play this other video in a minute which shows you inside the factory that makes you the Bmw i3.

The other main application of carbon fiber in the automotive world is in the 7-series Bmw. The way they approached it changed, this was mainly RTM in the i3 while here it is mainly compression molding of pre-preg. BMW had more quality issues and higher reject rates and dry spots and lots of trim in the RTM process. You'll see that here the prereg is more industrial (but the raw materials are more expensive). You take a roll of prepreg, and you compress it and you trim it. It's very robust. And also the volume went up from 100 cars per day to 300, with 4,000 parts per day being made for the seven series. It's quite a lot of pieces from a thermoset process and yeah, they changed their philosophy a bit.

In the BMW i3 video, it picks up a layer of the fabric into a preforming tooling and then places the fabric into a press followed by RTM and then water-jet cutting. Video is quite long in your own time. Everything is made, technical panels. That was automotive state of the art.

Wind turbine blades

Last section will be around wind energy. Wind turbines. These are huge composite structures and it's not until you see the scale of the people next to them that you really understand what's going on. That's a five Megawatt blade. This is a system being assembled. They are really big composite structures and we're going to see growth in these. My semester project, actually in 1990s when I was doing my degree was on wind turbine blades. I did some impact testing, thermography and some fatigue testing after damage. And back then it was an emerging way of making energy. It's carried on growing and it hasn't just grown in terms of capacity, they've also got bigger. So today we're at 125 meter diameter. For those of you who climb, that's two climbing ropes, 60 meter ropes, one this way and one that way. It's a big thing. In the future, they're going to get still larger.

What we see is the constituents of materials and carbon fiber is here, as is glass fiber. And with all the needs to generate renewable energy, we're going to see a lot more wind turbine blades and used. And this is going to need composite engineers to improve how blades are made, etc. So again, just showing you what a blade looks like when it's being made. The main reason why composites are used in wind turbines is fatigue. And if you look at the number of fatigue cycles in an aircraft and a helicopter, this is a number of cycles that we see in the application. A wind turbine blade has got a 30 year design life, which ends up being 10^9 so giga cycle. With aluminium alloys we don't have a defined fatigue limit, they just keep on reducing the ultimate stress. With steel and composites we have run out, so you reach a certain stress, it continues to perform at a certain stress level. You can run basically indefinitely. So they're excellent in fatigue. And that's glass composites and that's why you don't see aluminium wind turbine blades and you don't see steel because they'd be so heavy. Glass fiber has found a very natural niche, and there's a nice data base around the high cycle fatigue of composites.

These are the main elements of a wind turbine blade. This is the last video in this lecture and they show you how a wind turbine blade is made. And we'll look in the third lecture again at recycling of wind turbine blades and what some of the trends are there and what can be done. We talked about the spark cap. If you just remember that spark cap is this area here, People are starting to use carbon fiber in these for longer blades. Zoltek, E.g. is making carbon fiber, 50 K roving and impregnate that with a resin. And it makes a UD strip that can then be built up to make the spar cap. That's where carbon fiber is being used. The other area of research that companies are looking at is changing the formulation of E glass to a higher performance glass where you get a 25% increase in strength just by changing the glass formulation. It's also higher stiffness, not very much, but the main changes in strength, strain energy, and even bigger increase in fatigue resistance. It's a big enough market for them to develop specific glass grades.

Again, what we've seen are the composite materials are an established material class in aerospace automotive. It's early adoption I would say, with significant use in wind. That's really the first lecture, is just to step the scenery before we go into the next lecture, which will be around sustainability in the circular economy, leading into what about composites? How can we transition composites into a circular economy? Thank you for your attention.