THE KNOWLEDGE IN PRACTICE CENTRE: A RESOURCE FOR APPLYING SCIENTIFIC KNOWLEDGE TO COMPOSITES MANUFACTURING

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ABSTRACT

The Knowledge in Practice Centre (KPC) is a subset of the Composites Knowledge Network (CKN) initiative intended to provide value to Canadian SMEs looking to expand their capabilities within the realm of composites engineering. The KPC is an online resource that follows a generalized framework for composites manufacturing, wherein manufacturing is examined using a systems approach to composites. Various processes are discretized into a set of equipment and tooling that is used to perform a specific action on the part or material. The interactions that occur within each factory cell, as well as the outcomes, can be classified according to processing themes.

The framework of the KPC structures information in a systematic way. It helps the user locate information efficiently from the foundational engineering principles to practice as needed. This approach is based on the thinking that the field is a spectrum of information from knowledge to practice. The knowledge end provides information on why we are performing tasks while the practice end provides information on how to perform tasks. This paper introduces and explains how information is organized and structured in the KPC framework.

1 INTRODUCTION

As the demand for composite materials increases, education on the subject must also increase. More established fields have well documented resources such as text books, design manuals, standards, and procedures, however, since composites is a relatively new area these are not as well established yet. Knowledge exchange and the communication between interdisciplinary product development teams are cited as barriers to its effective use [1]. Resources, such as the Composite Materials Handbook-17 (CMH-17) [2], are typically oriented towards one industry and/or above the level of novices. The Composites Knowledge Network (CKN) is a not-for-profit that focuses on composite materials knowledge mobilization and connecting industry with leading edge technology. One of the main activities of the CKN is the Knowledge in Practice Centre (KPC), an online resource that presents composites manufacturing practices in an easy-to-navigate manner, including foundational and systems-level knowledge, practical advice, and case studies.

The KPC uses a novel framework to deliver these resources to all levels of users, from undergraduate students interested in basic information, to experienced engineers with decades of experience. Knowledge in the KPC is presented as a spectrum from foundational engineering science to systems level knowledge, through to practice. The KPC is comprised of seven volumes that make up this spectrum. ‘Introduction’ is the first volume. It provides an introduction to composites including the background of composites and understanding the link between designing and manufacturing with composites. The KPC then transitions to 'Foundational Knowledge'. This volume has information about the fundamentals and underlying science of manufacturing and designing with composites. Once the foundation is established, knowledge is incorporated into various systems in the 'Systems Knowledge' and 'Systems Catalogue' volumes. These volumes have a systems-level description of equipment, tools, parts and materials, how they interact to achieve desired outcomes and how to manage, optimize and control the system. Application of this knowledge is presented in the 'Practice' volume. This area houses science-based recommendations and guidance to support decision-making processes for new product development, building up composite factory capabilities and optimizing or troubleshooting existing composite factories. To help put this knowledge in context, the 'Case Studies' volume shows how this knowledge has been used in a variety of projects. Finally, the spectrum ends with the 'Perspectives' volume, which presents historical perspectives on composites research and manufacturing, interviews with leading composite materials experts from industry and academia, and monthly Application and Impact Mobilization (AIM) Webinar events that go into more detail on a specific subject.

The Knowledge in Practice Centre is built on the concept of a systems approach to manufacturing, where a complex process can be discretized into a set of equipment and tooling that is used to perform a specific action on the part and material. It also categorizes information according to manufacturing themes and manufacturing outcomes. Much of this framework was part of the doctoral work of Dr. Janna Fabris (2018) under the supervision of Dr. Anoush Poursartip. It is founded on conceptual frameworks such as the knowledge-to-action framework by Graham et al [3], [4] in the health science domain and the relationships between data, information, knowledge and decision making described by Hicks, et al [5] in engineering design. Links to various pages including the home page of the KPC (https://compositeskn.org/KPC) will be included throughout the text for easy access.

2 SYSTEMS APPROACH TO COMPOSITES

A practitioner is always driven by the performance (function) of the product, but constrained by the manufacturing. In the case of composite materials, manufacturing is often challenging. In order to reduce the risk associated with composites manufacturing, a structured systematic approach should be taken towards the development of best practice.

As popularized by Ashby, engineering design can be described as the interplay of four classes of choices: the intended function/performance, the choice of material, the choice of shape, and the process that can turn the required material into the desired shape of the product [6]. Figure 1 (left) shows this approach. From this thinking comes a structured approach to selecting the best material and shape for the product, while taking into account the feasibility of such material/shape combinations through consideration of the process. However, and in particular with composites, the definition of process should be expanded to cover two other items, namely tooling and equipment, that then allow for a full definition of the process. In this extended approach, the process step (P) is not only a function of the material (M) and shape (S), but also the tooling and consumables (T), and equipment (E) that are used. This expansion of the definition of process is abbreviated as MSTEP. Figure 1 (right) shows this approach.

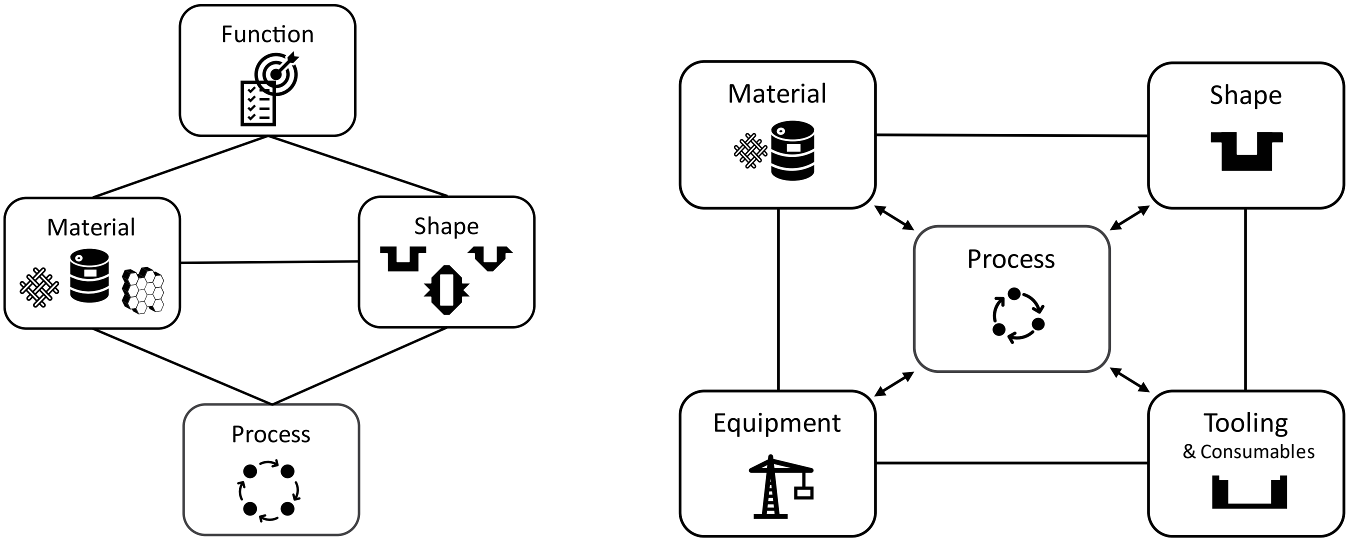

Figure 1: Ashby's traditional framework for engineering design and manufacturing, concept from [6] (left), CKN's expanded MSTEP approach to manufacturing (right)

Note that the MSTEP depiction of a manufacturing process must be considered for each process step of the entire manufacturing workflow. The complete manufacturing process is a collection of individual process steps that come together to form the factory manufacturing process.

3 MANUFACTURING THEMES AND MANUFACTURING OUTCOMES

The interactions that occur within each factory cell, as well as the outcomes, can be classified according to processing themes. Manufacturing outcomes are the result of the intrinsic material process-structure-properties-relationship associated with composite materials. Outcomes are those parameters that are tracked for evaluation to define quality and producibility. Themes and outcomes are used throughout the KPC to structure knowledge.

3.1 Themes

In the processing of composite materials, there are five primary processing themes: Thermal and Cure/Crystallization Management, Material Deposition and Consolidation Management, Residual Stress and Dimensional Control Management, Machining and Assembly Management, and Quality/Inspection Management. A given manufacturing process may incorporate multiple themes, however this discretized structure can still be used to systematically approach the problem. In order to achieve intended manufacturing outcomes, one must properly control and track all process state-variables across each of the themes. Any outcomes arising in upstream processes (those within thermal management for example) will influence downstream outcomes (those within residual stress and dimensional control management for example). The page on systems approach to composite materials including themes and outcomes can be found here: https://compositeskn.org/KPC/A230. These themes, in order of general manufacturing steps, are described below.

3.1.1 Thermal and Cure/Crystallization Management (TM)

Thermal management is concerned with knowing, understanding, and managing the thermal response of raw materials, tooling, and the part as they move through the factory. This theme covers the thermochemical management of materials in storage or handling and the subsequent thermal response of the tool and part assembly during cure. It is the first of the five themes to be considered as it begins from the moment the raw material is produced, through to the final process steps in a factory workflow. Its outcomes are key to the other themes.

Several manufacturing outcomes are directly related to thermal management. These include minimum and maximum part temperatures, cure or crystallization development, final degree of cure or final degree of crystallinity, final glass transition temperature, and others. In order to attain acceptable outcomes, it is crucial to manage the part's thermal response appropriately. Furthermore, if at any stage the thermal history of the part or raw material does not meet the intended material specifications, knock-on effects will be seen down the line across each of the subsequent themes [7]. This may negatively impact the final part quality. As such, thermal management is one of the most important considerations in any composite manufacturing system. The Thermal Management theme page can be found here: https://compositeskn.org/KPC/A107.

3.1.2 Material Deposition and Consolidation Management (MDCM)

Material deposition and consolidation management (MDCM) is concerned with knowing, understanding, and managing how the constituent materials of a composite part are placed and consolidated onto the tooling. Whereas thermal management is relatively independent of process, material deposition and consolidation management is highly dependent on the process, which is likely why most processes are colloquially named after their MDCM step. Material deposition processes can be broadly separated into two categories:

- Deposition of the reinforcement onto the tool followed by the deposition of matrix (Tool + Reinforcement + Matrix)
- Reinforcement and Matrix combined, then deposited onto the tool ((Reinforcement + Matrix) + Tool)

Regardless of the manufacturing process, material deposition and consolidation have direct impact on cost and final part quality. Depending on the process, material form and part shape, deposition and consolidation can consume a huge amount of time and resources in a manufacturing system, especially for complex and high-performance applications. The combined effect of the material deposition and consolidation and the subsequent thermal transformation steps will determine local porosity, resin volume fraction leading to either resin rich or resin starved areas, and fibre misalignment.

Material deposition and consolidation is a major cost driver in composite manufacturing. The capital and overhead cost of MDCM accounts for 40 - 60 % of the total cost depending on part complexity and production volume [7]. Several manufacturing outcomes are directly related to MDCM. This includes wrinkling, fibre waviness, fibre volume fraction, porosity (void content), residual stress, and others. Further, material deposition rate can directly impact throughput. Choosing the correct manufacturing process and appropriate processing parameters is essential to a composite manufacturing system. The Material Deposition and Consolidation Management theme page can be found here: https://compositeskn.org/KPC/A157.

3.1.3 Residual stress and dimensional control management (RSDM)

Residual stress and dimensional control management (RSDM) is a system-level problem concerned with knowing, understanding, and managing how residual stresses build up throughout the manufacturing process so one can consistently produce composite structures with controlled tolerances.

Unlike thermal and material deposition and consolidation management, which are comprised of imperative process steps, RSDM can be perceived as dealing with unwanted stresses and deformations that should ideally be minimized or eliminated in a composite manufacturing system. If not controlled, residual stresses can lead to matrix failure and unexpected dimensional changes which can significantly increase manufacturing time and cost.

While there are ways to mitigate the amount of residual stress developed in a part during manufacturing, in practical applications it is impossible to eliminate all residual stresses. Therefore, the pragmatic approach is to understand the amount of deformation that will occur and compensate the dimensions of the tool so that the as-produced part — after distortion due to residual stress — has the correct dimensions. Residual stress and deformation simulation is often used for this purpose. The simulations can be used for evaluating dimensional conformance (how well the cured component dimensions will agree with engineering specifications), dimensional stability (the ability of a manufacturing process to consistently produce parts with repeatable dimensions) and dimensional control (how well this agreement can be controlled). However, at the time of this writing, the ability to consistently produce composite structures with controlled tolerances remains a challenge.

Several manufacturing outcomes are directly related to RSDM. This includes reduced performance, process induced damage, and dimensional control problems. Residual stress can lead to matrix failure in the form of matrix cracking and delamination/disbonding, as well as dimensional discrepancies between the true geometry and designed geometry. The dimensional discrepancies often require either custom shimming processes or forced assembly, which can be costly and/or reduce structural performance. The Residual Stress and Dimensional Control theme page can be found here: https://compositeskn.org/KPC/A165.

3.1.4 Machining and Assembly Management (MAM)

Machining and assembly management deals with aspects related to finishing of composite parts and assembly/joining of composite parts. Finishing operations include part trimming, hole drilling, hole cutting & general machining. Assembly operations include fastener assembly methods, inserts, bonding, co-curing, etc. Assembly can also include shimming of components, which is a direct consequence of residual stress and dimensional control management. The priority of this theme is to manage the process of machining and/or assembling composite parts to obtain desired outcomes. The Machining and Assembly Management theme page can be found here: https://compositeskn.org/KPC/A287.

3.1.5 Quality/Inspection Management (QIM)

Quality/inspection management is concerned with monitoring the quality of the manufacturing processes at every step of part production. This might include explicit inspection steps using specific inspection equipment, or it may be more subtle in using process data that is already collected as part of the manufacturing process in order to verify that the process is operating within specifications. The Quality/Inspection Management theme page can be found here: https://compositeskn.org/KPC/A288.

3.2 Outcomes

Manufacturing outcomes are the result of the intrinsic material process-structure-properties-relationship associated with composite materials. Outcomes are those parameters that are tracked for evaluation to define quality and producibility. Outcomes that fail to satisfy the set of manufacturing requirements of the processed material are known as defects.

Manufacturing outcomes may be measured or tracked as:

- Intermediate outcomes – (e.g. temperature seen in a material) changes of a material during a process step.
- Final outcomes – (e.g. final resin degree of cure) usually measured at the end of a process step and independent of any knowledge of process history.

It should be pointed out that manufacturing outcomes are often dependent on system interactions. For a given manufacturing outcome of interest, upstream dependencies have the potential to be root causes for downstream dependencies as 'knock-on' effects. The page covering outcomes can be found here: https://compositeskn.org/KPC/A108

4 FRAMEWORK

The framework of the KPC structures information in a systematic way. It helps the user locate information efficiently and move towards knowledge/theory or practice as needed and is based on the thinking that the field is a spectrum of information from knowledge to practice. The practice end provides information on how to perform tasks while the knowledge end provides information on why we are doing them. The span between them builds on the basic theory by adding more and more applied information. Figure 2 shows the architecture of the KPC. Each of the headings shown are referred to as volumes and will be discussed in more detail below. One could imagine that the open literature could be positioned to the left of Introduction to composites and industrial documents (perhaps proprietary and confidential) to the right of Perspectives.

Most of the information is presented at Level I, Level II, or Level III to provide different levels of depth on a subject. Level I provides a high-level overview of the subject, typically does not include equations or detailed theory, and provides enough information for the reader to develop a high level understanding. Level II and Level III go into more detail, respectively. This allows the user to extract information in an efficient, 'right sized' manner. If they are looking for a high-level overview then Level I will provide enough information, without excessive detail. If more detail is required, then the user may select the appropriate level for their needs.

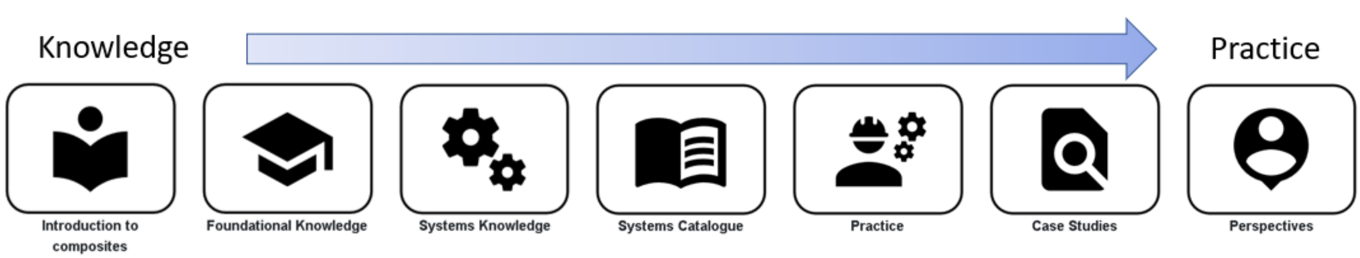

Figure 2: KPC Architecture

4.1 Introduction to Composites

The first volume is Introduction to Composites. This volume introduces the fundamentals of composite materials, and the systems approach to the design and manufacturing of composite materials that is utilized in the CKN Knowledge in Practice Centre (KPC). Regarding the manufacturing of composites, this volume introduces the systematic KPC approach of breaking down the manufacturing process (P) into considerations of the interactions between material (M), part shape (S), tooling and consumables (T), and equipment (E) – abbreviated (MSTEP). The mission of the KPC content is to make the user aware of these interactions, understand how one parameter affects another, and understand how to analyze a manufacturing process using this systems-based approach. This volume can be found at: https://compositeskn.org/KPC/A2.

4.2 Foundational Knowledge

Foundational Knowledge is the second volume. It contains a collection of knowledge-based articles and method documents covering the governing science of composite materials design and manufacturing. The Foundational Knowledge volume exists to complement the content of the other KPC volumes, where going further into the foundational science is outside the scope of those pages.

The pages in this volume provide KPC users a quick resource to the foundational science background to relevant topics. Users may wish to further explore topics through self-directed learning. Where appropriate, pages include resources for further independent learning. This volume can be found at: https://compositeskn.org/KPC/A3.

4.3 Systems Knowledge

This volume lays out and describes a science-based, systems level approach to tackle composite manufacturing problems. Just as in engineering design [6], all manufacturing processes can be broken down into components and sub-assemblies, which form the basis of a manufacturing system. In that way, a systems-level approach can be applied to manufacturing engineering. Systems knowledge focuses, from a physics-based perspective, on the interaction between system components and how these interactions influence the system outputs. The framework for this method of thinking, as applied to composites manufacturing, was developed as part of the doctoral work of Dr. Janna Fabris [7] under the supervision of Dr. Anoush Poursartip.

The design and workflow of a manufacturing factory is a complicated problem, but one that is important for ensuring part quality. Approaching the factory from a systems level perspective allows for the problem to be deconvoluted. A factory can be broken into multiple cells where the different process steps of the factory take place, from receiving of raw materials through to shipping of the completed part. Raw material is brought into the cells, shaped on tooling, and passed through various equipment to create the part. The interaction between the material (M), shape (S), tooling and consumables (T), and equipment (E) for a given process (P) define the part quality. This is the basis of the MSTEP approach used throughout the KPC. The interactions between M, S, T, and E (known collectively as MSTE) can be categorized into themes such as thermal management (TM), material deposition and consolidation management (MDCM), residual stress and dimensional control management (RSDM), machining and assembly management (MAM), and quality/Inspection management (QIM).

This volume focuses on the interactions between material, shape, tooling, and equipment with respect to the part for each of the manufacturing themes. Refer to the Level I view to navigate to the Systems Knowledge content quickly. This volume can be found at: https://compositeskn.org/KPC/A4.

4.4 Systems Catalogue

The Systems Catalogue volume provides information about the physical assets of the factory. This includes information on the factory layout, individual MSTE objects, and general processing steps. In that way, it is laid out according to where (factory layout), what (which objects), and how (what processing steps). Whereas, the Foundational and Systems Knowledge volumes map to the physics of the system, the Systems Catalogue maps to factory hierarchy and asset tracking. In addition to describing the physical factory, the Systems Catalogue also includes a resource section, where users can explore information on various software packages or connect with industry experts.

With regards to the object pages, typical specifications are provided where applicable. For example, typical equipment and material specs are given. Users are reminded to review and follow the guidance of WHMIS Safety Data Sheets (SDS), user manuals, and to contact suppliers for clarification if necessary. This volume can be found at: https://compositeskn.org/KPC/A5.

4.5 Practice

Practice is where engineers spend most of their time and where a substantial amount of value and cost can be gained or lost. Good decision-making when putting knowledge into practice means that little rework needs to be done on the physical parts and the processes used to make the parts. This leads to efficient factories with minimal downtime, rework & intervention, non-conformances, scrapped parts, etc. The Practice volume consists of a number of practice documents that provide guidance on design analysis steps within each of three workflows:

- Development
- Optimization
- Troubleshooting

The guidelines are presented with the goal of assisting the knowledge users with understanding what steps are best taken in order to make sound decisions while navigating these workflows. The practice documents rely on Foundational knowledge, Systems knowledge and information from the Systems catalogue when describing how and why certain steps should be taken. Method documents are particularly important and referenced throughout the practice documents since a given practice consists of executing the relevant methods. While practices for different factory layouts may have different high-level content, it is important to note that much of the low-level content (method documents, foundational knowledge and systems knowledge) is identical throughout, and that the same physics and interactions apply in all cases, even though some aspects may be more important to certain manufacturing processes than others. This volume can be found at: https://compositeskn.org/KPC/A6.

4.6 Case Studies

This volume provides users with three different types of case studies: development, optimization and troubleshooting case studies. The case studies describe industrial projects as actually performed. As they are faithful chronicles of industrial projects, often the guidelines provided in the Practice volume might not have been followed. This is highlighted as clearly as possible. Also, the case studies might differ from the practice described in the Practice volume as best practice evolves over time. This is also pointed out where possible. However, exhaustive mapping of any difference is outside the scope of the KPC. This volume can be found at: https://compositeskn.org/KPC/A7.

4.7 Perspectives

This volume is primarily based on multimedia content and serves as a bridge for linking what was learned in the other volumes of the Knowledge in Practice Centre to what other practitioners are doing in their projects and research. The three types of content linked below include presentations, interviews, and Application and Impact Mobilization (AIM) event recordings/Webinars. Presentations and interviews are the primary sections linking out to external perspectives on composites, while the AIM event recording section contains CKN's perspective on how to apply composites knowledge.

The AIM event recordings are timestamped throughout when various subjects are discussed. The timestamps reference KPC pages on those subjects so viewers can get more information. Figure 3 shows and example of this.

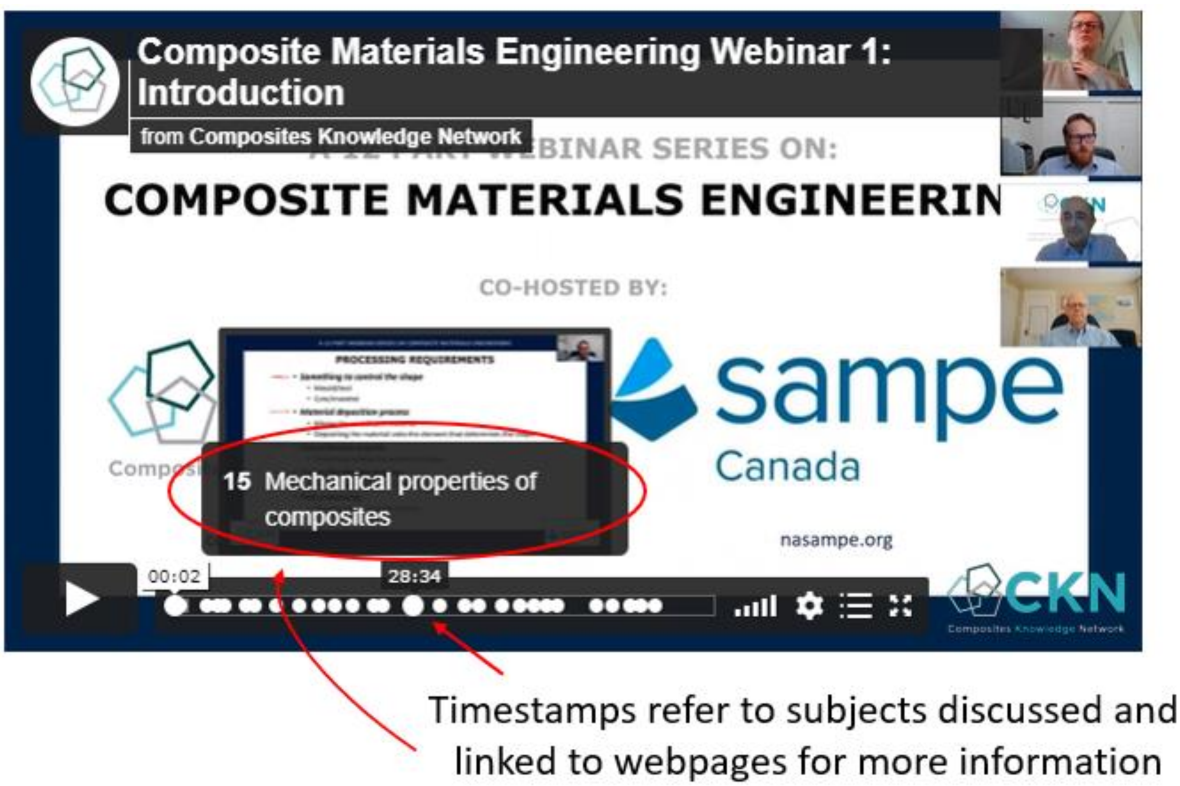

Figure 3: AIM Event recordings are timestamped and linked to webpages

5 CONCLUSION

The KPC uses a novel framework to deliver composite materials resources to all levels of users, from undergraduate students interested in basic information, to experienced engineers with decades of experience. The website attempts to address the need for a composites resource that helps the user navigate through tasks by providing supporting theory at levels that are suitable to novices and experts alike.

The framework of the KPC structures information in a systematic way. It helps the user to locate information efficiently and move towards knowledge/theory or practice as needed, and is based on the thinking that the field is a spectrum of information from knowledge to practice.

The KPC and more information about it can be found online at https://compositeskn.org/KPC.

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