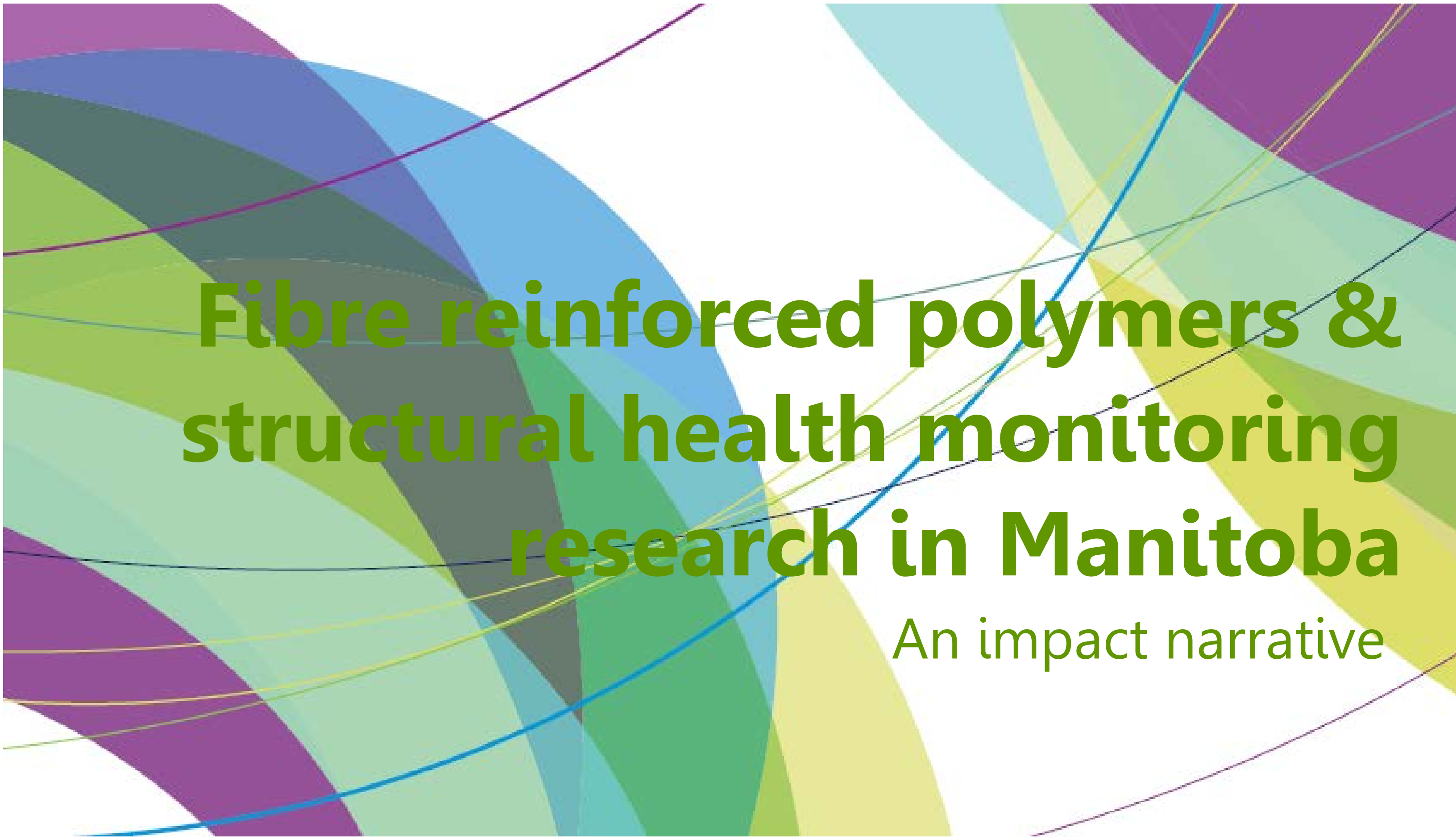

Fibre reinforced polymers & structural health monitoring research in Manitoba

An impact narrative

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List of Acronyms

BWIM	Bridge Weigh-in-Motion
CHBDC	Canadian Highway Bridge Design Code
CIRC	Canadian Infrastructure Report Card
CSA	Canadian Standards Association
FHWA	Federal Highway Administration
FRP	Fibre reinforced polymers
GFRP	Glass fibre reinforced polymers
HQP	Highly qualified personnel
IIFC	International Institute of FRP in Construction

ISIS Canada	Intelligent Sensing for Innovative Structures
ISHMII	International Society for Structural Health Monitoring of Intelligent Infrastructure
LCC	Life cycle cost
NCE	Networks of Centres of Excellence
SHM	Structural health monitoring
SIMTReC	Structural Innovation and Monitoring Technologies Resource Centre

EXECUTIVE SUMMARY

SIMTReC (Structural Innovation and Monitoring Technologies Resource Centre) is a globally recognized organization focused on advanced composite building materials and structural monitoring innovations. Founded in 1995 as ISIS Canada (Intelligent Sensing for Innovative Structures) a Network Centre of Excellence (NCE), the organization has transitioned into a leading Research and Resource Centre providing structural health monitoring technological services and innovations in infrastructure. SIMTReC's track record of transferring the research, technologies, applications, and knowledge to industry is groundbreaking. Currently, the centre is dedicated to continued advancement in high-level user-focused research and innovation for construction materials, advanced technologies and structural monitoring using sensors – for buildings/bridge structures, and heavy vehicles and equipment.

To highlight the achievements of SIMTReC, an impact narrative has been developed by Research Manitoba. The objective of this narrative is to link the outcomes and impacts to SIMTReC's research activities, and communicate the impacts of research to a variety of audiences such as academics, industry, community groups, the public and other knowledge users.

An interview guide was developed to capture the impacts of the work of SIMTReC in advancing the application of fibre reinforced polymers (FRPs) and structural health monitoring (SHM) in North America and across the globe. A total of 15 individuals from SIMTReC, the private sector, the public sector, former SIMTReC trained students, and representatives from the University of Manitoba were interviewed to inform and complete this impact narrative. Secondary data shared by SIMTReC and from publicly available sources were also used to tell the impact story. To illustrate the significance of the research conducted by SIMTReC, this impact narrative will focus on the novel application of FRPs and SHM to civil engineering infrastructure.

The primary benefit of SIMTReC is in the advancement of knowledge, knowledge transfer, and leveraged collaboration in research, design, implementation, and applications of FRPs and SHM. SIMTReC has produced 2,500 technical papers (journals and conferences), five patents and trained 700 highly qualified personnel. Currently, SIMTReC-trained highly qualified personnel (HQPs) are utilizing their knowledge of FRPs and SHM to decrease the cost of infrastructure repairs and maintenance across Canada. SIMTReC's impacts from the novel application of FRPs and SHM in civil engineering are presented in three categories: advancing knowledge, capacity building and broader impacts e.g. economic benefits.

First, SIMTReC *advanced knowledge* about FRPs and SHM by:

- conducting over 100 demonstration projects that were selected in consultation and partnership with industry leaders, manufacturers, and public officials;
- writing and publishing nine educational modules including seven on FRPs, one on SHM, and one on life cycle costing;
- writing and publishing six design manuals for engineers and practitioners to support the use of FRPs and SHM in the field;

- writing section 16 of the Canadian Highway Bridge Design Code (CHBDC) and the Canadian Standards Association (CSA) S806 that allowed design engineers to use FRPs without assuming unnecessary exposure to liability;
- facilitated 47 conferences, workshops and events across Canada inviting/hosting numerous international scholars, private/public sector members as well as students.

Capacity building: SIMTReC has trained 700 HQPs from 1995 until 2017 that now hold many prominent positions throughout Manitoba, Canada, and other countries. Furthermore, SIMTReC's strength is in the ability to coordinate collaborative efforts. Its past experience included the coordination of 14 Canadian universities and 150 national researchers with leading industry and government partners. The ability to effectively collaborate not only with academics, but with private and public-sector organizations is seen by the world as a strong accomplishment for Canada and a point of pride for SIMTReC.

Broader impacts: the knowledge gained and transferred about SHM and FRP repair applications and new design saves billions of dollars on increasing infrastructure costs wherever they are utilized. Due to the extensive work by SIMTReC, FRPs are now considered a mature product in civil engineering by many public and private sector leaders. Specifically, FRPs have been used in numerous demonstration projects across Canada and recent evaluations have found that they are performing well after 20 years of service. FRPs avoid the issue of steel corrosion so well that better concrete is now required to match the service life performance of FRPs. Additionally, FRP repairs have been able to extend the life or eliminate the need to replace buildings, bridges, and wharfs across Canada and the US. The cost savings of these repairs are significant. As an example, a timber bridge was repaired for only 15% of the cost to rebuild the bridge e.g. $120,000 compared to $800,000. FRP Rebar is now used in 202 Canadian bridges across four provinces.

Pertaining to SHMs, the broad impacts are twofold: first, the use of SHM allows engineers to make tactical and timely repairs. For instance, significant repairs or replacement can be eliminated by using sensors to detect early cracks in a structure and preventing them from developing into large, more costly problems; second, SHM allows for informed decision making when deciding to repair or replace a structure near the end of the assumed service life. Previous to the use of SHM, engineers would have to manually inspect structures to ensure the structural integrity. However, guidelines for these decisions were not standardized and were costly especially for remote structures. Fortunately, SHM provides the tools to determine the true performance of the bridge to justify a decision in making a specific repair, and in some cases eliminating the need to repair or replace a structure.

Overall, the application of FRPs and SHM continues to grow due to the influence of numerous ongoing demonstration projects, the continued research, and SIMTReC's effective engagement with key public and private sector members. However, there is some persisting skepticism amongst private and public members/organizations that are not famililar with FRPs and SHM. Consequently, the full potential of FRPs and SHM has yet to be realized. To address this, SIMTReC's future plans incorporate stronger messaging, expanded research, and increased training.

Part I: Introduction

1. Background

In Canada, nearly 60% of Canada's core public infrastructure is owned and maintained by municipal governments and has a combined estimated value of $1.1 trillion. In 2004, the Federation of Canadian Municipalities sent out a survey to 589 Canadian municipalities to report on the health of their infrastructure and received responses from 167 municipalities. The results of the survey found that there was a $44 billion infrastructure maintenance deficit at the time. Furthermore, roads, sidewalks, and bridges were in most need of repairs compared to other infrastructure and the report recommended that there should be a focus on maintenance and reconstruction of infrastructure, instead of new construction. Finally, the report concluded that deterioration is the primary factor for the infrastructure deficit as "three decades of deferred maintenance work have created a situation where if the deterioration is not halted, the associated costs will escalate exponentially".[1] Since 2004, the Canadian Infrastructure Report Card (CIRC) has consistently found that 30% of municipal infrastructure across Canada is rated as either fair, poor, or very poor. Furthermore, in 2016 the CIRC concluded that reinvestment rates to maintain or repair infrastructure are inadequate. Therefore, the CIRC has consistently recommended that municipalities invest in regular repairs and preventative maintenance.

To address infrastructure issues in Canada and internationally, innovative materials have been researched e.g. FRPs and promoted as part of the solution. However, in 1999 Dr. Farhad Ansari, Professor from the University of Illinois, wrote a letter to the Federal Highway Administration (FHWA) indicating that investing in bridges that have innovative materials e.g. FRPs is a mistake if there is no augmenting investment in monitoring the conditions of the novel structures. To address this issue, SIMTReC developed civionics or structural health monitoring (SHM), which is a process of attaching sensors to a structure, collecting data at a central monitoring site, and analyzing the data to assess the capacity/health of a structure. The benefits of utilizing SHM is to reduce the number of site visits, accurately assess the performance of built structures over time, make informed and tactical decisions on the need for repairs, and the ability to monitor remote structures.

Overall, the use of FRPs and SHM are significant developments because they allow governments to shift from an acute infrastructure maintenance plan of fixing and replacing failed infrastructure to a preventative infrastructure maintenance plan. Acute plans based on a lack of preventative repairs and maintenance lead to safety issues for citizens, larger service disruption from larger repair/replacement construction, and substantially higher costs in comparison to a preventative infrastructure maintenance plan. FRPs and SHM allow governments to adopt a cost effective, preventative infrastructure plan that reduce the overall costs of infrastructure maintenance and repairs as well as reduce traffic/social disruption by eliminating the need for major repairs.

a. About the Structural Innovation and Monitoring Technologies Resource Centre (SIMTReC)

Prior to SIMTReC, there was no industry or organization promoting the use of FRPs for applications in civil engineering in North America. However, FRPs were being widely used in the aerospace, marine, and automotive industries since the 1940s because they were strong, lightweight, and resistant to corrosion.

In the late 1980s the field of civil engineering understood that steel corrosion was decreasing the life span and increasing the costs of maintaining civil structures such as bridges. After meeting with Dr. Urs Meier of Swiss Federal Laboratories for Materials Science and Technology (Empa), Dr. Aftab Mufti, Dr. Leslie Jaeger and Dr. Baidar Bakht, authors of the article *Has the time come for advanced composite materials in bridges?*[2] saw the potential of utilizing FRPs and SHM and sought to galvanize their use and implementation in Canada. Upon securing funding from NCE of Canada program, SIMTReC was formed to research and utilize FRPs and SHM to address the problem of corroding steel in bridges and position Canada as a global leader in civil engineering.

Since 1995, SIMTReC has been centrally located at the University of Manitoba with its network embracing relationships across Canada, including 14 Canadian universities, 30 engineering professors, as well as 205 government and industry partners. As a global leader in the application of FRPs and SHM, SIMTReC has established partnerships with other universities, government policy decision makers, manufacturers, and civil engineering practitioners to focus their research on developing and testing practical solutions for civil structure issues. SIMTReC, through the leadership of Dr. Aftab Mufti, was instrumental in founding the international organizations ISHMII (International Society for Structural Health Monitoring of Intelligent Infrastructure) and IIFC (International Institute of FRP in Construction). Dr. Mufti was the founding president of ISHMII. ISHMII is a non-profit organization of leading structural health monitoring institutions and individuals with a global representation from the applied and theoretical arenas. The IIFC is the only international professional organization dedicated to the use of FRP in civil infrastructure. The creation of the Civionics Research Centre at the University of Western Sydney, Australia in 2009 is another example of SIMTReC's international impact; Dr. Aftab Mufti advised Prof. Brian Uy on establishing the Centre. The national and international impact of SIMTReC has been significant. Without SIMTReC's initiatives, codes, demonstration projects and influence, FRP, SHM and Civionics would not be utilized at the current level in Canada. On an international level, partnerships with Europe and Japan have led to mutual advancements and influence in the field. The impact of SIMTReC can also be seen in the 202 bridges in Canada and the 65 bridge installations in the USA using concrete deck with rebar/grid.[3] Additionally, SIMTReC has conducted research as well as created educational material and instigated policy changes to support the application of FRPs and SHM within Canada. The results of SIMTReC's collective efforts are:

- more than 2,500 published papers,
- nine educational modules,
- six design manuals,
- enactment of a policy change in the Canadian Highway Bridge Design Code (CHBDC),
- five patents, two spin-off companies,
- numerous demonstration projects to highlight the benefits of FRPs and SHM.

Presently, SIMTReC is engaged in the development of cost-effective SHM products as well as continuing to provide consultation services to public and private sector organizations that do not have the expertise to utilize SHM products/technologies.

SIMTReC's achievements have been the driving force behind the transitioning of the Centre's activities into a national hub of research and innovation. The research scope covers Construction Materials, Advanced Technologies and Structural Monitoring using sensors – for buildings/bridge structures, and heavy vehicles and equipment. SIMTReC's community is expanding, broadening the Centre's network of expertise and increasing its end-user base creating new opportunities for industry engagement and exchange of ideas. Research themes include sensor technologies, structural monitoring, fibre reinforced concrete (FRC's), fibre reinforced polymers (FRPs), masonry, and heavy vehicles. SIMTReC is establishing and building a Manitoba End-User Network to strengthen relationships with end-users in its home province. The Centre's training activities are expanding to support the needs of industry and facilitate company growth and capacity. The Centre is well positioned both through its HQP training of graduate and post-graduate students and mature postdocs, and by its offerings of specialized training to engineers to integrate new advancements and technologies. SIMTReC is creating a pipeline of skilled talent that can integrate new advancements and innovations, and is providing training that responds to the needs of Industry to update and increase the skillset of existing employees.

b. About fibre reinforced polymers (FRPs)

Fibre reinforced polymers (FRPs) are a composite material of glass, carbon, or aramid fibres in a matrix of epoxy or vinyl ester resin. Prior to the application of FRPs in the construction industry, FRPs have been utilized extensively in the aerospace and automotive industries. In the construction industry, FRPs are used because they perform better than steel in a corrosive environment because they are non-magnetic and are 80% lighter than steel. FRP product applications include: Deck Panel System; Deck Superstructure; Girder/Beam; Concrete Deck with rebar/grid; Tendon/Cable; Panel; Abutment/Footing; Parapet, Barrier, Enclosure, sidewalk; Piling/Column; Pier (Column) Fendering Systems; FRP/Glulam Beam; and Carbon Fiber/Glass Concrete Filled Arch.

c. About structural health monitoring (SHM)

Dr. Meier's research in FRPs and sensor technology was the catalyst for SIMTReC's SHM research that developed alongside FRPs throughout the 1990s and into the 2000s. Similar to FRPs, the concepts of SHM were not novel. However, the development of professional expertise, effective technology transfer to the field of civil engineering and knowledge creation were innovative. For instance, SIMTReC created 'civionics', which is a new discipline drawn from civil and electrical engineering. Furthmore, SIMTReC developed processes for the proper use and installation techniques of sensor systems to monitor the health of civil structures with electronic and photonic sensors. A long-standing issue with the use of SHM is having a high influx of data that requires professional expertise to discern useful information. As a result, SIMTReC developed a resource in 2005 to partner with public and private industry in the application and analysis of SHM sensor technologies and the resulting data. Overall, the benefits of SHM include:

- Obtaining accurate information as to the performance of existing infrastructure.
- Determining the health status of civil structures at the end of the projected service life.
- Quickly and accurately identifying structural integrity issues for repairs through the service life of a civil structure.
- Confirming assumptions utilized to build structures from data analysis of existing structures.

These benefits will lead to significant cost savings by: improving future designs, and delaying or removing the need to replace existing civil structures, thereby decreasing traffic congestion; creating the ability for accurate inspection of remote infrastructure; and providing better data through standardized inspection of civil structures for decisions on the need for maintenance action.

2. Impact narrative approach/methodology

Outputs, outcomes and impacts in this narrative are examined through the lens of the Research Manitoba impact framework, which is divided into five categories:

a. **Advancing knowledge** involves creation/co-creation of knowledge, new discoveries and breakthroughs arising from research, and contributions to the knowledge pool.
b. **Building capacity** refers to the development and enhancement of the ability of individuals and teams to conduct and sustain research.
c. **Influence on perceptions, thinking, awareness and decision making** because of research activities/findings that can take numerous forms but largely refers to the influence and effects on government; industry; the research enterprise; not for profit organizations; individuals, groups and communities; educational institutions; and the public.
d. **Applications and changes** are the outcomes and impacts that result from research in natural sciences and engineering disciplines.
e. **Broad benefits** include economic, technological, environmental, social/societal, and cultural impacts such as wellbeing and prosperity**.**

For this impact narrative, secondary data was initially collected and analyzed to identify four impact areas. These included: building capacity, influence on codes/policy, innovative products, and economic impacts. These broad impacts were discussed with the SIMTReC management team and became the focus of the narrative.

To identify and understand the extent of the impacts as well as the work of SIMTReC this narrative poses two evaluation questions:

1) What are the impacts from SIMTReC's research on FRPs and SHM locally and internationally?
2) To what extent has SIMTReC's activities contributed to the identified impacts?

To answer the first evaluation question, Research Manitoba discussed with the researchers and groups/organizations that work with SIMTReC to construct an impacts-and-research diagram (Appendix 1). The diagram illustrates, in broad strokes, the scope of the impact narrative including: determining the impacts that will be highlighted, identifying the evidence that connects the impacts with the original research activities, and linking the appropriate research activities and inputs to the identified impacts. For the second question, contribution analysis or a theory of change model is used to illustrate how SIMTReC's activities e.g. research and knowledge translation, have led to the identified impacts. Contribution analysis is a causal model that shows the links between activities, outputs, outcomes, and impacts.[4] Through this model, selected projects show how SIMTReC's activities have contributed to its primary goal of supporting the application and adoption of FRPs and SHM in civil engineering infrastructure.

To collect data for the impact narrative, an interview guide was developed focusing on the inputs, outputs and outcomes of research into FRPs and SHM (Appendix 2). Due to the large volume of demonstration projects conducted by SIMTReC since 1995, select applications of FRPs and SHM were identified to indicate the broad benefits and application of FRPs and SHM. Fifteen individuals from SIMTReC, the private sector, the public sector, former SIMTReC trained students, and representatives from the University of Manitoba were interviewed to inform and complete this impact narrative (Appendix 3).

Mr. Ryan Catte, M.A., Evaluation Assistant, worked with Ambrosio Catalla, Evaluation & Policy Analyst at Research Manitoba to prepare this impact narrative from June to October 2017.

3. Limitations

This narrative was successfully completed with the support of the SIMTReC team. The following restricted the acquisition and analysis of further forms of data:

- The products/technologies discussed in this narrative are primarily created and maintained as public products intended for general implementation and not commercialization. Therefore, this impact narrative about SIMTReC focuses on the breadth of applications and ability to solve public infrastructure repair/maintenance needs as opposed to spin-off companies, patents/licensing, and revenue generation from product sales.
- Most of the SIMTReC clients have non-disclosure agreements for their projects. Consequently, it was not possible to gather information about nor quantify certain types of impacts e.g. sales, jobs, or cost savings.
- A limited number of respondents declined to be included in this research project.
- The recording of in-kind contributions was not consistent and therefore the types of analysis available with this information was limited.

4. About the report

The outline for this report will begin with the background of infrastructure across Canada as well as a description of FRPs and SHM, approach/methodology, findings, discussion and conclusion.

- The background section focuses on contemporary infrastructure needs within Canada, a description of FRPs and SHM, and the history of SIMTReC.
- The approach section discusses how the data was obtained based on Research Manitoba's impact framework. Data has been collected from 15 interviews as well as through secondary data sources e.g. project documents, public record documents, and academic publications.
- The findings are divided into three sections: a) the inputs into the research, b) outputs, and c) outcomes of the research. The inputs look at the funding, the persons involved, and the institutional support provided to each of the research projects. The outputs and outcomes touch on

the HQPs mentored by SIMTReC, the research findings on FRPs and SHM, and how the research discoveries have been and are now being applied.
- The discussion and conclusion sections elaborate on the current and future impacts of the work conducted by SIMTReC.
- Lastly, the limitations section presents the constraints in developing this narrative.

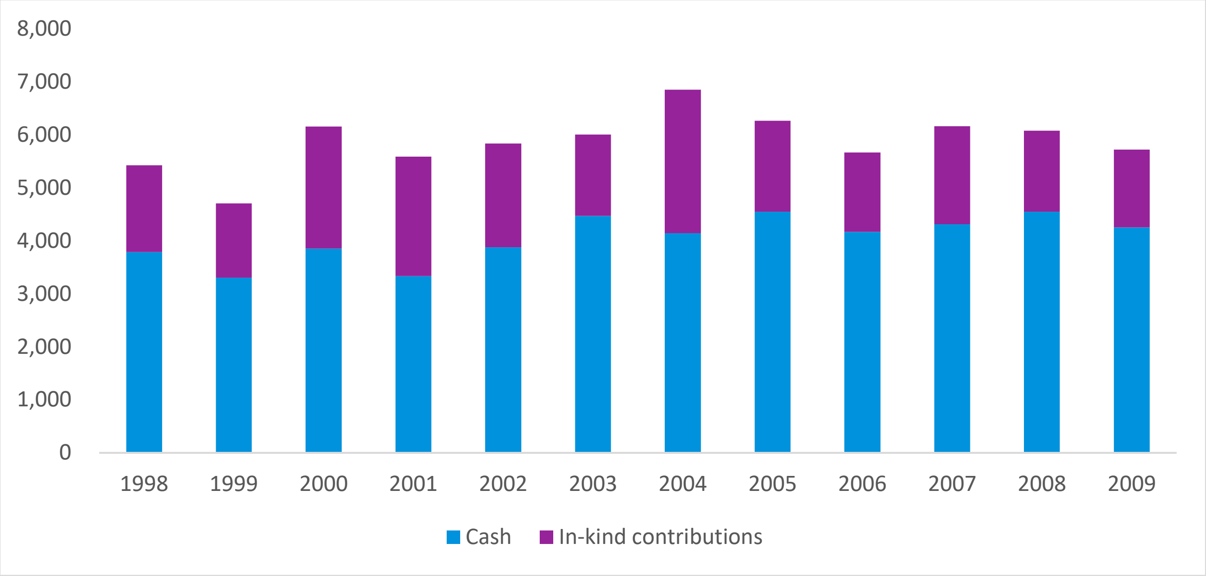
PART II: Findings

1. Research inputs

a. Funding

From 1998 to 2009, SIMTReC received funding from the Networks of Centres of Excellence (NCE), other federal sources, provincial governments, industry partners, universities, and other sources totaling $71.8 million that includes cash as well as in-kind contributions. Over the same period, SIMTReC received $48.6 million in funding plus $23.2 million in-kind contributions. On average, in-kind contributions accounted for about a third of total funding support (Figure 1).

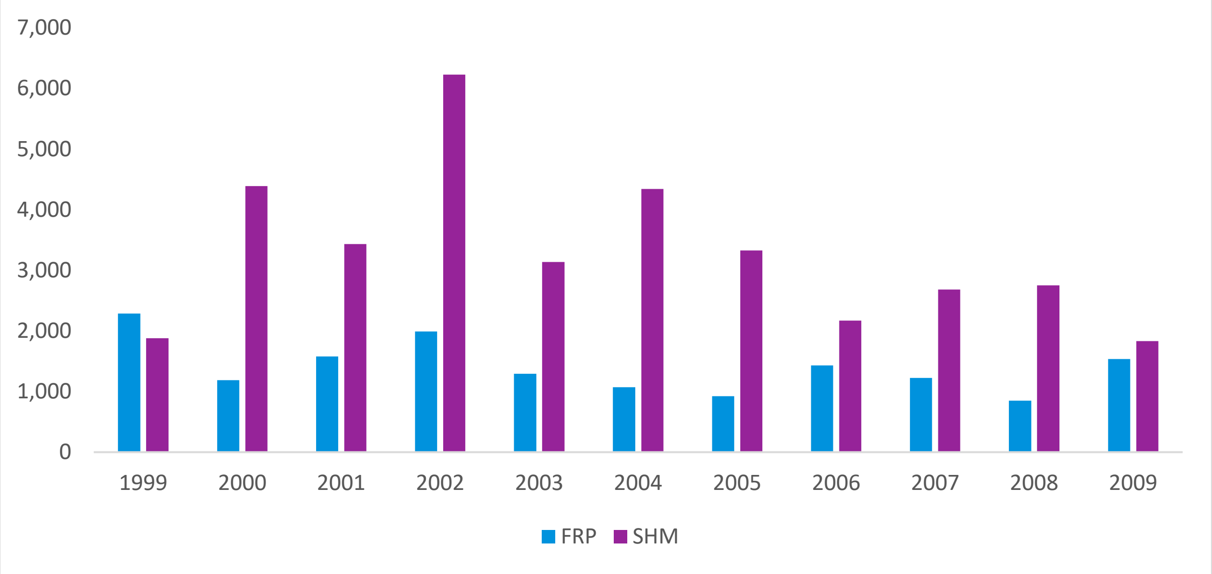
Figure 1. Cash and in-kind funding received by SIMTReC, 1998-2009 ($ '000)



Between 1999 and 2009, $15.4 million and $36.2 million was invested in FRP and SHM related research activities, respectively. SHM related research averaged 69% over the same period (Figure 2).

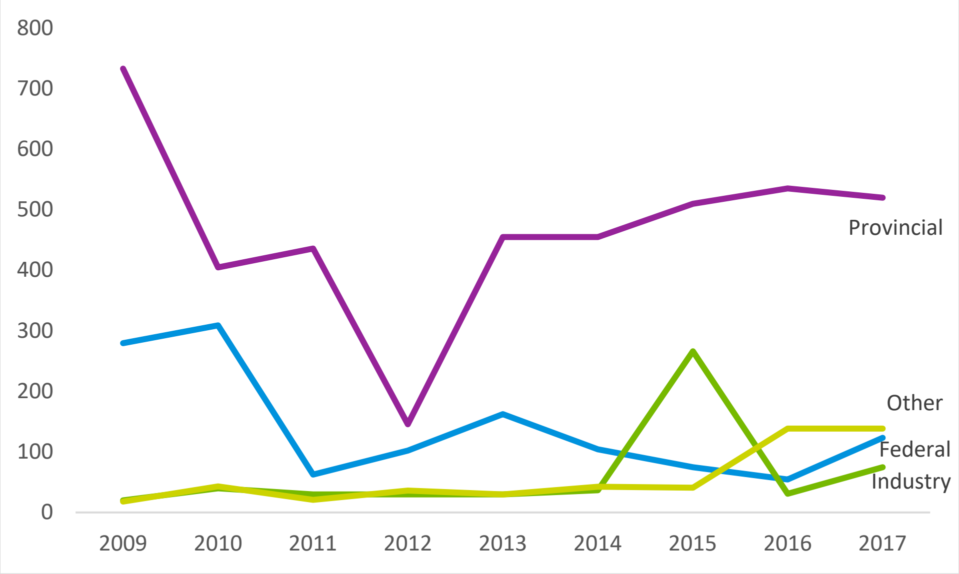
Over the period 1998 to 2009, every provincial dollar invested into SIMTReC leveraged $6.85 in funding and $17.58 for in-kind contributions.

Figure 2. Funding for FRP and SHM research, 1998-2009, ($ ‘000)



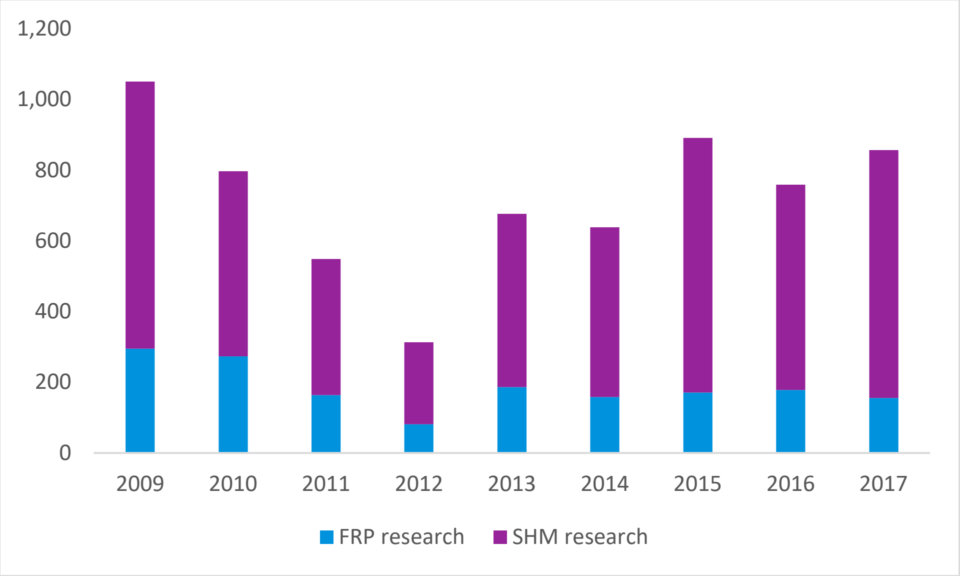
Most Network of Centres of Excellence close their doors once the NCE funding ends, but from 2009 to the writing of this impact narrative, SIMTReC has continued their ground-breaking work finding support through industry partners, the Province of Manitoba, and the federal government such as NSERC and Mitacs (Figure 3).

Figure 3. SIMTReC's funding by source, 2009-2018 ($ '000)



From $1.1 million in 2009, SIMTReC's research funding declined to $313,646 in 2012, before it began to increase again reaching $856,740 in 2017 (Figure 4). Over the same period, most of the funding has gone to SHM research, averaging 75% of the total with the remaining going to FRP research.

Figure 4. SIMTReC funding by research theme, 2009-2017 ($ ‘000)



b. Research team and activities overview

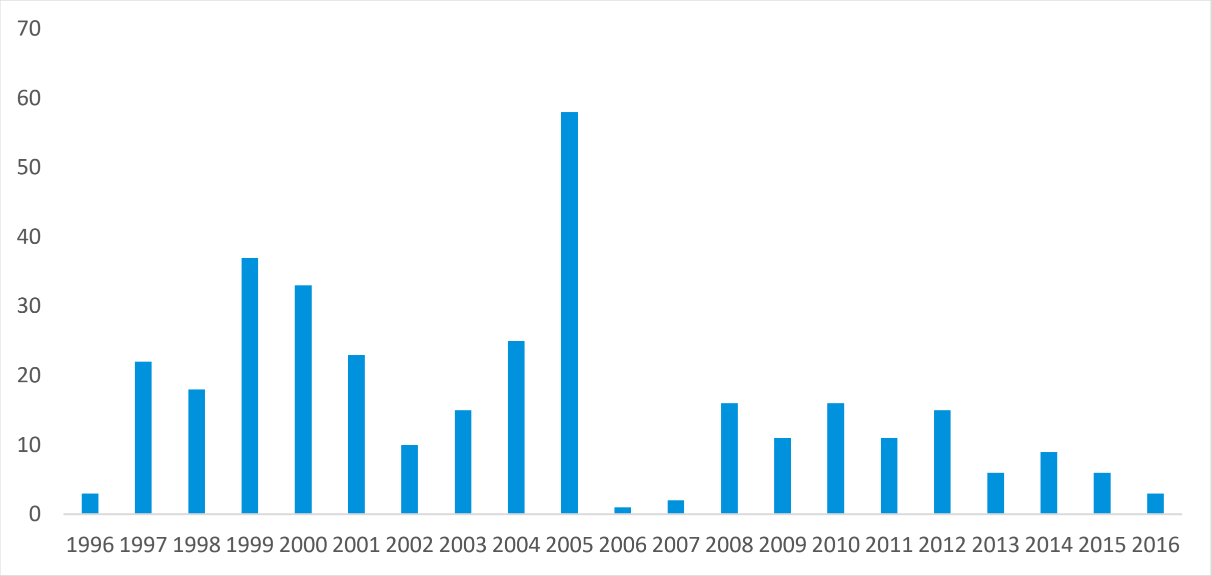
Since its inception, SIMTReC’s research areas have been in FRPs and SHM exclusively. Within FRPs and SHM research, SIMTReC’s research areas are further distinguished into seven themes headed by leaders who are scientific experts in their fields (Appendix 4). At present, there are twelve ongoing research projects in the following themes: Sensor Technologies, Structural Monitoring, Fibre Reinforced Polymers (FRPs), Fibre Reinforced Concrete (FRCs), Masonry, Heavy Transportation Motor Vehicles, Building Information Modeling (BIM) and Geotechnical and Structural Monitoring. Providing direction to SIMTReC’s research and development activities is the Senior Management Team (SMT), consisting of the Director, the Chairs of the Advisory Board, the Business Development Committee, and the Research Advisory Board. Lastly, SIMTReC’s core team members include: Director, Associate Director, Manager of Operations, Office Manager, Research Liaison, Strategic Consultant, Industry Partnerships Facilitator, and Research and Development Consultant.

2. Outputs

a. Highly qualified personnel

Between 1995 and 2016, SIMTReC produced more than 700 HQPs that are now working in the private and public sector including master’s students, PhD candidates, post doctorates, technicians, and researchers. In the same period, there were about 390 SIMTReC graduates. As Figure 5 shows, the number of graduates fluctuated annually due to the number of projects available to complete thesis work, with the most trainees graduating in 2005. The numbers in this chart represents only about 60% of the total HQPs produced due to the challenge involved in tracking them.

Figure 5. Number of SIMTReC graduates, 1996-2016



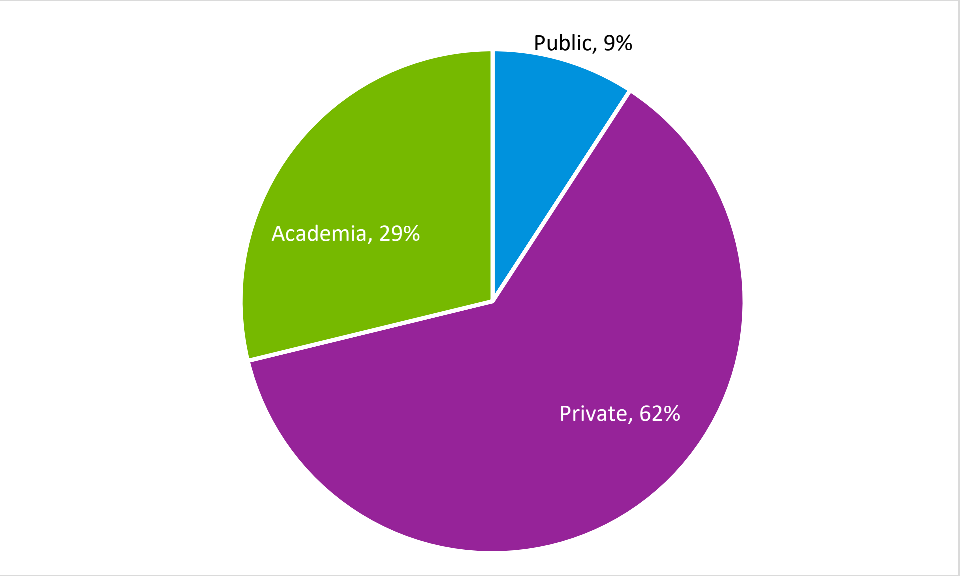
Since completing their training with SIMTReC, many of the graduates have remained in Canada and have entered the civil engineering field in private and public-sector positions. Among the graduates who are in Canada, which accounts for 53% of the total graduates, 39% are in Manitoba (Table 1). The specific locations of 29% of the graduates trained by SIMTReC is unknown. However, some HQPs that have left Canada have been confirmed to be applying their knowledge of FRPs and SHM in the United States, Australia, United Kingdom, Africa, and the Middle East.

Table 1. Location of SIMTReC graduates

Location	Number of graduates		Percent	
Canada				
Alberta	18		9	
British Columbia	12		6	
Saskatchewan	5		2	
Manitoba	81		39	
Ontario	50		24	
Quebec	40		19	
New Brunswick	2		1	
Sub total		208	100	53
USA		29		7
Other locations		43		11
Unknown		114		29
Total		394		100

By sector, nearly two thirds or 62% of SIMTReC graduates are employed in the private sector, while 29% are furthering their education or employed by an academic institute, and 9% are in the public sector (Figure 6).

Figure 6. Distribution of SIMTReC graduates by sector, 1996-2016



b. Fibre reinforced polymers (FRP)-related outputs

Outputs that SIMTReC has produced from FRP-related research include: six education modules, three design manuals, and many demonstration projects that highlight the ability for FRPs to repair damaged civil structures, repurpose old infrastructure, extend the life of civil structures, and be applied to other forms of infrastructure e.g. marine structures. Each of these will be discussed below separately to illuminate what they are and what benefits they provide.

Education modules

SIMTReC was aware from the beginning that the application of a novel product or technology requires the development of the product/technology together with the training of researchers and practitioners. Consequently, SIMTReC developed educational modules for professors, students, and practitioners across Canada and internationally to learn about as well as the application of FRPs. Ideally, if a professor, student, or engineer became aware of FRPs as well as how to use them then they would be able to research or add them to their 'tool box' of solutions in the field. This was a goal of SIMTReC and one that led to the development of seven FRP education modules:

1. Mechanics examples incorporating FRP materials
2. An introduction to FRP composites for construction
3. An introduction to FRP reinforcement for concrete
4. An introduction to FRP strengthening of concrete structures
5. Handling and application of FRPs
6. An introduction to prestressing with FRPs
7. Durability of composites for construction

All education modules were the first of their kind and since the modules became available in 2004 (with revisions in 2007 and 2010), they have supported universities with a civil engineering department to establish courses on FRPs. The primary reason for offering courses on FRPs is because the field of civil engineering has recognized the importance of them as well as the increasingly effective applications that they will continue to have in the future.

Design manuals

To effectively promote the use of FRPs by private and public-sector officials, SIMTReC established standards for use as well as guidelines for the interpretation of the data. SIMTReC wrote and published design manuals utilized by the engineering field to apply products and/or technologies. Design manuals are similar to journal publications in other fields, however they are written specifically to enable the use of a particular technology or product. SIMTReC wrote and published the following FRP design manuals:

1. Reinforcing Concrete Structures with Fibre Reinforced Polymers (FRPs)
2. FRP Rehabilitation of Reinforced Concrete Structures
3. Prestressing Concrete Structures with FRPs

These manuals are key publications within the engineering field and a key resource for the application of products and technologies. Consequently, the implementation and development are effective indicators for the uptake of innovative products and technologies within the engineering field. Since being published in 2000, the FRP design manuals have been downloaded by 2,810 practitioners and students across 48 countries in North and South America, Europe, Africa, Asia and the Middle East (Appendix 5).

Demonstration projects of FRP applications

Civil engineers are not quick to adopt novel products or technologies because of concerns of public safety e.g. a bridge collapsing unexpectedly because of the failure of a not properly tested product. Therefore, novel products and technologies in civil engineering generally take 20 years from inception to general adoption as confidence is built through lab tests as well as controlled real world applications. Demonstration projects are a form of controlled real world application that are conducted to achieve a specific objective involving real structures and are essential for securing code changes that are required to utilize a novel product/technology. Since 1995, SIMTReC has conducted numerous demonstration projects with FRPs in an iterative process to demonstrate the ability for FRPs to repair, repurpose, and be applied to alternative infrastructure needs e.g. marine infrastructure. To this point, the following sections highlight the different applications of FRPs and the corresponding demonstration projects in Manitoba and Nova Scotia that remains in use to this day.

Ability to repair

There are 575 timber bridges across Manitoba as well as many more across Canada and the world. Most of the timber bridges in Manitoba were built prior to 1980 and were not built to withstand the increased traffic loads allowed by the traffic authority currently. In the early 2000s, the province of Manitoba estimated that it would cost $260 million to replace the aging timber bridges in the province. However, SIMTReC's research into glass FRPs (GFRPs) created novel techniques to strengthen existing timber bridges to meet modern requirements and effectively eliminate the need for sweeping timber bridge replacements across the province. Specifically, SIMTReC's technique calls for GFRP bars to be embedded into the stringers (supports) using an epoxy resin to hold the GFRP bars in place. GFRPs are ideal because they are light weight, easy to install, do not require any disruption to traffic flows for installation, and do not corrode when exposed to road salt.

> *“SIMTReC (formerly Intelligent Sensing of Innovative Structures Canada) were instrumental in our decision to design and construct bridge deck structures with extended service life and reduced long-term maintenance costs by utilizing Glass-Fibre Reinforce Polymer (GFRP) reinforcement bars as internal reinforcement. Since our initial installation in 2007, we have 14 bridge structures with deck reinforced entirely with GFRP bars, one of which had GFRP reinforcement in the substructures as well.*
>
> *In the future, we see an additional 16 structures being designed and constructed with GFRP reinforcement within the sub-structure and deck structure and we hope to design and construct a completely steel free structure in the very near future. This would not have been possible without SIMTReC's support in the early stages of design and planning and throughout the construction phases.*
>
> *Darrell Evans, P.Eng.A/Assistant Director*
> *Capital Projects Division*
> *PEI Transportation, Infrastructure and Energy*

Ability to repurpose

Although civil infrastructure is understood as static over time, the purpose or needs may change over time due to increasing rates of traffic, speeds, and weights of vehicles. Generally, older infrastructure that cannot meet the new demands are simply replaced as they cannot respond to these requirements. However, carbon FRP wraps that were tested by SIMTReC are able to strengthen existing infrastructure to meet contemporary needs. In 1999, SIMTReC partnered with the University of Manitoba and the City of Winnipeg to use carbon FRP wraps to reinforce the Maryland Bridge. The bridge was originally constructed in 1969. Engineering analysis indicated that it was no longer able to carry the vehicle weight limit set by the City. A carbon fibre wrap was designed to strengthen the structure. After application, there was no need to replace the bridge or reduce the posted weight limit, saving the City and users millions of dollars. Another example of the ability for FRPs to repurpose existing buildings is when the City of Winnipeg reinforced the roof of the Water Pollution Control Centre. The City was planning to replace the entire roof of the Centre to meet the new weight requirements for an addition to the building. Supported by SIMTReC research, engineers were able to design and apply a carbon FRP to the roof panels to meet the new requirements and eliminate the need to replace the Centre’s roof.

Ability to provide longer lifespan of key infrastructure

Research by SIMTReC has concluded that FRPs in bridge decks will last between 75 and 100 years. In comparison, the service life of steel in bridge decks is much less and requires regular maintenance and repairs that are not required by FRPs. The extended service life of FRPs are highlighted in their application in the Manitoba floodway expansion bridges and Hall’s Harbour Wharf in Nova Scotia.

In 1968, the 47-kilometer Manitoba floodway was built to divert water around Winnipeg and avoid flood damage. During the expansion of the floodway that began in 2007, 43,000 square meters[5] of new bridge deck was required. An important consideration in the construction of a bridge deck were the materials used since the bridge deck has the shortest lifespan compared to all other components of a floodway structure. In the late 1990s, SIMTReC patented a steel-free bridge deck utilizing FRP materials that would last 75 years with little to no maintenance required. This is significant, because conventional steel material cannot last 75 years and require repairs every 20 years. As the most cost-effective material, the province of Manitoba chose to use GFRP reinforcement in six floodway bridge decks. The Manitoba floodway includes one of the largest FRP reinforced bridges in North America using 150 tons of GFRP and the largest steel-free deck (Figure 7). Without the research and data from previous demonstration projects, the province would not have utilized FRPs for the floodway bridges because they would not have had enough information to legitimize their decision or known of its existence. Since then, the civil engineering field has noted that the development of a steel-free bridge deck was one of the most important developments in the bridge engineering field in the past 50 years.

Figure 7. Floodway bridge in Winnipeg, Manitoba with Nebraska University prestressed deep concrete girders and the University of Manitoba Steel Free Deck

100 year life Superstructure

NU Girders

MORE THAN 50,000 m2 Steel Free Bridge Decks

The life span of marine infrastructure has also benefited from the use of FRPs. Marine infrastructure made of concrete and steel have a relatively short service life and require regular maintenance due to exposure to salt water. Since FRPs do not corrode, their use doubles the service life of marine infrastructure and requires less maintenance. An example is Hall’s Harbour Wharf in Nova Scotia. The Wharf is located on the Bay of Fundy shore, which has a large tidal range, daily freeze-thaw cycles, and severe storms. One particular storm in 1998 caused the collapse of the mid-section of the wharf. As the only harbour on the north shore kept open year-round, the wharf needed to be repaired. Hall’s Harbour wanted to find a long-term solution for the repair that utilized 21st century technologies. Consequently, the municipality partnered with SIMTReC and installed GFRPs that cost an additional 4.5% or $20,000 in upfront costs compared to using steel. The larger upfront costs were rationalized utilizing a life cycle costing method that showed the cost savings due to a longer life span (30 years with steel versus 60-80 with GFRPs) in addition to requiring less maintenance and repair.

Novel applications of FRPs

The primary purpose of utilizing FRPs is to address the issue of steel corrosion in bridge decks since the materials used in the manufacture of FRPs do not corrode from exposure to water or salt. Steel rods deteriorate over time after cracks form in the concrete and water as well as salt leak onto the steel bars. Originally used to replace bridge components, FRPs have been found to be effective in different constructions and conditions such as: cemetery markers, anchorage for post-tensioned masonry structures, civil structure dowels, and ground anchors.

Additionally, research has been conducted to verify the use of FRPs as an alternative material in transmission poles as well as supports for residential, mid- to high-rise balconies. First, in Manitoba there was an increasing need by Manitoba Hydro for transmission poles that were usually made with wood or steel and last 20 years before requiring repairs. However, shortages of wood poles and increasing costs of steel poles led to SIMTReC partnering with Manitoba Hydro to conduct research and demonstration projects to determine the viability of FRP and wood/FRP hybrid transmission poles. Demonstration projects found that FRP transmission poles last longer as well as require less repairs in comparison to conventional wood and steel poles. SIMTReC and the Faroex Filament Winding research facility in Gimli, Manitoba conducted research and development of FRP transmission poles for Manitoba Hydro to use. Second, research is being conducted on the viability of utilizing FRPs instead of steel for supports in mid- to high-rise residential balconies. Using FRPs instead of steel to anchor a balcony to the exterior wall addresses the issues of excessive heat loss in the building as well as deterioration of the balcony/exterior wall due to the corrosion of steel. While preliminary results of FRP have been found to solve these issues, further research and demonstration projects are required. If the preliminary results continue to be verified, then FRPs may be applied commercially to new residential high-rises and be able to increase the energy efficiency of these buildings.

c. Structural health monitoring (SHM) related outputs

SIMTReC has developed: three education modules, three design manuals, and conducted demonstration projects to establish the viability and benefits of SHM. The following will discuss each of these outputs for SHM and their benefits.

Education modules

The board of directors of SIMTReC knew that before a product or technology can be applied, it needs to be fully developed and the ability to effectively utilize the product/technology must be present. Consequently, SIMTReC developed educational modules for professors across Canada and the world to help teach their students about SHM and how to apply it. Consequently, when they graduate and begin their careers in the civil engineering field, SHM plays an important role in the solutions they bring to their engineering challenges. This was a goal of SIMTReC and one that led to the development of three SHM education modules:

1. SIMTReC introduction to structural health monitoring.
2. An introduction to life cycle costing for innovative infrastructure.
3. Durability of composites for construction.

Educational manuals were downloaded by 1,298 users in 42 countries including Canada. It is important to note that in 2004 the educational modules were the first of their kind to be developed. Since the modules became available, they supported universities with a civil engineering department to establish courses on SHM for their students. SHM technology is now understood by the civil engineering field as an increasingly important tool to help address increasing infrastructure needs across the globe.

Design manuals

To effectively promote the use of SHM by the private and public sectors, SIMTReC established standards for use and guidelines for the interpretation of the data collected. To accomplish this goal, SIMTReC wrote and published design manuals that are standardized texts utilized in engineering. Design manuals are similar to journal publications in other areas of research e.g. health; however, they are written specifically as a guide for the use of a particular technology or product. SIMTReC wrote and published the following SHM design manuals:

1. Installation, Use and Repair of Fibre Optic Sensors
2. Guidelines for Structural Health Monitoring
3. Civionics Specifications

There were 903 downloads of the manuals in Canada and 38 countries in North America, Europe, Africa, Asia, and the Middle East.

Demonstration projects of SHM applications

Similar to FRPs, demonstration projects have been initiated by SIMTReC to highlight the capabilities of SHM technologies. SHM research conducted by SIMTReC has focused extensively on creating and testing different types of sensors, data collection and analysis software, as well as power and data transferring techniques in partnership with public and private sector partners. This form of research is referred to as civionics which is the application of electronics to civil engineering structures and was pioneered by SIMTReC. The broad benefits of civionics are discussed below:

From acute to preventative repairs

The Golden Boy, placed on top of Manitoba's legislative building in 1919, is a landmark that is meant to symbolize, in part, the call for the youth of Manitoba to develop the future prosperity of the province. In 2000, the Golden Boy was found to require major repairs to its support structure. While the repairs were carried out, SIMTReC was contracted to design and install four types of sensors (accelerometer, strain, electric resistance, and temperature) so that the structural health of the Golden Boy and its supporting structure could be monitored. The demonstration of SHM in the Golden Boy project is important because it a) showed that SHM sensors are non-invasive i.e. they do not impede the aesthetics or structural integrity of the Golden Boy statue; b) the non-invasive sensors allow engineers to adopt a preventative model of maintenance, instead of the current acute model of maintenance. Essentially, the data provided by the sensors could be used to allow for the identification and repair of small, inexpensive problems to prevent them from becoming larger, more expensive problems. Since the use of SHM technologny in the Golden Boy, the technology has been applied to roads, bridges, residential buildings, the Canadian parliament building, and the Tomb of Jesus for various purposes. Presently, the value of SHM technology is still being actively researched and evaluated to investigate a growing number of helpful applications of this technology.

Knowledge acquisition and enforcement tool

Every bridge is constructed with particular sets of assumptions about the number, weight, and speed of the vehicles that will cross over it. However, over time the number, weight, and speed of those vehicles may all increase with the passing of new laws, consumer needs, or commercial shipping routes. For certain bridges, these increasing demands may place an excess burden on their structural components and consequently decrease their life span. Generally, transportation bodies will include signs to communicate to drivers that vehicles in excess of a certain weight are not allowed to use these bridges. Unfortunately, not all drivers adhere to the warnings and rules are difficult to enforce due to cost and location of the bridges. Therefore, SIMTReC in partnership with two of their private sector partners have developed a Bridge Weigh-in-Motion (BWIM) sensor that is non-invasive, undetectable to drivers, and economical. Although the sensors are able to communicate the current strains being placed on a bridge due to traffic, the purpose of the BWIM is to enable the enforcement of rules when commercial vehicles with heavy loads exceed the posted weight limits. This project demonstrates the potential for not only monitoring the health of structures, but also ensures that commercial road users are adhering to the safety restrictions of the publicly funded infrastructure they use.

For consistency, remote application, and timely repair

Sensing technology has been continually evolving since 1995 when SIMTReC began research using fibre optic sensor technology. During the 1990s and early 2000s SIMTReC successfully developed fibre optic sensors that could be installed within FRPs. These sensors utilized light and laser sensing to provide accurate data for engineers. However, the cost of these sensors was too high in comparison to the benefits for the adoption by most governments. Fortunately, with the advancement of cellular and internet technology, the cost of sensing technologies has been reduced substantially. For instance, a fibre optic sensing system in the early 2000s would have cost approximately $250,000 compared to the new cellular sensing system that costs $10,000. One particular cost effective sensor is the Binary Crack Sensor for Steel Girders that was produced in response to the growing need to monitor steel girders that are at risk of cracking. Currently, many bridges across North America are over 50 years old, constructed with steel girders. Some are beginning to crack due to the expected wear over time as well as poor construction materials/methods. At present, the only way to inspect these civil structures is by visual inspection, which is time consuming, costly especially for remote infrastructure, and difficult to maintain regularly (usually only done every 1 to 2 years). Also, comparing the results of inspections is difficult to do. Fortunately, the binary crack sensor technology that is currently being field tested addresses all these problems and may be applied to various civil structures including bridges.

Application to extreme cold in northern remote roads

Road access to the north is essential for ensuring goods are transported to remote communities in Canada as well as addressesing the goals of northern economic development and strengthening of

Canadian sovereignty in the Arctic. The northern environment and the increasing effects of climate change, however, pose serious challenges in the construction and serviceability of highway embankments in Canada's North. The highway from Inuvik to Tuktoyaktuk in the Northwest Territories is a recent SIMTReC project in partnership with a public transportation body, where SHM is being utilized in an extensive field monitoring program. Advanced geotechnical sensors are monitoring deformations and temperatures and the results obtained will require data analysis to assess the condition of the test embankment and how the seasonal winter freezing and spring thawing cycles impacts its service life. The project will help in designing and constructing northern infrastructure that are sustainable and easily maintained and will lead to innovative solutions to construct northern roads in permafrost conditions.

3. Outcomes

a. Fibre reinforced polymers (FRP)-related outcomes

Policy change: design code on utilization of FRPs

Civil engineering is critical to the development and maintenance of infrastructure in any modern society. Due to the importance of civil structures, practitioners, researchers, and owners are reluctant to adopt new technologies or products that have not been rigorously tested. Additionally, utilizing new products and technology exposes engineers and owners to liability issues when no formalized guidelines exist i.e. design codes that specify the use of products for civil structures. Therefore, engineers and owners will only approve the use of products that have already been tested, demonstrated in the field, are in the national design codes, and are able to be installed within the allotted deadline of a project. However, the process for utilizing new products/technologies that introduce major changes will generally take 20 years to fully integrate in the civil engineering field. Developing design codes is the most important step to ensure the implementation of a novel product/technology. Consequently, SIMTReC created a subcommittee that was chaired by Dr. Mufti and wrote section 16 in the Canadian Highway Bridge Design Code (CHBDC) in 2003 for the use of FRPs. At that time, it was the only design code in the world that permitted the use of FRPs for rehabilitating and constructing new timber and concrete structures. Design codes, particularly section 16, has allowed FRPs to become increasingly useful in the field of civil engineering. In addition, Dr. Dagmar Svecova, representing SIMTReC and the University of Manitoba, was a member of the committee writing Canadian Standards Association (CSA) S806 Design and Construction of Building Structures with Fibre-Reinforced Polymers that has been instrumental for implementation of FRPs in structures other than bridges.

Leadership in FRP applications in civil structures

SIMTReC's primary goal was to apply FRPs to the civil engineering field to address issues of corrosion with conventional steel products. The accomplishments of SIMTReC are understood by many as a success that is uniquely Canadian since it involved the collaborative effort of 30 principal investigators and more than 185 researchers from 14 universities. The collective effort of SIMTReC required strong leadership to ensure success. To this point, former Deputy of Manitoba Infrastructure Andy Horosko said that, "Canada has been fortunate to have champions like Dr. Rizkalla and Dr. Mufti who headed SIMTReC, and Dr. Bakht. These champions have helped the early use of FRPs in Canada".

Building capacity

Since 1995, SIMTReC has trained and developed over 700 graduate students and postdoctoral fellows. After graduating, they have entered the public or private work force in Canada as well as internationally. They now occupy senior posts and are pursuing FRP and SHM research or applying FRP and SHM technologies. Additionally, SIMTReC has collaborated with numerous private and public sector organizations/institutions to share their knowledge of FRPs and SHM to help install and utilize them in an ever going list of applications. With regards to the benefits of SIMTReC's collaborative work:

> *"Manitoba Infrastructure has enjoyed a long history of working collaboratively with SIMTReC to develop cost-effective solutions to address our infrastructure issues using new and innovative technologies. A good example of this collaboration is in the use of GFRP reinforcement in our concrete bridge decks which has been shown to be cost-effective through life cycle cost analysis over the life of the bridge.*
>
> *Together, we have also developed a GFRP strengthening system for timber bridges, are gaining a much better understanding of how our bridges behave under actual vehicle loading from structural health monitoring systems, and have verified the in-service performance of new and innovative technologies such as precast concrete deck panels."*
>
> *Ruth Eden, M.Sc., P. Eng.*
> *Acting Assistant Deputy Minister, Water Management and Structures*
> *Manitoba Infrastructure*

b. Structural health monitoring (SHM)-related outcomes

Research findings in the area of structural health monitoring have resulted in two main outcomes:

- More informed judgements about the optimal course of action for civil structures at the end of the projected service life, and
- Civil structures, including remote ones, are monitored more frequently.

Prior to the development and application of SHM, the decision to repair, replace, and maintain the status quo of a structure was based on: their assumed service life; current use; and visual inspections. The consequences of an error as a result of these assumptions may be repairs to incorrect components of structures or to parts that do not require repair, and even the unnecessary replacement of a civil structure. SHM has allowed engineers to assess the health of a structure and carry out repairs if necessary as a result of better data from sensors in comparison to visual inspection methods. Before SHM, engineers were not able to accurately determine the current strains on, or the health of a structure. For structures in remote locations, the installation of sensors provides accurate data regularly regarding their health and has eliminated the need for costly inspections. Finally, inspecting existing civil structures is costly because of the large number of structures that need inspection, their location, and the labour inherent in visual inspections.

In 2005 SIMTReC developed a structural health monitoring resource centre with the goal to close the gap between existing research on SHM and FRPs and economically viable commercial products and services. Specific actions taken by SIMTReC has been to:

- Establish a team to develop application guidelines to build the capacity to interpret data for SHM technologies
- Support trained personnel to travel to sites applying SHM technologies
- Provide monitoring equipment to clients that are trained in applying SHM

Since the inception of SIMTReC's SHM Resource Centre, SIMTReC has found that it is now the 'go-to-centre' for SHM for the Canadian engineering design, construction, and manufacturing community'.[6] Members from the private and public sector based in Manitoba that were interviewed for this impact narrative indicated that using SHM technologies would not have been possible without SIMTReC's assistance since they do not have the knowledge amongst their staff to utilize the technologies. SIMTReC has played and continues to play a pivotal role in development and realization of the full potential of SHM technologies in Manitoba and across Canada.

4. Challenges

a. Fibre reinforced polymers (FRPs)

SIMTReC's application of FRPs to the civil engineering field has in the past faced several challenges including:

1. Higher initial costs of FRPs compared to conventional material e.g. steel
2. The long-term durability of FRPs in extreme environmental conditions was not understood
3. Lack of awareness and perceived risk of FRPs in the design engineering field, and
4. No design codes for design engineers to support using FRPs

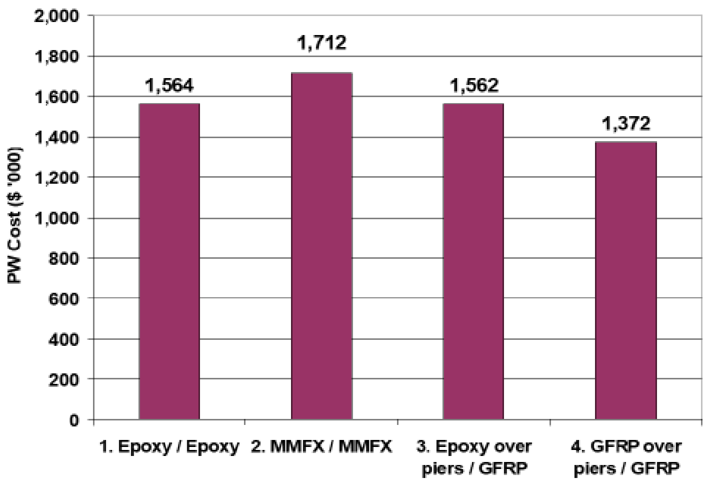
First, carbon and glass FRPs are more expensive building materials to use in comparison to conventional steel materials available on the market. There have been times when the cost of FRPs became relatively close to the cost of steel, but since 1995 it has generally been more expensive. However, this initial extra cost has been found to be justified when calculating the life cycle cost of using FRPs in comparison to steel. This is because FRPs last longer than steel and requires less maintenance over time. To prove this point, SIMTReC developed a life cycle costing analysis tool that could be utilized by design engineers to show the lower expense of FRPs over time compared to steel. Specifically, life cycle costing provides estimates that allow decision makers to compare the initial and stream of maintenance and repair costs over the service life of a structures designed with different materials.

The economies of using GFRP are illustrated in the following cost comparison bar chart. Figure 8 provides the expected present worth costs over a 100 year planning horizon for a deck slab designed with 4 different steel and GFRP reinforcement alternatives. Basic costing assumptions have been made using a discount rate of 5%; and including only agency cost for initial construction, maintenance and decommissioning.

This field example is for a deck slab on an urban bridge carrying 20,000 vehicles per day. The bridge had the following details:

- 2 lanes
- 7 spans @ 43.5 m each
- 6 piers – continuous over piers
- Length – 304.5 m
- Deck width – 11.64 m
- Roadway width – 10.4 m

Figure 8. Expected value of life cyle (agency) costs



The life cycle cost estimate indicates that GFRP arching design concept dominates.

The second ongoing challenge to the use of FRPs is the question of their ability to withstand the alkali characteristics of concrete. During the 1990s, FRPs' alkali resistance was tested by comparing FRPs and concrete samples immersed in water to FRPs in a very aggressive alkaline solution that was intended to simulate the effects of long term FRP exposure in concrete. These studies found that FRPs failed the artificial tests and concluded that FRPs should not be used in concrete. However, studies conducted by SIMTReC in the lab using similar methods found that as long as the maximum stress levels (i.e. the most strain that can be placed on a material before it breaks) are kept below 25%, FRPs suffer no degradation. Furthermore, FRPs installed in SIMTReC's five field demonstration projects after eight and fifteen years showed no degradation. The five structures included the Hall's Harbour Wharf in Nova Scotia, Crowchild Trail Bridge in Calgary, Joffrey Bridge in Quebec, the Chatham Bridge in Ontario, and the Waterloo Creek Bridge on Vancouver Island. Contrary to the belief that FRPs would deteriorate in concrete alkali environmental conditions, SIMTReC's durability study and analysis found that the FRPs installed had not degraded since their installation eight and fifteen years prior. Notwithstanding the results of these studies and demonstration projects, there is still resistance from private and public-sector decision makers about using FRPs that inhibits their widespread adoption.

Finally, a lack of awareness and perceived risk among the design engineering field has been a major challenge to the greater use and acceptance of FRPs. An evaluation conducted by NEXUS on behalf of SIMTReC in 2005 found that 75.9% of the 130 civil engineering industry members who responded to their survey from Alberta, Ontario, Quebec and Atlantic Canada had not heard of FRP technology prior to 1995 and the commencement of the NCE (SIMTReC). Furthermore, 44% of survey respondents only became aware of FRP technology because of SIMTReC and from their colleagues engaged on SIMTReC projects.[7] The results of the evaluation were published in 2005, which was the same year that FRPs were adopted into section 16 of the Canadian Highway Bridge Design Code. Unfortunately, there has been no follow up evaluation on the results of the 2005 survey that would determine if the use and challenges associated with FRP technology has changed over time. However, the interviews conducted for this report support the awareness that the codes have significantly helped reduce the perceived risk with the use of FRP technologies. In addition, the design manuals produced by SIMTReC increased engineers' comfort by providing design examples.

b. Structural health monitoring (SHM)

Relative to FRPs, SHM is still a developing technology and faces two key challenges: high cost and a lack of knowledge by members of the private and public sector. First, in 1995 SIMTReC began to develop fibre optic sensors that utilized light and lasers to provide accurate data about the strain being placed on civil structures. However, these systems were expensive and would usually cost $250,000 as well as on-going maintenance costs. At the time, industry leaders and governments struggled to reconcile the benefits of SHM and their high cost. However, the simplification of SHM systems and increasing capabilities of cellular and internet technologies have substantially reduced the cost of implementing and maintaining contemporary SHM systems. Second, the use of SHM requires special knowledge for their implementation as well as data analysis. Interviewees from the public and private sector for this impact report indicated that since the technology and use of SHM is relatively new they did not have the time nor the personnel to utilize SHM in their departments or companies. As a result, their partnership with SIMTReC was one of the primary reasons that they have been able to apply and expand their application and use of SHM. However, once the sensors have been applied to a structure the amount of data obtained is large and requires effective analysis and interpretation. Assistance in this area is also necessary due to public and private sector lack of expertise and/or human capital and time restraints. At present, SHM research is addressing the issue associated with big data i.e. large amounts of data that needs to be analyzed to yield benefits. Overall, these challenges speak to the need of having a hub of experts e.g. SIMTReC, to help realize the full potential of SHM technology.

PART III: Discussion

1. Impacts and attribution

One of the purposes of the impact narrative is to disseminate the outcomes that can now be observed, and attribute those outcomes to the research activities by SIMTReC. Establishing linkages between the impacts and research helps to highlight the value of the research conducted to the public, funders, stakeholders, and the researchers themselves. It also helps to understand the uptake of research findings and its influence and effects.

Contribution analysis (CA), an approach to exploring cause and effect, is used to frame the discussion around attribution. It is based on generative frameworks; a process view of causation that identifies the causal links and ‘mechanisms’ that explain effects. This approach involves identifying the attribution problem, developing a theory of change, collecting evidence, and assembling a strong contribution story. Utilizing a results chain, it assembles the different pieces of evidence that illustrate the process by which outcomes have been achieved. It addresses the difference i.e. impact, that the research has made, and how much of that impact has been contributed by the research. In this paper, CA is used to answer the following questions on the work of SIMTReC in establishing the use of FRPs and SHM in civil engineering:

1) What are the impacts from the work of SIMTReC in the application of FRPs and SHM locally and internationally?
2) To what extent has the activities of SIMTReC contributed to the identified impacts?

The theory of change (Appendix 6) addresses these two questions by identifying the impacts of SIMTReC’s research activities as well as showing the connections between the work of SIMTReC and the outcomes within Manitoba, Canada, and other countries. SIMTReC’s collaborative, organizational structure has been the catalyst for application and maturity of FRPs in civil engineering and developing applications of SHM. The efforts of SIMTReC and its partners has led to cost-effective applications of FRPs in new structures and as repairs for bridges, buildings, parking garages, marine infrastructure, telecommunication poles, and cemetery headstones. Pertaining to SHM, the pioneering efforts by SIMTReC has led to the development of technologies and products that has led to more consistent inspections of civil structures, especially remote locations, and a shift from acute to preventative structural maintenance. To date, the developments in FRPs and SHM initiated by SIMTReC has led to a greater ability to construct and repurpose civil structures to extend their life or eliminate the need for replacement as well as shift from acute to preventative repair processes for existing civil infrastructure.

The primary organizational goal of SIMTReC since its inception in 1995 was to make Canada a leader in civil engineering by pioneering the application of FRPs and SHM. The application of FRPs and SHM in North America continues to grow and SIMTReC has unquestionably been the driving force behind this development since its founding. Specifically, SIMTReC has:

- Partnered with 14 Canadian universities as well as numerous public and private sector partners to research and conduct demonstration projects about the applicability of FRPs and SHM to civil engineering;
- Published six design manuals and held numerous workshops, and advocated for and created section 16 of the Canadian Highway Bridge Design Code and CSA S806 to validate, train, and educate engineers, government representatives, and private sector members about the utility of FRPs and SHM as well as guidelines for their use; and,
- Finally, SIMTReC created nine educational modules and trained over 700 highly qualified personnel (HQP) that includes masters and PhD students, post-doctoral fellows, and research associates.
- Developing a pool of HQPs will facilitate the utilization of new technologies and creation of benefits arising from FRPs and SHM.

Unique to Canada and SIMTReC was the ability for the network to collaborate the efforts of 14 universities, 185 researchers, and 30 principal investigators. According to Dr. Mufti and Dr. Bakht, “…a network concept is very Canadian. Canadian's have a culture that encourages collaboration. American culture is more competitive; thirteen universities tried to collaborate without success." Presently, the US, Europe, China, and Japan are applying FRPs and SHM to help address their infrastructure problems. SIMTReC's research activities and resulting outputs and outcomes have led to significant impacts in repairing and repurposing civil structures and the use of FRP and SHM in new structures. Furthermore, the cost savings from utilizing FRPs and SHM are being realized in a growing number of civil structure applications including marine infrastructure for Manitoba, Canada, and across the globe.

a. Building capacity in FRPs and SHM products and technologies

SIMTReC has built the local, national, and international capacity to understand and apply FRPs and SHM technologies in two ways: hundreds of HQPs have been mentored since 1995; and, by being part of SIMTReC's network, 14 universities across Canada as well as numerous government and private sector partners have gained the capacity to apply FRPs and SHM. SIMTReC helped build the capacity of students through the development of educational modules, as well as providing on the job training as research assistants, associates, and project coordinators. Many former students, fellows and associates now hold various significant positions in the public and private sector in Manitoba, Canada and around the world. Furthermore, SIMTReC's collaboration with external organizations has led to an increase of FRPs in new construction and FRP repairs by the province of Manitoba and Manitoba based private sector companies e.g. Vector Construction. As a result, Manitoba-based companies and governments in are now better able to identify, repair, repurpose and eliminate the need for replacement of different kinds of civil structures. These would not have been possible without the pioneering research activities conducted by SIMTReC.

"Vector's long-term association with SIMTReC in the development of structural monitoring, BWIM and SHM, and in the installation of systems in the field, has enabled Vector to engage in a significant number of new projects. SIMTReC's work is moving SHM towards commercialization. This progress has encouraged Vector to develop their own commercial web based SHM platform. Vector's involvement with SIMTReC and access to their specialist expertise has created the opportunity for Vector to move forward with this new platform. Vector now has the potential for further commercialization and installation of SHM in other projects, opening new markets. Vector has plans for new bridge projects and field work using SHM, in Canada and the US.

If not for SIMTReC and its code development and testing, FRP rebar would not be in commercial use. Vector's involvement with SIMTReC has led directly to Vector selling structural strengthening with FRP rebar and opening new business opportunities. SIMTReC's work in FRPs has led to Manitoba Infrastructure utilizing FRP rebar and expanding upon its use, and the Ontario and Quebec Ministries of Transportation specifying the use of FRP rebar in designs."

David W. Whitmore, P.Eng.
President and Chief Innovation Officer
Vector Corrosion Technologies Ltd.

b. Creation of a new field of study: SHM or civionics

Before SIMTReC, there was no attempt to apply electronics or data management to civil structures. Even with the increasing application of FRPs in the aerospace or the automotive sector that utilized electronic data management systems, the civil engineering field was not researching or applying these technologies. With the establishment of SIMTReC and its support, civionics has become an exciting and rapidly developing new field. Currently, private and public sector organizations in Canada and the US are developing more cost-effective SHM products. “I see in a 10 year span we will be able to integrate more SHM in materials and we can see a better turn around on efficiency for our construction and the money savings for our infrastructure in general,” according to Mr. Gamal Mustapha, Vice President of Program Management of SMT Research Ltd., a private company that provides SHM related services.

c. Influence on academic, public and private sectors

The influence of SIMTReC’s research discoveries is growing and the demonstration projects initiated and maintained by SIMTReC have played a big part. In many higher education institutions around the world, courses on civionics and FRP applications in civil engineering are becoming common. Engineers are guided by design manuals; particular to Canada, design codes are now part of the Canadian Highway Bridge Design Code and

SMT RESEARCH LTD.

Founded in 2006, SMT develops structure monitoring technologies that help:

1) Validate new materials and processes that facilitate innovation and the adoption of new technologies and processes.
2) Prolong a building’s life span by means of early moisture detection, and
3) Provide quality assurance during and after construction of residential and commercial buildings.

To date, this technology has helped address the leaky-condo crisis[1] in Vancouver that began in the 2000s as well as facilitated the construction of the tallest wood building in the world at the University of British Columbia in Vancouver. SMT is at the forefront in developing sensor detection systems that allow for predictive analysis of problems in buildings that may be addressed with internal systems or by dispatching maintenance crews for repairs. For example, the green roof of the new Red River College Skilled Trade and Technology Centre in Winnipeg has been setup with moisture detection sensors, thermal efficiency sensors, and drone technologies to autonomously gather data and inspect the building. Leaks or construction issues are quickly identified and repaired to mitigate damage. Additionally, data from the RRC building will help to evaluate and make informed decisions about how the construction materials and modular green roof planters perform in extreme weather conditions. Lastly, SMT in collaboration with the University of Manitoba Human Computing Interface lab is helping to develop data visualization tools and techniques using Virtual Reality and Augmented Reality systems. This technology allows users to inspect sensor data on a building component using a smartphone camera. By downloading an application on a smartphone, individuals can use the camera to see the pipes, wires, and sensors in the walls of a building.

Overall, the impacts of these technological advancements have benefits for a wide breadth of industries e.g. roofing, prefabrication, construction, all of which are rooted in the pioneering research conducted by SIMTReC in sensor technology and civionics. Moreover, the founding members of SMT forged the necessary professional relationships at the University of Manitoba Smartpark Business Incubator program i.e. a formal network between academics and private sector organizations established by SIMTReC. The work of SMT highlights the broad benefits of structural health monitoring research as well as the impacts that result when collaborations between academics and external organizations are established.

Building Code Section 8. The evidence from demonstration projects is invaluable for decisions on whether to construct new structures and/or repair or repurpose existing ones. In the private sector, there are examples of start-ups and existing companies that have taken advantage of FRP and SHM products and technologies.

> *"SMT – designing Internet of Things solutions used to monitor and evaluate the integrity and performance of buildings and infrastructure – has collaborated with SIMTReC since 2007 to devise new solutions for various signature projects. Our first interaction with SIMTReC was to provide researchers with sensors to monitor moisture content in masonry; SIMTReC researchers identified alternative methods to perform this analysis that led to the development of a new concrete moisture sensor, able to penetrate masonry. This sensor went from a prototype to a commercial product in a very short timeframe. SIMTReC's impact on SMT was to support the development of an enhanced sensor design for a specific application, the outcome of which resulted in using the sensors to monitor the moisture performance of new materials used in retrofits of Canada's parliament buildings. This, and a referral from SIMTReC, gave rise to yet another high-profile project providing and installing masonry moisture sensors to monitor and report on the wall moisture level of the renovated Tomb of Jesus, Church of the Holy Sepulchre, Jerusalem. Our relationship with SIMTReC facilitates the development of new infrastructure technologies and the opening of new avenues and possibilities; in turn opening new markets from buildings to infrastructure.*
>
> *Industry working with SIMTReC and the university is a win-win. All our hiring comes from the relationships we develop with highly qualified people engaged in our collaborative research projects. The impact is considerable for SMT – benefiting by profile and recruitment opportunities as well as access to cutting edge research giving us a significant competitive advantage in our industry."*

Gamal Mustapha, P. Eng., PMP
VP Program Management
SMT Research Ltd – Vancouver, BC

d. Cost savings

One of the major costs facing all provinces and territories within Canada is building and maintaining infrastructure. The Province of Manitoba is responsible for 3,000 civil structures not including infrastructure that is the responsibility of Manitoban municipalities. In addition, the province has extreme hot and cold temperatures that place greater strain on its civil structures compared to other jurisdictions across Canada and the globe. Using conventional materials and monitoring techniques for civil infrastructure instead of FRPs and modern SHM, forgoes opportunities for significant reductions in frequency of repairs, the costs of maintenance, and traffic disruption. Therefore, the development and application of innovative products such as FRP repairs, steel free bridge decks, and SHM technologies help add another tool in the tool box for design engineers in Manitoba to address these issues in an effective and efficient way. Specifically, the accomplishments of SIMTReC in developing FRPs and SHM will help:

- Accurately identify structural health issues and consequently shift civil engineering from an acute system of making repairs to a preventative maintenance system;

- Provide engineers with the ability to accurately identify the health status of a civil structure as well as the accuracy of the assumed strain on civil structures;
- Repair structures to extend their life with less traffic disruption; and,
- Establish the ability to repurpose civil structures.

Overall, civil engineering has had a fundamental shift in its future direction due to the research activities and knowledge translation of SIMTReC's novel application of FRPs and development of SHM or civionics. The collective effort of SIMTReC and its partners since 1995 has positioned Manitoba to provide cost-effective, long-term solutions to current infrastructure needs.

2. Knowledge translation and impacts

Knowledge translation (KT) is defined by CIHR as a "dynamic and iterative process that includes synthesis, dissemination, exchange, and ethically-sound application of knowledge to improve the quality of life of Canadians, and provide more effective services and products and strengthen the health care system". CIHR makes a distinction between integrated knowledge translation (iKT) and end of grant knowledge translation. In IKT, key stakeholders/intended knowledge users are included during some portion or all of the research process. End of grant KT on the other hand, are activities "aimed at diffusing, disseminating or applying the results of a research project".[8] For the purposes of this document, KT is the umbrella term for all activities involved in moving research from the research space (e.g. laboratory) into the hands of people, groups, and organizations who can put it to practical use. KT is not an action, but a spectrum of activities which change according to the type of research, the timeframe, and the audience being targeted. The extent to which KT is undertaken is influenced by funders, the researchers, and the type of research. However, the goal of this section is to synthesize the activities conducted by a research program that led to the identified impacts.

Using SHM to reduce costs in electrical power substations

A major power utility knew of SIMTReC's past work on monitoring. In the fall of 2015 they approached SIMTReC for technology solutions that could detect corrosion in the grounding grid system in electrical power substations. The standard approach, to dig up the grid, is both labour intensive and expensive; the client needed innovative and economically inexpensive technology to solve the problem. Pioneering approaches based on acoustic guided waves and electromagnetic waves have the potential to detect corrosion in grounding electrodes. SIMTReC proposed the Acoustic Method for the project and the first field tests in the summer of 2017 yielded good results. In collaboration with the industrial partner, the research is conducted in the laboratory and field-testing and deployment of the developed technology is conducted in the power utility's substations. HQP are receiving training in instrumentation and in industrial oriented collaborative research.

The resulting techniques will be helpful in improving facility maintenance and reliability of power utility infrastructure by enabling an early diagnosis of grounding faults. This will allow the service life of the grounding system to be predicted so that appropriate maintenance measures can be implemented prior to the occurrence of grounding failure that would impose negative commercial and human safety impacts. The company's international division may commercialize this technology with a service partner to reduce costs in the maintenance of their operations.

Understanding and optimizing how research is translated is critical to identifying and improving the outcomes that arise from research – including commercialization activities and broad social, environmental, and economic benefits to Manitoba and those that are non-commercial in nature such as behavior change interventions, policy changes and the like. Grimshaw et al (2012) notes that one of the most consistent findings in research is its failure to translate into meaningful changes in practice and policy.[9] Billions of dollars are invested every year into research that is meant to address problems and issues facing all facets of modern society.

Knowledge translation was identified by SIMTReC as an important activity in 1995 to ensure the uptake of their research into FRPs and SHM. Recognizing a lack of knowledge amongst practitioners and building guides required to utilize FRPs and SHM products/services, SIMTReC worked with government, private sector construction companies, as well as the engineering and academic communities to address their needs. Below are three key activities taken by SIMTReC to translate research to impacts:

a. Proof of concept

To illustrate the feasibility of FRPs and SHM for use in civil infrastructure, SIMTReC initiated the establishment and operation of over 100 demonstration projects beginning in 1995 until today. In engineering, demonstration projects are instrumental in the adoption of novel products since they involve a controlled, iterative process that addresses the issues associated with the development of new products and technologies. Demonstration projects avoid consequences of hasty implementations e.g. a bridge may collapse because the products used in the construction were inadequately tested. The 100 projects directly addressed the concerns of industry regarding the applicability of FRPs and SHM outside the laboratory in different physical and environmental conditions. For instance, FRPs when used as a wrap or as a replacement for steel rods in bridge decks reinforce structures. However, without the initial research and testing of the FRP wrap in demonstration projects, its use as a reinforcing material would not have been realized. Even though FRPs are not universally considered a mature product in engineering, SIMTReC successfully championed for its use in Canadian infrastructure eight years after research commenced. Typically, it takes most products in the field of structural engineering 100 years before they mature and widely used e.g. the transition from wrought iron to steel during the 19th century took 100 years. Because the demonstration projects actually confirm the value of using FRPs in different kind of infrastructures in different conditions over a long period of time, SIMTReC was able to dramatically shorten the period from research and development to practical use.

b. Championing SIMTReC's research

SIMTReC's research and development in FRPs and SHM were championed in two distinct ways. First, since SIMTReC's establishment, members of its Senior Management Team, recognizing the practical and long-term impacts of FRPs and SHM products and technologies, actively and continuously worked to enable end users, particularly government agencies and industry, to adopt them. Specifically, they proactively engaged with external regulatory organizations through committees, presentations, conferences, and meetings to have FRPs approved for use by key stakeholders in the structural engineering field. For instance, Dr. Aftab Mufti created a subcommittee that wrote section 16 in the Canadian Highway Bridge Design Code in 2003. Section 16 was the first in the world that permitted the use of FRPs for rehabilitation and new construction. This code addressed liability concerns from public and private members to use FRPs in their designs. This form of engagement/advocacy was instrumental in the proliferating use of FRPs in Canada and a unique activity by SIMTReC compared to other funded research networks.

Second, research champions leveraged their existing professional relationships in addition to developing new partnerships and collaborations with key decision makers and stakeholders to secure hundreds of demonstration projects. Each demonstration project was key because they were operational in the ‘real world’ and allowed the team to explain the research on FRPs and SHM and show that they were viable and safe to use. Recognizing that there is inherent risk in implementing novel products for any organization/institution, SIMTReC champions have continuously provided expert support, encouraging public and private sector companies and departments to use FRPs or SHM products/services.

c. Developing the capabilities to use FRPs and SHM

SIMTReC knew that if public and private sector organizations were to adopt FRPs and SHM they would require the necessary knowledge and training. As a result, SIMTReC developed education modules, wrote technical papers, facilitated presentations and workshops, created design manuals, and mentored/trained students and members of the private sector. Specifically, SIMTReC wrote 7 design manuals, 9 educational modules, wrote 2,500 technical papers, conducted 47 conferences, workshops, and events across Canada. The education modules and design manuals have been downloaded thousands of times in Canada and around the world. Furthermore, SIMTReC has trained and mentored over 700 HQPs that are now conducting further research in FRPs and SHM or implementing the products and technologies. Some of the SIMTReC graduates now hold various prominent positions within the public and private sectors including CEOs and infrastructure department directors. These HQPs ensure the sustainability of developments in the applications of FRPs and SHM in the structural engineering field. At present, hundreds of projects, millions in infrastructure savings, and the advancement of FRPs and SHM applications across the globe are happening because capabilities around FRPs and SHM are being used.

In summary, the translation of research activities by the SIMTReC team to impacts has been the result of implementing demonstration FRP and SHM projects, championing their research and innovations, and developing the capacities to use FRPs and SHM products and technologies in Canada and around the world. Using demonstration projects, the members of the SIMTReC team utilized their professional standing as well as professional relationships with key public and private sector partners to show the benefits of utilizing FRP and SHM. Additionally, SIMTReC established and maintained effective networks with their academic peers to effectively and efficiently coordinate research efforts. An effective network enabled SIMTReC to conduct the necessary laboratory and demonstration project research for the advancement of FRP and SHM in Canada and across the globe. As a result of their research and demonstration projects, SIMTReC was able to establish themselves as a knowledge broker for public and private sector organizations that has helped them to continue to succeed after the conclusion of their NCE funding. Private and public-sector representatives who were interviewed indicated that they would not have utilized FRPs or SHM technology in their past and current projects without support from SIMTReC. Through continued collaboration and partnership with public and private sector members, SIMTReC has been able to modify FRP and SHM applications to meet their needs and warrant continued collaborations and partnerships.

3. Time to impacts

In the late 1980s, three researchers from Canada – Dr. Mufti, Dr. Jaeger, and Dr. Bakht – learned about FRP and SHM technology after attending an international conference and subsequently published a paper outlining the reasons for applying advanced composite materials in Canadian bridges. After a successful application for a National Centre of Excellence award, SIMTReC was formed in 1995, to conduct research, provide training activities, and carry out demonstration projects around FRPs and SHM across Canada. Between 1995 and 2017, SIMTReC collaborated with municipal, provinicial, and federal levels of government as well as private industry partners on hundreds of demonstration projects, publications, education modules, and design manuals. By 2000, there was sufficient laboratoryand practical knowledge relating to FRPs that Dr. Mufti chaired a subcommittee in charge of writing section 16 in the Canadian Highway Bridge Design Code. Section 16 was followed by two additional codes, CSA S806 (approved in 2002) and S807 (approved in 2010), both initiated and written by SIMTReC and its researchers. S806 dealt with the use of FRPs in buildings. The success of section 16 and S806 gave rise to the need for quality specifications of FRPs contained in S807. These codes on composite reinforcement for concrete addressed the liability issue for design engineers to use FRPs and were the first of their kind in the world. Integrating design code section 16 into the CHBDC, the first visible impact arising from SIMTReC's research activities, took about eight years from SIMTReC's founding and 14 years from when researchers first argued for the use of advance composite materials in bridges. Subsequent reported impacts include the use of FRPs and SHM by private companies and the establishment of new companies using FRP and SHM technologies to extend the service lifespan of infrastructures by repurposing and repairing instead of building new, and the associated cost savings from repairing and repurposing.

The design community, manufacturers, distributors, and end-users began or expanded their use of FRPs significantly as a result of SIMTReC's work facilitating the application of FRPs and changes to the code. Two years after the approvals for each code, FRP usage increased; between 2005 and 2010, the number of installations using FRPs tripled in Canada. Pertaining to SHM, the first generation of SHM sensor technology started as a result of SIMTReC in 1995. Further developments in the SHM sensor industry were facilitated by SIMTReC by supporting the creation of sensors that were more cost effective. Examples of companies collaborating with SIMTReC and developing and applying sensor technologies include: IDERS and fibre optic sensors applied to rail safety, SMT and sensors to monitor moisture content in masonry, and FOX-TEK providing fibre-optic sensor systems. Atlantic Industries Ltd. (bridge and infrastructure solutions, and culvert replacement) collaborated with SIMTReC researchers to use SHM technologies developed by Dr. Baidar Bakht of MTO (Ministry of Transportation – Ontario) and later by Dr. John Newhook of Dalhousie University. A two to five year time frame from research to market is typical for impact results to occur. In addition, the following monitoring and FRP related spin off companies were created by professors, postdoctoral fellows, doctorate students or staff of SIMTReC as a result of SIMTReC research and support:

- ElectroPhotonics Corporations (1996) - Dr. Tino Alawie
- JMBT Structures Research Inc (1997)- Dr. Aftab Mufti
- VSSLI (1996) - Mr Ralston MacDonell

- SHM Canada (1999) - Dr. Vidya Lemay
- Civionics Inc - Dr. Chad Klowak (2008)
- Intelligent Structures Company (2016) - Dr. Doug Thomson
- SIMTReC Civionics Engineer, Geoff Cao, is in the process of establishing a company to market BWIM and SHM systems including all DAQ (data acquisition) and device hardware and software products in Canada and China, which he developed while at SIMTReC.

4. Future of Fibre Reinforced Polymers & Structural Health Monitoring

SIMTReC continues its dedication to being Canada's leading and most influential Resource Centre for structural, materials and monitoring innovation. The SIMTReC Resoure Centre is focused on high-level, user-focused research and innovation for advanced construction materials, advanced technologies and structural monitoring using sensors e.g commercial and residential buildings, bridge structures, and heavy vehicles and equipment. The Centre's future is based upon a successful history of research and the development of applications in infrastructure by SIMTReC since 1995 as well as its "research to market" approach of structural health monitoring and advanced composite materials that has proven highly effective for both SIMTReC and its clients. Responding to industry requirements to update and increase the skillset of existing employees, SIMTReC will expand its industry training program, aligning with end-user needs. Expanding the Centre's training activities will actively support the needs of industry by creating a pipeline of skilled talent that can integrate new advancements and innovations. Specialized training for engineers currently working in industry to integrate new advancements and technologies is a key component to the transfer and use of new technologies.

The Centre's 5-year plan addresses the economic, innovation, and training needs of the Canadian infrastructure market and will focus on:

- Applying SIMTReC's resulting technologies to relevant industries for the benefit of the end-user community and the Canadian economy. Establishing and building a Manitoba End-User Network is a priority. A dynamic, expanding network where end-users are consulted and engaged will continue to demonstrate value and demand for SIMTReC innovation.
- Being the research and innovation link between the engineering faculty and industry needs and demands. Optimizing and building partnerships with universities, colleges and other organizations will bring unique benefits for all parties. Researcher engagement will be strengthened and expanded to include a wider group of disciplines. SIMTReC's value will be communicated and new initiatives created that offer greater benefits and increased collaboration within an expanded community.
- Positioning SIMTReC as a Centre of user-focused innovation.
- Training highly qualified individuals in the transfer of technical knowledge to industry and end-users. SIMTReC's training of highly qualified graduate and post-graduate students and mature postdocs will help to facilitate growth and build capacity for industry and government organizations.
- Providing a pipeline of talent that will facilitate the staffing and growth of Canadian companies and Government organizations

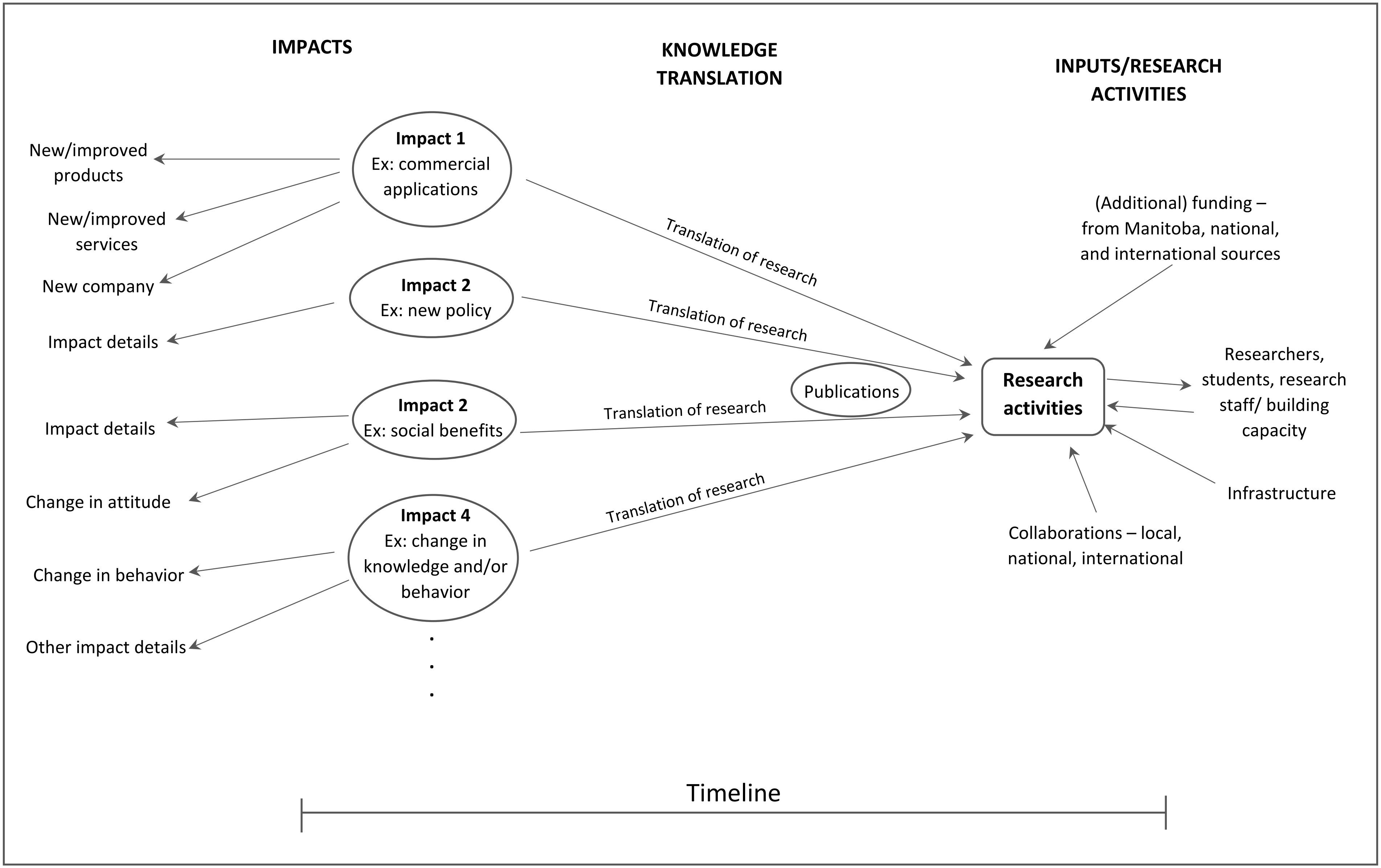
Part IV: Conclusion

The impact of SIMTReC's research and innovation is evident in the public and private sectors as decisions around new construction and the repair/maintenance or replacement of infrastructure are informed by the application of FRPs and SHM. In Manitoba, FRPs are now considered another 'tool in the toolbox' and there is a growing recognition among entrepreneurs and existing companies in Manitoba in the value of utilizing FRPs and SHM in new and existing structures. Across Canada, as well as in countries across the globe, the adoption of FRPs is faster in comparison to SHM. However, reductions in the cost of SHM are leading to increasing opportunities that are being realized by various private sector companies e.g. SMT Research. The research and knowledge translation activities carried out by SIMTReC since 1995 has established the foundation for current and future entrepreneurs and business opportunities in Manitoba, Canada, and around the world. Specifically, SIMTReC has made opportunities possible through:

1. Knowledge/discoveries in FRPs and SHM with practical and diverse applications in construction and maintenance of infrastructure. Most importantly, FRP-related design codes have been developed and integrated into national Canadian policy for use by civil engineers.
2. Canada is still in need of viable and cost-effective options to complete new infrastructure projects as well as repairing and maintaining existing infrastructure that FRP and SHM applications are able to address.
3. Finally, the built capacity to put FRPs and SHM into practice through the development of a pool of HQPs that are now in the public and private sectors across Canada and the globe.

SIMTReC aims to continue forming effective partnerships and establishing collaborations through its resource centre by acting as a knowledge broker between academia and the private and public sectors. The future is bright for SIMTReC and the myriad applications of FRPs and SHM to address Canada's new and existing infrastructure needs.

Appendix 1. Linking impacts and research



Appendix 2. Interview questions

Interview questions with past or present members of SIMTReC

1. Was there an industry for FRP and SHMs? If no, when did FRP and SHMs start being used in the infrastructure sector? If yes, what was the size of the industry in Manitoba, and Canada?
2. At the time that SIMTReC was established, what kinds of research were being conducted on FRP and SHM/ sensing technologies?
3. Why was SIMTReC established?
4. How did SIMTReC start?
5. Who started and helped develop SIMTReC?
6. Were there any (integral) partnerships that help developed SIMTReC?
7. What funding was provided to SIMTReC research projects?
8. Who did the research team partner with locally, national, and internationally?
9. What research infrastructure/technical support was required and provided by governmental or private organizations?
10. What are the research projects that can be linked to the impacts we are highlighting? For instance, building capacity, economic impacts, innovative products, influence on codes and policy
11. How were these projects initiated? Were these projects initiated by industry or SIMTReC?
12. What collaborations and partnerships resulted from the research projects?
13. How many publications have been produced as a result of the research projects?
14. Has there been any pilot projects/ demonstrations done as a result of the research projects?
15. Who are the champions of this research program?
16. What role did they play in developing this research program?
17. What role did they play in the uptake of findings by knowledge users?
18. What are educational modules and who were they created for?
19. What media engagements were utilized to disseminate the research results?
20. Were there meetings with policy and building codes decision makers?
21. What other activities helped move the research findings/discoveries to practical applications?
22. Where there any consortiums and/or networks established through this project?
23. How many HQPs were involved?
24. What is SIMTReC's contribution to the Faculty of Engineering and the University?
25. Did the research project attract research talent to Winnipeg?
26. Has this research program led to an impact in teaching?
27. What additional resources (funding, expertise, infra) has been leveraged by SIMTReC in and outside Manitoba?
28. What impact has the research projects on government policies/regulations/building codes?
29. What has been the impact of SIMTReC's influence on building codes/policies?
30. What products and innovations were developed as a result of SIMTReC research?
31. What has been the impact on the industry since their release to market? How have these products impacted the industry since there release?
32. Were there any spin-off companies from SIMTReC?
33. What patents and licensing has been established since the inception of SIMTReC?
34. Has there been any jobs created as a result of SIMTReC and the research?
35. Are there any other ways that SIMTReC has influenced industry and government?
36. What are some future applications of the FRPs, SHM, sensing technologies, and other products?
37. What are the future research and organizational goals of SIMTReC?

Interview questions with participants from the University of Manitoba

1. How long have you known about SIMTReC?
2. Could you describe how SIMTReC and the U of M work together?
3. How has the relationships been between the U of M and SIMTReC developed over time?
4. How much funding/other forms of support has SIMTReC received from the U of M?
5. Is the U of M looking to support SIMTReC in the future?
6. What value does SIMTReC provide to the U of M? (staff and students and U of M as an institution) and Manitoba?
7. What kind of value does SIMTReC provide outside of the U of M?
8. Is the network approach of SIMTReC unique?
9. What do you think the future directions and potential application is for SIMTReC's research?

Interview questions with participants from the private sector

1. Could you tell me a little about your current position?
2. How long have you known/worked with SIMTReC?
3. Were you involved in any demonstration projects? If so, which ones.
4. What is the existing need/demand in Manitoba (Canada?) for new infrastructure or infrastructure repairs?
5. How are FRPs and SHM utilized in Manitoba to address the needs of Manitoba infrastructure? Needs of Canada?
6. What value does FRPs and SHM provide? What are the applications of FRPs and SHM that Manitoba (government) finds important/practical/ valuable/useful? In own position/job?
7. What role do you believe the government plays in supporting innovative research? I'd like this to be more specific to SIMTReC so I suggest "What role do you believe the government plays in supporting SIMTReC's research and the uptake of discoveries?"
8. As a public official for MB infrastructure, what barriers to innovative products like FRPs and SHM need to be addressed to be utilized?
9. What do you think are the future research directions/areas and applications of SHM? Of FRPs?

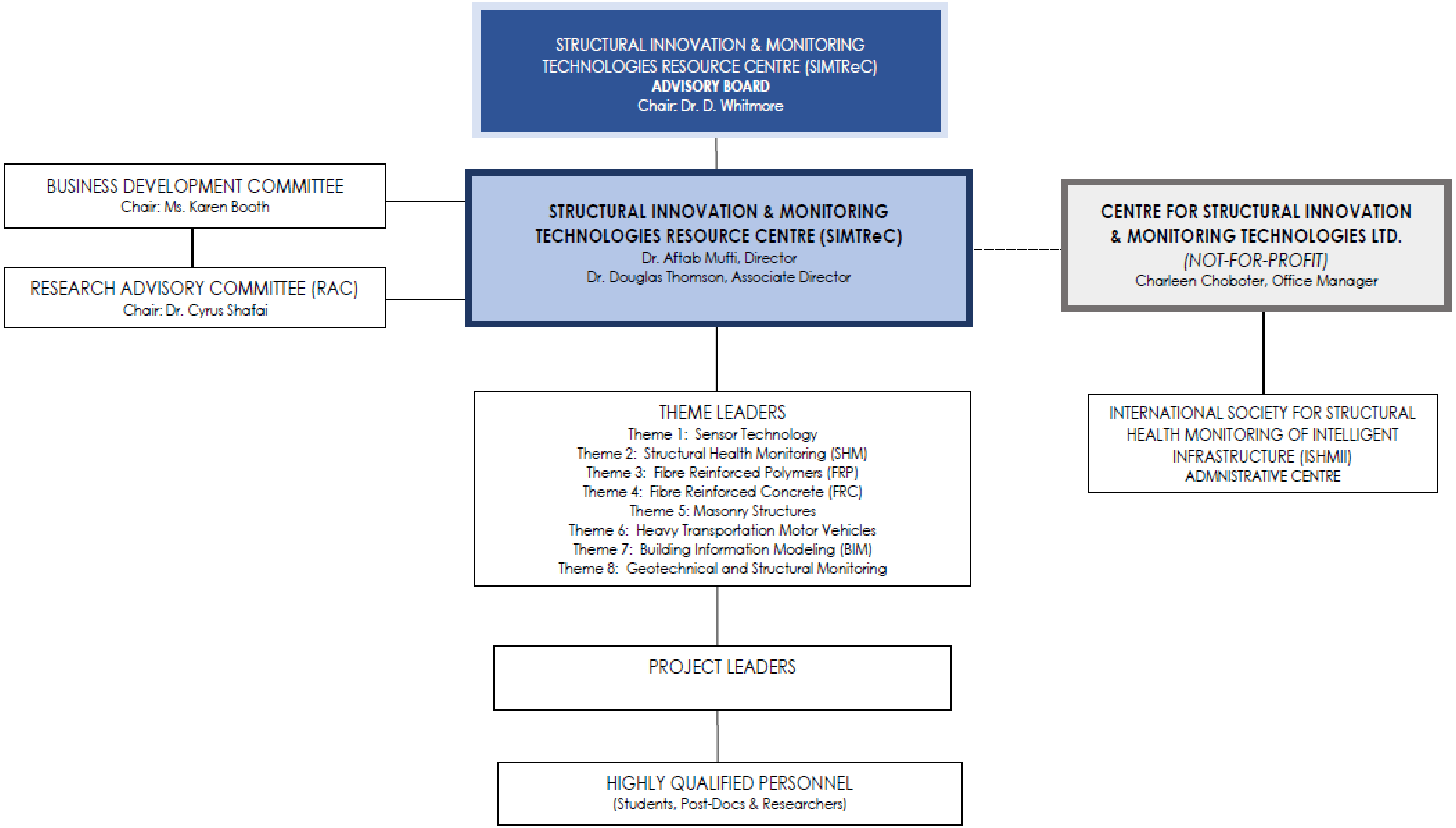
Interview questions with participants from the public sector

1. Could you tell me a little about your current position?
2. How long have you known/worked with SIMTReC?
3. Were you involved in any projects with SIMTReC? If so, which ones.
4. What about FRPs/SHM technology are you using/selling/developed into a product in your company?
5. How are FRPs and SHM utilized in the projects that you have mentioned?
6. Job creation because of FRPs/SHM – own company, industry
7. Sales of company/industry because of FRPs/SHM
8. What is the current relationship between your company and SIMTReC? What should be done to enhance this relationship?
9. What barriers to innovative products like FRPs and SHM need to be addressed for their continued growth?
10. What do you think are the future research directions/areas and applications of SHM? Of FRPs?
11. What is the size of the industry using FRPs/SHM?
12. How many private companies in MB/Canada are selling/marketing FRPs/SHM related products/ technologies?
13. How many FRPs/SHM related products/technologies are in the market?
14. Is the Manitoba industry/private sector a leader in bringing FRPs/SHM technologies in the market?

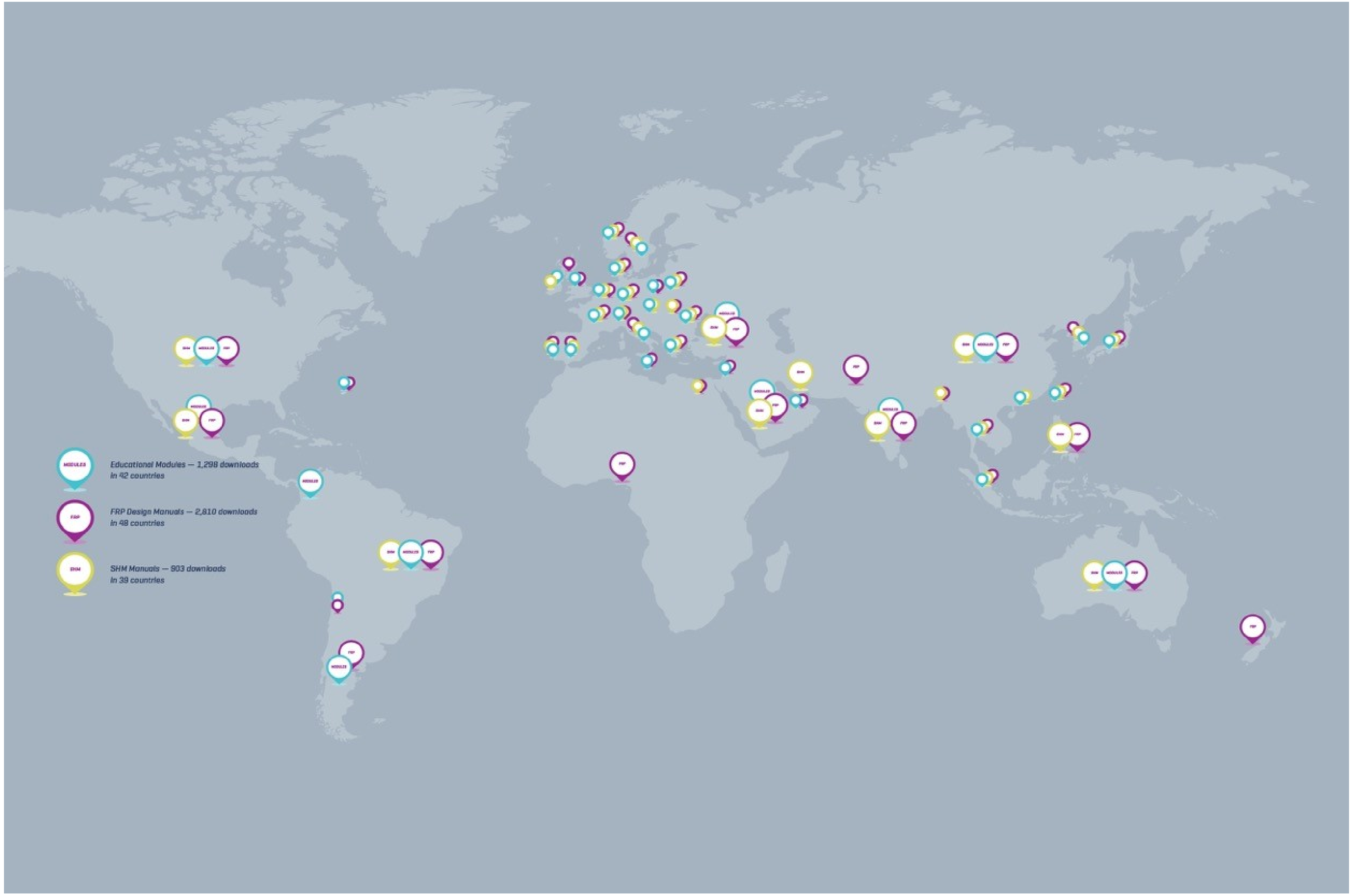
Appendix 3. List of persons interviewed

Name	Affiliation
Dr. Aftab Mufti	Past SIMTReC President / Current SIMTReC Director
Dr. Baidar Bakht	Part / Current SIMTReC consultant / Research Advisory Committee Member
Dr. Dagmar Svecova	Former SIMTReC Director
Lloyd McGinnis	Former SIMTReC CEO
Dr. Sami Rizkalla	Former SIMTReC Scientific Director
Andy Horosko	Former Deputy Minister, Manitoba Infrastructure, Current Research Liaison, SIMTReC
Evangeline Murison	Former SIMTReC graduate and project leader / Current Structures Research, Materials and Standards Engineer with Manitoba Infrastructure and Transportation
Dr. Farhad Ansari	University of Illinois Associate Vice Chancellor for Research
Doug McMahon	Assistant Deputy Minister Water Management and Structures Division Manitoba Infrastructure and Transportation
Ruth Eden	Former SIMTReC graduate and project leader / Current Executive Director of Structures at Manitoba Infrastructure and Transportation
Gamal Mustapha	Vice President of Program Management, SMT Research Ltd
Garth Fallis	Vice President at Vector Construction Group
Emile Shehata	Former SIMTReC graduate / Senior Vice President Infrastructure and Environmental at Tetra Tech
Dr. Joanne Keselman	Former University of Manitoba Vice President of Research and SIMTReC Board Member
Dr. Digvir Jayas	Current University of Manitoba Vice President Research

Appendix 4. SIMTReC's organizational chart

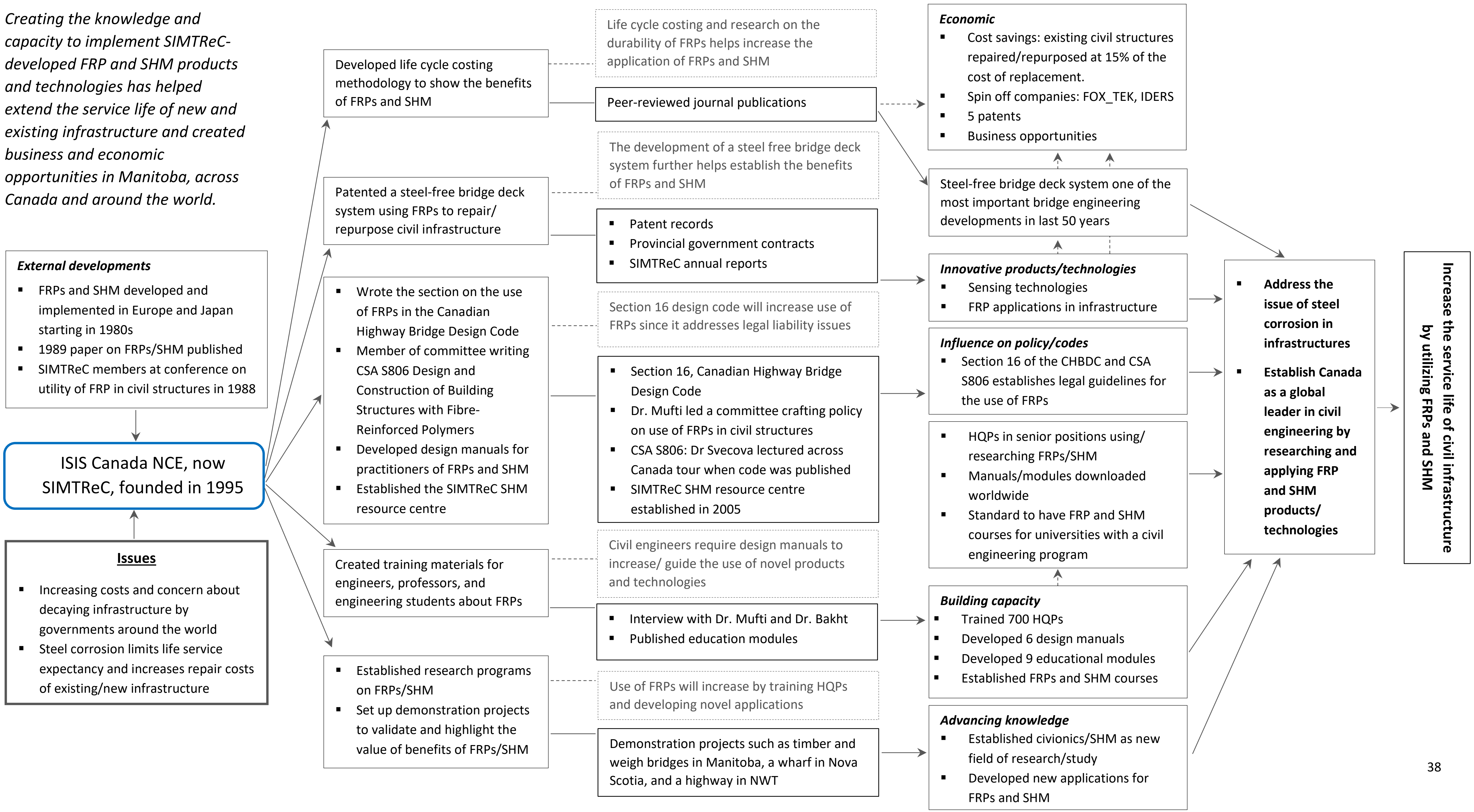


Appendix 5. Global downloads of SIMTReC education modules and design manuals



Appendix 6. SIMTReC theory of change

Creating the knowledge and capacity to implement SIMTReC-developed FRP and SHM products and technologies has helped extend the service life of new and existing infrastructure and created business and economic opportunities in Manitoba, across Canada and around the world.



External developments

- FRPs and SHM developed and implemented in Europe and Japan starting in 1980s
- 1989 paper on FRPs/SHM published
- SIMTReC members at conference on utility of FRP in civil structures in 1988

ISIS Canada NCE, now SIMTReC, founded in 1995

Issues

- Increasing costs and concern about decaying infrastructure by governments around the world
- Steel corrosion limits life service expectancy and increases repair costs of existing/new infrastructure

Research activities

Developed life cycle costing methodology to show the benefits of FRPs and SHM

Patented a steel-free bridge deck system using FRPs to repair/ repurpose civil infrastructure

- Wrote the section on the use of FRPs in the Canadian Highway Bridge Design Code
- Member of committee writing CSA S806 Design and Construction of Building Structures with Fibre-Reinforced Polymers
- Developed design manuals for practitioners of FRPs and SHM
- Established the SIMTReC SHM resource centre

Created training materials for engineers, professors, and engineering students about FRPs

- Established research programs on FRPs/SHM
- Set up demonstration projects to validate and highlight the value of benefits of FRPs/SHM

Evidence/Assumptions

Life cycle costing and research on the durability of FRPs helps increase the application of FRPs and SHM

Peer-reviewed journal publications

The development of a steel free bridge deck system further helps establish the benefits of FRPs and SHM

- Patent records
- Provincial government contracts
- SIMTReC annual reports

Section 16 design code will increase use of FRPs since it addresses legal liability issues

- Section 16, Canadian Highway Bridge Design Code
- Dr. Mufti led a committee crafting policy on use of FRPs in civil structures
- CSA S806: Dr Svecova lectured across Canada tour when code was published
- SIMTReC SHM resource centre established in 2005

Civil engineers require design manuals to increase/ guide the use of novel products and technologies

- Interview with Dr. Mufti and Dr. Bakht
- Published education modules

Use of FRPs will increase by training HQPs and developing novel applications

Demonstration projects such as timber and weigh bridges in Manitoba, a wharf in Nova Scotia, and a highway in NWT

Outputs and Outcomes

Economic

- Cost savings: existing civil structures repaired/repurposed at 15% of the cost of replacement.
- Spin off companies: FOX_TEK, IDERS
- 5 patents
- Business opportunities

Steel-free bridge deck system one of the most important bridge engineering developments in last 50 years

Innovative products/technologies

- Sensing technologies
- FRP applications in infrastructure

Influence on policy/codes

- Section 16 of the CHBDC and CSA S806 establishes legal guidelines for the use of FRPs

- HQPs in senior positions using/ researching FRPs/SHM
- Manuals/modules downloaded worldwide
- Standard to have FRP and SHM courses for universities with a civil engineering program

Building capacity

- Trained 700 HQPs
- Developed 6 design manuals
- Developed 9 educational modules
- Established FRPs and SHM courses

Advancing knowledge

- Established civionics/SHM as new field of research/study
- Developed new applications for FRPs and SHM

- **Address the issue of steel corrosion in infrastructures**
- **Establish Canada as a global leader in civil engineering by researching and applying FRP and SHM products/ technologies**

Increase the service life of civil infrastructure by utilizing FRPs and SHM

Endnotes

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[1] Assessing Canada's Infrastructure Needs: A Review of Key Studies – Research and Analysis Infrastructure Canada 2004, p.3

[2] Canadian Civil Engineering, 1989

[3] American Composites Manufacturing Association, 2016

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