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Risks Associated With New Materials

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1 Introduction

New materials and technologies help to increase energy efficiency, improve the quality of life and the impact on the environment as well as bring down the costs of construction and operation.

New materials are being developed and implemented quicker than ever before as a result of new technologies such as computer-aided generative manufacturing processes and 3D printing. Start-up companies in the construction sector have raised a significant amount of capital over the past few years. According to CB Insights, more than 400 construction-tech firms have formed since 2009, raising USD 2.9 billion in funding [1]. A large share of these investments relate to new materials and technologies (*Figure 1*)

Figure 1: Segments of the concentric circle pie chart refer to share of the total number of start-up investments in that field. Figures in brackets refer to the corresponding number of deals [1]

When successful, new materials and products they can provide enormous benefits to society but with anything new the risk of failures is higher than for something that have been tested and applied for decades. Besides the higher risk of triggering serial losses during construction/ erection, the long- term behavior of the materials and interactions with the operating environment (e.g. exposure to other components, temperature and pressure changes, operational cycles and parameters) are unlikely to be fully understood.

According to Allianz Global Corporate & Specialty (AGCS) analysis of 13,599 insurance industry Engineering claims between July 2013 and July 2018, defective products and faulty workmanship account for more than a third (36%) of all engineering claims. The major cause of these losses are: collapse of building/structure/subsidence due to faulty work; failed or injurious treatment by a practitioner; damage caused by scaffolding/building materials on the highway; wrong design, calculation; breaching a work contract [2]. The risks associated with new materials and products therefore demands attention from the insurance industry.

This working group paper will focus on the categories of new materials and technologies seen in the engineering sector, the associated risks for the insurance industry and how these risks can be managed through the underwriting process.

2 What are new materials?

It is first important to consider what we mean by "new materials" and "new technologies". When discussing the term in this paper, we use materials which fall within the following four categories:

1) Newly developed materials of existing material classes or the combination of known materials

   For example:
   - new metallic alloys for increased strength, increased creep, corrosion or oxidation resistance, resistance against chemicals or radiation
     - Advantages: Higher operating temperatures and pressures with resulting higher process efficiency, longer part lifetime, enabler for new processes
     - Applications: Such materials are often seen in the area of power generation, used for turbine disks, turbine blades or coatings
   - hybrid materials, which are a combination of different materials either as matrix or sandwich to leverage the positive properties of the components. Examples include fibre reinforced composites such as plastic fibre composites, Metal Matrix Composite (MMC), Ceramic Matrix Composits (CMC) or Cermets
     - Advantages: Low density with high stiffness, high temperature resistance without cooling, resistant against Lightning Strike
     - Applications: Vehicles or aircrafts, wind turbines for higher power output through large rotor diameter and light turbine blades
   - new insulation gasses, replacing existing insulation gases with high green house gas potential
   - superconducting materials for power transmission with reduced losses

2) Materials of new material classes

   For example:
   - carbon nano tubes. These have low density and high mechanical strength, low thermal expansion and good electrical conductivity
   - adaptive and intelligent materials that change their mechanical and electrical properties resulting from changes of temperature, pressure or electrical field to applied in actuators, engines or sensors piezo elements
   - materials with specific capabilities like phase change materials (PCM) self-healing materials, biodegradable materials, materials with modifications in the atomic or microscopic scale for specific applications

3) Known materials not used before for the purpose, the character or the ambient conditions of the specific construction project

   For example the use of ester fluids as transformer dielectric fluid, which have different chemical and physical properties than the mineral oil they replace.

4) Materials of known chemical composition, but produced in a new way

   For example by additive manufacturing (AM). Additive Manufacturing or 3D printing is a process that builds parts layer-by-layer from sliced CAD models to form solid objects. It may change the material properties due to different microscopic structure, compared to long established material characteristic. Smaller dimensions, together with different surface properties like roughness or size accuracy compared to conventional production methods may change the behavior of AM parts, for example the heat transfer parameters. Additive Manufacturing is already used in gas turbines, aerospace, the automotive industry and motorsport.

Figure 2: Additive manufactured Gasturbine components [3]

Although they may bring technological and cost advantages, there are undoubtedly risks associated with the application of new materials and technologies in engineering projects. We consider below a few of the high level risks that often emerge from the use of new technologies:

1) **New materials having challenges in planned modification issues**

   These are materials that need to be machined (cut, drilled, abraded etc), welded or jointed by other methods, heat treated or coated during a construction project. Materials always need detailed modification instructions like welding procedure specifications (WPS) including post weld heat treatment instructions. Such instructions may not be properly validated yet with new materials or the required equipment for doing this work is not available.

   Examples: Welding of new materials for membrane walls, composite materials

2) **New materials being susceptible to ambient conditions**

   New materials may be susceptible to environmental conditions during storage, before being put in service or later after having been put into operation. Possible contributors are humidity, temperature, temperature changes, air pollution or combinations of these factors. Consequences that may arise are corrosion, erosion, change of material properties e.g. by the ambient temperature or the activation of the material, increasing its susceptibility to complex failure mechanisms like various forms of stress corrosion cracking later during commissioning or operation. This susceptibility may not be known when new materials are introduced, but manifest only later when they come into operation.

   Materials must be selected carefully for the environment they will operate in, and storage, preservation, protection and initial operation instructions must be carefully followed.

   Examples: Metallic alloys used in power plants, polymers and fibres used for wind turbine blades. Ester filled transformers at low ambient temperatures.

3) **New materials being susceptible to handling issues**

   As with susceptibility to ambient conditions, handling conditions may affect a material, for example by exceeding plastic deformation limits, inducing rapid changes in temperature or introducing stress that may be a contributor to later stress corrosion cracking.

Handling, transport, lifting or activities must be carefully assessed and monitored. If required, temporary measures must be used – for example support structures

Examples: Metallic alloys used in membrane walls, large structures like wind turbine blades, superconducting cables.

4) **New materials having an unexpected behavior during commissioning and initial operation**

New materials may be an internal part of a larger structure like machinery. When this machinery is put into service, these "black boxed" materials may show unexpected behavior like premature cracking, corrosion, erosion, oxidation, creep, loss of bonding or complex failure modes like stress corrosion cracking or stress assisted grain boundary oxidation. Furthermore, such materials may show deviations from predicted properties like strength, vibrational behavior, heat transfer capabilities, electrical or mechanical load carrying capabilities.

These risks can be partially controlled by the selection of proven equipment designs and machinery, together with strict compliance to storage, handling, installation and operation instructions as well as long term tests and validations.

Examples: New turbine blade materials prematurely failing, gas turbine thermal barrier coating spallation, materials produced in new production processes like additive manufacturing.

3 Examples of new materials

We consider below in more detail how certain new materials and new technologies are being used in the civil engineering industry.

3.1 New Materials

Cement

Cement is one of the most manufactured materials in the world. The cement industry is also responsible for up to 7% of the world's carbon dioxide (CO_2) emissions, according to think tank Chatham House.

Due to the impact of CO_2 on global warming, low carbon cements have gained more attention and many companies are working on new mixtures to improve the environmental footprint.

Hoffmann Green cement has developed a cement which is based on alkaline-activated clay and silicate. According to the company this cement will reduce the carbon footprint by approx. 80% compared to conventional cement at the same or higher levels of performance [4].

Solidia cement delivers a CO_2 cured concrete instead of water and contribute to the reduction of CO_2 emissions. Furthermore, it requires less energy. The company estimates the reduction of the greenhouse gas during the manufacture by up to 40%.

Other industrial byproducts such as ground granulated blast-furnace slag or pulverized fuel ash waste from agricultural processes such as rice husk ash, will also be mixed in the concrete to reduce the consumption of cement and thus to improve the environmental footprint [5].

Another innovative development relates to self-healing cement. Cement structures can experience a crack which let water enter into the concrete. Often it results in corrosion of the steel structures inside the concrete. Materials scientists developed a concrete with a mix of bacterial spores in small, water-permeable capsules which can be mixed into wet concrete. Once the concrete sets and dries, the spores remain in suspended animation. When a crack opens the concrete and with entering water, the spores begin to grow and produce calcite, a crystalline form of calcium carbonate found in marble and limestone. The calcite fills the cracks in the concrete and hardens, preventing the crack from getting any wider. Self-healing concrete can improve the lifecycle of buildings, tunnels, bridges, and other structures without significant repairs or replacement [6].

Waste Material

Waste causes major problem for the environment due to land, water and air pollution. Waste organic and inorganic materials are used in construction field to prevent waste from being deployed for landfill and incineration. Waste can be applied in the construction industry in two ways: by reusing (reuse components) and recycling (processing waste into raw materials used in the production of building materials).

Increasing use of organic waste in construction will decrease the consumption of raw materials and enable the development of a new business field. Over 100 companies around the world are delivering building products from industrial, agricultural or food waste — ranging from interior partitions and finishes to insulation materials, furniture, and cladding. Waste materials such as plastics and disposed tires are also used to reinforce asphalt mixes for highways.

The influence of the additives on properties of the concrete such as bulk density, flexural strength, compressive strength and water absorption has been researched. Additives such as plastic raw materials have a significant influence on the properties of the cement concrete, which depends upon the type of additive and the amount of the mixture. Plastic decreases the bulk density, and consequently reduces the weight of the products [5].

Bricks

New type of bricks has been developed and tested to clean polluted air. The so called the breathe bricks on the outside of the building clean pollutants from the air prior to entering the building. A cyclone filtration, which works like a modern vacuum cleaner, cleans the heavy pollutant particles from the air and drops them into a removable hopper at the base of the wall. Wind tunnel tests showed that this system is capable 30% of fine particles from the air and 100% of coarse particles such as dust [7].

The Institute of Advanced Architecture of Catalonia designed a new bricks that has a cooling effect on building interiors. They applied a combination of clay and hydrogel (Hydroceramic) to create a cooling effect that results from the introduced the hydrogel in the structure. It absorbs water that is released to reduce the temperature during hot days leading to reduction indoor temperature by 6 degrees Celsius. [https://materialdistrict.com/article/the-cool-brick/]

Figure 3: Cooling system in bricks [8]

The market acceptance of these new materials will depend on aspects such as reliable technical performance, standards and regulations. In order to increase the feasibility and reduce resulting exposures for the insurance industry independent long-term testing and validation of the durability as well as certifications need to be conducted thoroughly.

3.2 New Technologies in Buildings

In the last decades there has been a trend towards simplified as well as cost and time effective construction technologies for building.

Modular construction

Modular construction is a form of off-site construction in which a building’s components, or modules, are produced in a factory followed by the transportation to the site for assembly into a larger building. All works are carried out sequentially and on-site, which enables adjustments to design and construction during the works. In comparison to standard prefabricated building parts, modular construction features the construction of full rooms or units, which are completed upon arrival at the construction site.

In the last few years, modular construction is facing a new wave of attention and investment, and several factors suggest it may have renewed staying power. The maturing of digital tools has radically changed the modular-construction proposition — for instance, by facilitating the design of modules and optimizing delivery logistics [9].

According to the Modular Building Institute, modular construction is expected to rise to 5% of all new commercial construction in North America by 2021 [10].

Figure 4: An example of Modular Construction [11]

Despite many advantages such as better-quality control in factory environment, reduced space demand and costs as well as time savings, modular construction raises certain legal questions. One legal question is whether the producing company of the individual units is regarded a manufacturer of goods or if it appears as a subcontractor, which in turn defines the legal liability. Further issues may arise from transportation risk from the factory to the construction site as well as insolvency risk of the producer which cannot be substituted by another company as is the case for traditional subcontractors. Another major critical issue is the susceptibility to serial loss. The proper risk management in the entire production until the construction process is indispensable.

3D printing

In the construction industry, 3D printing can be used to produce construction parts or even to 'print' entire buildings. Construction is well-suited to 3D printing as much of the information necessary to create an item will exist as a result of the design process, and the industry is already experienced in computer aided manufacturing. The recent emergence of building information modelling (BIM) in particular may facilitate greater use of 3D printing.

Construction 3D printing may allow, faster and more accurate construction of complex or bespoke items as well as lowering labour costs and producing less waste. It might also enable construction to be undertaken in harsh or dangerous environments not suitable for a human workforce, such as in space [12].

Figure 5: An application of 3D Printing [13]

Major concerns regarding 3D prints are discussed in section 3.3.1.2.

3.3 New Technologies in Infrastructure projects

In the last years there have been major developments in the technologies of infrastructure projects. We consider below some of the most significant such developments.

3.3.1 Bridges

Over the past 50 years, many innovative construction methods have been evolved to reduce traffic impact, facilitate building in congested areas, reduce overall construction schedules, and improve the long-term service life of structures.

The most significant shift, however, is the move towards mechanized construction which saves labour, shortens project duration and improves quality.

During recent years, contractors have developed the so called "segmental construction" process. The segmental technology approach is becoming a proven method for delivering durable structures that are both cost-effective and visually appealing.

Segmental construction is often considered when one or more of the following conditions exist:

- The bridge is long and/or tall, and there is a potential for repetitive construction details.
- Construction access is very limited and/or traffic disruptions are unacceptable.
- Aesthetics play a significant role in the project

Together with improved modern IT technologies the market had successfully implemented bridge quality best practices and quality control management.

The recent spread of BIM design for bridges (so called "BrIM" Bridge Information Modeling) provides a complete representation of the physical and functional characteristics of a bridge asset, offering an information resource for its entire lifecycle.

This design tool boosts the quality of design with accurate information, consistent documentation, and improved constructability of structures. BrIM allows for accurate pre-fabrication and just-in-time material deliveries and supports project collaboration across disciplines.

Furthermore, new generation bridge construction equipment technologies are becoming more and more complex and delicate.

There are six basic modern bridge forms: the beam, the truss, the arch, the cantilever, the cable-stayed, and the suspension.

Today the longest spans in the world are suspended (the longest main spans are the Akashi Kaikyo Bridge, Hyogo, Japan, 1,990 m). Combination spans are often used to bridge even longer stretches of water: San Francisco–Oakland Bay Bridge, noted for its three long spans, of which two are traditional suspension spans and the third a self-anchored single-tower suspension, has a total length of 13.2 km.

Apart from this "consolidated" technology trends, in the next part of this paper we consider three specific new technologies in more detail:

- Floating bridges evolution
- 3D printed bridge
- Ultra-High-Performance Concrete material

3.3.1.1 Floating bridges evolution

Although this cannot be considered a brand-new technology (the oldest concrete pontoon bridge, the Lacey Murrow Memorial Bridge, was completed in 1940) during recent years there have been a number of new projects, particularly in Norway and the Seattle area, which have pushed the limits of the technology.

In Seattle the designers are introducing a brand-new technical innovation: the first rails on a floating bridge. This floating light rail corridor will link Seattle to the city of Bellevue on the east side of Lake Washington by 2023. Many tests have been conducted to adapt the structure to the movement of the train on the bridge. That is feasible because the track ties on each platform rest on pairs of flexing bearings (similar to seismic dampers).

As the floating bridge moves, the flexible parts within the platform should pivot only one-half of a degree. As a result, the rail moves with the changing lake and bridge conditions.

Another ambitious project is the floating bridge concept for crossing the Bjornafjorden in Norway: more than 5.5 km of floating bridge.

The deep fjords in Norway makes it extremely costly to place a pylon in the center, as this pylon would need to be the same size as a skyscraper. The solution proposed is to utilise know-how from the offshore oil and gas industry and replace the ground-based pylon with floating pontoons.

Figure 6: Floating Bridge [15]

Lesson learned from previous incidents puts the attention on two main aspects: design and maintenance activities.

Winds and waves exert significant forces on a floating structure, and these environmental loads are difficult over the long term.

Maintenance plans are fundamental: water leaking into the interior of a floating bridge can cause progressive failure, eventually sinking the bridge. Maintenance personnel must respond to damage of a floating bridge quickly, especially when water begins to leak into the structure. Negligence in the implementation of preventive measures could also be a critical insurance issue.

Another significant challenge is at the hinges that join the floating and fixed sections of the bridge together. Below the deck, pontoons are linked together, and steel cables anchor them to the lakebed, which helps reduce violent movement during strong winds and fierce waves.

Floating bridges require more maintenance than their fixed equivalents, and usually the joints will experience a larger degree of movements since the bridge is floating. The movements will cause more wear and tear of the joints during normal operation.

A "wear and tear" exclusion is highly recommended for these kinds of insured civil items. There is also a risk of accidental pollution from caissons or from the road, which raises liability issues.

3.3.1.2 3D printed bridge

Constructing roads and bridges using 3D printers is already happening. In 2017, two 3D printed bridges were installed: one was a pedestrian bridge in Madrid, and the other was a cyclist bridge in the Netherlands. There are numerous benefits, such as the elimination of waste since the printer uses the precise amount of cement required.

3D printers have been developed which are tailored to the construction industry to work almost like robots. For example, in the case of steel structures, a 3D printer/robot can print a small section of steel using metallic powders in a process known as direct metal laser. The result is an entirely new structure constructed wholly by the 3D printer.

The use of 3D printers in the construction industry will have legal implications that will affect owners, contractors, manufacturers and software developers.

Innovation and disruptive technology bring new legal risks and implications. In the context of construction defects claims, 3D printers will expose manufacturers and developers to liability and claims that would normally be attributed to human error.

Instead of human workers building a structure, a 3D printer will manufacture it according to a pre-generated plan which is uploaded to the printer. Whether the 3D printer is owned by the contractor, is being leased as equipment or is the equipment of a subcontractor may affect liability:

- If the defect is the result of the printer’s malfunction, the contractor will have warranty and indemnity claims against the manufacturer arising out of privity from purchasing or leasing the 3D printer.
- If the defect is the result of a software malfunction, that could open the developer to negligence and warranty claims for the value of the defects in the project at issue.
- If there is an independent technician, acting as a subcontractor, then they could also be open to liability if the defect was the result of improperly uploading the plans or operating the 3D printer.

3.3.1.3 Ultra-High Performance Concrete material

Ultra-high performance concrete (UHPC) is generally defined as concrete with a compressive strength greater than 150 MPa. UHPC typically is made with high-strength steel fibres, fine sand, cement, fly ash, a large volume of SF, and a low amount of water (a w/cm ratio less than 0.20).

While considerably more expensive than conventional concrete, UHPC is highly durable and provides excellent protection of embedded steel reinforcement. UHPC was used in several bridge projects in the US (first application was at the Mars Hill Bridge in Wapello County, Iowa, completed in 2006 – 33 m span bridge).

So far, implementation of UHPC in bridge structures has generally been in the form of pilot projects in which the design did not significantly deviate from conventional geometry and dimensions to take full advantage of the favorable behaviour and strength properties of the material.

The recent development of UHPC is based on advances in the materials science of cementitious materials, producing materials with improved mechanical and durability properties.

Nevertheless, a considerable effort is required to transfer and implement the knowledge gained at the material level in structural engineering and design. Aside from empirical approaches, based on large-scale testing of structures, recent progress in constitutive modeling of materials and model-based simulation can considerably contribute to attaining this goal.

The optimization of a design solution first requires the adoption of appropriate design criteria for UHPC structures subjected to a specific loading. In contrast to standard reinforced concrete design criteria, based primarily on maximum material strength criteria, UHPC must be based on a critical crack opening below which the material achieves capacity with high confidence.

UHPC was first used in bridges in 2006, but further work is required to move this from the "prototypical" category. For this reason, the design error (LEG 1) could be appropriate when UHPC material/technology is used.

3.3.2 Tunnels

The technology used in tunnels has also been developing quickly, and this will be discussed in the following section.

3.3.2.1 Immersed Tunnels

In recent years a number of immersed tunnel construction projects have been completed around the world.

Underwater tunnels can either be bored or immersed, with bored tunnels generally more expensive and therefore less frequently used.

Immersion tunnels involve dredging a trench across the seafloor, laying a foundation bed of sand or gravel, and then lowering precast concrete tunnel sections into the excavation and covering it with a protective layer of backfill several meters thick.

Figure 7: Immersed Bridge [16]

The precast concrete tunnel sections generally have a rectangular cross-section (rectangular shapes being more cost effective) containing separate passageways for cars and trains, together with a service passageway.

The final tunnel is made of separate elements, each prefabricated in a manageable length, the ends of which are sealed with bulkheads so they can be floated. The next stage is to place the elements into place, each towed to the final location, in most cases requiring some assistance to remain buoyant. Once in position, additional weight is used to sink the element into the final location, this being a critical stage to ensure each piece is aligned correctly. After being put into place, the joint between the new element and the tunnel is emptied of water then made watertight, this process continuing sequentially along the tunnel.

The trench is finally backfilled and any necessary protection, such as rock armour, added over the top. The ground beside each end tunnel element will often be reinforced, to permit a tunnel boring machine to drill the final links to the portals on land. After these stages the tunnel is complete, and the internal fit out can be carried out.

After the 2013 Marmaray Tunnel, connecting the European and Asian sides of Istanbul, Turkey (the world's deepest immersed tunnel at 55 m below sea level), the longest immersed tube tunnel is the 6.7 km tunnel portion of the Hong Kong–Zhuhai–Macau Bridge, completed in 2018. The Fehmarn Belt Fixed Link that is going to connect the Danish island of Lolland with the German island of Fehmarn, crossing the 18 km wide Fehmarn Belt in the Baltic Sea, will be becoming the world's longest road and rail tunnel.

Next generation technology could be **Submerged Floating Tunnel (SFT)** which is used to cross straits, large lakes or deep rivers. It generally consists of tunnel tube suspended in water, anchor cables fixing displacement of tunnel, deep water foundations and revetments connecting quayside. A typical submerged floating tunnel is shown in *Figure 8*.

Figure 8: Submerged floating tunnel [17]

The main advantage of an immersed tube is that it can be considerably more cost effective than alternative options (a bored tunnel beneath the water or a bridge). This is mainly because of the speed of construction, resistance to seismic activity and safety of construction (for example, work in a dry dock as opposed to boring beneath a river).

These construction risks have to be analyzed:

- Durability problems: the chloride ion in seawater is an important factor for the corrosion of steel and concrete especially once the crack occurs (the chloride ion will seriously damage steel bars, reduce load bearing capacity and shorten service life).
- External risks: immersed tunnels are often partly exposed (usually with some rock armour and natural siltation) on the river/seabed, risking a sunken ship/anchor strike;
- Serial losses: the segmental approach requires careful design of the connections (and careful waterproofing design around the joints) where longitudinal effects and forces must be transferred across
- TPL accidental pollution: environmental impact of tube and underwater embankment on existing channel/seabed has to be carefully considered.

3.3.2.2 Excavated Tunnels: TBM Next steps

Apart from the above-mentioned immersed tunnels projects (generally on the seabed), most of recent tunnel experience are involving the **Tunnel Boring Machines (TBM)** technology.

TBM technology is continually improving. For example, TBM manufacturers have developed methods for replacing cutting tools under atmospheric pressure, improving mixing of the muck within the chamber, addressing abrupt or large change in the face pressure across the height of the chamber, backfilling and lubricating the shield gap, and for rapidly filling the annular gap between the liner and the excavated ground.

Despite great progress observed in recent times, the construction of traffic (rail and road) tunnels with the TBM technique still faces significant challenges.

Contractors are facing new technical issues in recent projects due to the use of large diameter TBMs (approximately 17.5 m diameter) in order to reduce number of excavated tubes and with that the project costs.

In addition, designers have to take account of numerous safety regulations. Generally, in long rail tunnels (tunnels over 1 km in length) for safety reasons two separate tunnels have to be drilled, each for a direction of traffic, with a complex system of cross-passages connecting the two tubes.

In order to overcome the above limitations, A tunnel multi-gallery (TMG) and tunnel multi-floor (TMF) concepts, for TBM rail and road tunnels respectively, were recently developed.

The TMG Concept

The "**tunnel multi-gallery**" concept allows, with a single TBM tunnel, the creation of rail tunnels with completely independent directions of traffic and the installation of appropriate means that provide a dedicated and very reliable system for local access of the emergency personnel and the evacuation of users, in the event of an accident or fire inside the tunnel.

Figure 9: A sketch of T.M.G. Concept [18]

In the TMG concept, the tunnel is constituted by the external wall (1) made by the TBM, a slab (3), placed slightly above the bottom of the tunnel and the entire width, and a separating wall (2), placed in the middle of the tunnel and its entire height, so as to form two independent rail galleries, disposed side by side (4) (5), one for each track, and a service gallery (6) below.

In both sides of the tunnel, vertical access galleries (7), regularly spaced and provided with escape doors (8) in both rail galleries, are also created, allowing for the safe passage of people to the service gallery (6) in the event of an accident or fire inside the tunnel. Inside the service gallery (6), emergency vehicles (9) of monorail type are installed to provide local access to the emergency personnel and the evacuation of users to outside.

This tunnel concept will be constructed for an undersea train tunnel from Tallinn in Estonia to Helsinki in Finland.

The TMF Concept

The "**Tunnel Multi-Floor**" concept allows with a single TBM tunnel the creation of road tunnels with two identical road galleries, isolated and independent, and the installation of appropriate means that provide a dedicated and very reliable system for local access of the emergency personnel and the evacuation of users, in the event of an accident or fire inside the tunnel. The TMF concept is illustrated in following *Figure 10*.

In the TMF concept, the tunnel is constituted by the external wall (1) made by the TBM and two slabs (2) (3), built at its full width, one placed roughly at half the height of the tunnel and the other placed slightly over the bottom of the tunnel, so as to form two superimposed two road galleries (4) (5), one for each direction of traffic, and a service gallery (6) below.

Figure 10: A sketch of T.M.F Concept [19]

In one of the sides of the tunnel, vertical access galleries (7), regularly spaced and provided with escape doors (8) in both road galleries, are also created, allowing for the safe passage of people to the service gallery (6), in the event of an accident or fire inside the tunnel. Inside the service gallery (6), emergency vehicles (9) of monorail type are installed, to provide local access to the emergency personnel and the evacuation of users to outside.

From a technical point of view, some critical aspect in the TMG / TMF concept, should be the erection of the slab of the traffic separations walls/slab inside the "external TBM wall".

Generally, when using a large TBM it should be always be borne in mind that if poor design result in failure, no changes can easily be made to the machine (or project) once the construction has started. So it is essential to have a precise and timely knowledge of the characteristics of the ground to be drilled.

3.3.2.3 TBM & Tunnel Equipment Evolution

This section will consider other recent technological improvements which have been made to increase the practicality of TBMs.

A-TBM: Autonomous Tunnel Boring Machine

The inexorable rise of autonomy in modern machines has disrupted many industries, from transport to manufacturing, leading to a new revolution called Industry 4.0. Riding on this wave of technology, the tunneling industry has developed the Autonomous Tunnel Boring Machine (A-TBM).

The system is based on custom artificial intelligence control algorithms analyzing machine data in real time and assuming control of the various operational subsystems of the TBM with minimal human input. Sensor fusion is coupled with autonomous control algorithms (ACAs) to steer and operate the A-TBMs with minimal human intervention.

The potential for autonomous control of these functions has been available in the past. The difference is the possibility to gather the tremendous volumes of data from monitoring sensors, adding that to the capabilities of modern computing and big data management systems, applying the data to machine learning and the development of artificial intelligence, and bringing this all together in real-world TBM operations.

Defining and assigning liability will be more challenging for (re)insurers due to grey areas on who is liable when a technology fails and an accident occurs.

As manufacturing becomes more technologically advanced, challenges will arise on assessing liabilities, D&O covers and policy wording. For example, claims may be filed against not just manufacturers but also the companies providing their manufacturing technologies.

FULL ELECTRIC TBM

Elon Musk, owner of Tesla and SpaceX, has also entered the tunneling industry with his futuristic view of Hyperloop technology, a future mass transportation concept, which could carry passengers in a pod through a high-speed vacuum tunnel. In this challenging context the Musk company called "The Boring Company (TBC)" completed and deployed its custom-designed tunnel boring machine - a fully electric, zero emission TBM.

One of the most interesting innovations in the sector relates to constructing the tunnel using all-electric tunneling equipment, including an all-electric segment liner truck (formerly an all-electric locomotive), resulting in a cleaner tunnel with simpler ventilation requirements due to the lack of diesel fumes.

The latest generation TBMs, in addition to all-electric tunnelling equipment, have incorporated the following design changes and modifications:

- Surface launch and proposing: Launching the TBM directly from the surface eliminates the need to excavate a TBM launch pit, which is expensive and slow.
- Continuous mining: Installing the tunnel's precast segments simultaneously with mining eliminates the need to stop the TBM every five feet (these stoppages are standard on soft-soil TBMs).
- Tripling the TBM's power: Combining tripling the machine's power output with the appropriate upgrades in cooling systems.
- Eliminating rail: Utilizing rubber-wheeled segment trucks instead of traditional rail-based locomotives. This eliminates the time-consuming rail installation and maintenance, along with certain safety hazards, such as derails.

The Boring Company has now focused its efforts on its first public tunnel. The $52.5 million public transport system runs two miles and is designed to transport people from the West Hall of the Las Vegas Convention Center to the South Hall.

Currently, an there is no evidence on the detailed technology used to build this TBM, however the insurance on this CPE has to be considered as prototypical.

SBM: SHAFT BORING MACHINE

Used to excavate deep deposits safely, economically, and above all quickly, Herrenknecht engineers have developed the Shaft Boring Machine (SBM). A highly mechanized machine has been designed for full-bottom shaft sinking to depths of up to 2,000 meters and for diameters of up to 12 meters in stable consolidated rock.

When developing the new SBM, whose design resembles a conventional tunnel boring machine, some fundamental differences in comparison to horizontal tunneling had to be considered. A major challenge was collecting the rubble from the shaft bottom and transporting it vertically through the machine to the point of transfer to the shaft conveyor. The solution: the cutting wheel was positioned vertically.

Figure 11: SBM Head [20]

Excavation of the rock takes place in two consecutive steps. In the first step, the cutting wheel penetrates vertically into the rock, creating a 1.5 meter deep cut. In the second step, it rotates 180° around the vertical machine axis to cut out the entire shaft profile. The cutting wheel not only loosens the rock, it also works in a similar way to a bucket wheel for collecting the muck. The rubble is directed to the centre via integrated muck chutes. There, the material is transferred to a vertical conveyor, which transports it to the transfer point at the shaft conveyor.

3.3.2.4 Other Improvements in Tunneling Technologies

Several innovative businesses are working with new materials to provide tunnel owners with different options during the construction phase.

FIBRE REINFORCED CONCRETE PRECAST LINING

The present market trend in tunnel construction is to use steel fibres as reinforcement of concrete (FRC) segments, replacing the conventional use of rebars due to easier production and higher performance. Current guidelines and design standards allow using different methods for analyzing FRC segments, ranging from simplified equations to advanced FE models.

EXPANDED CLAY SOFT FILLING

In current design practice, overstressing in the final lining is expected when the surrounding rock mass presents either poor mechanical parameters or particularly high cover. When mechanized excavation with shield TBM is selected, one possible countermeasure for this problem can be the implementation of a compressible filling for the annular gap.

During the Brenner Base Tunnel the application of expanded clay was investigated. Due to its mechanical properties this material provides an effective support during segment erection, keeping under control long term rock mass pressures.

RUBBER GASKETS DEVELOPMENTS

Other recent innovation in the gasket design is the use of fibre anchorage technology with the elimination of footed legs in anchored gaskets and application of plastic fibres as anchoring element.

This new technology, similar to regular anchored gasket system, offers an additional pull-out resistance compared to the conventional glued gasket system. In addition, it provide several advantages over anchored gasket including: easier handling, improving the fixation in longitudinal direction, reduced risk of spalling, no possibility of wrong installation (anchored feet up or down), more economic packaging, easier repair procedure because of perfect groove bottom (no holes from the anchored feet) and no possibility for air entrapment in the anchorage area.

NEW MECHANICAL CUTTERS

Much effort is being devoted to improving current mechanical cutters search for entirely new rock-cutting methods (some nearing a pilot application), including high-pressure water jets, electron beam, flame jet (often combined with abrasive powder).

Other methods under research involve lasers and ultrasonic.

4 Considerations when insuring projects with new materials

4.1 Introduction

This chapter considers the effect on insurance coverage of insuring new materials and technologies. We focus on Construction All Risks (CAR) and Erection All Risks (EAR) policies and will refer to the standard Munich Re CAR/ EAR policy as a point of reference.

The use of new materials in construction and engineering can bring enormous and varied benefits to a project. For example, such materials might reduce project cost, reduce carbon footprint, allow for more innovative design or increase efficiency in the construction phase.

However, new materials also come with inherent risks for insurers. It goes without saying that any new product is, in general, at a higher risk of failure than a product that has been tried, tested and refined over decades. It is essential, therefore, that insurers carefully consider how their policies respond to defects when writing cover for projects which contain new materials.

4.2 Defect and Damage

CAR/ EAR policies are typically triggered by physical loss or physical damage. Insurance is not there to provide a guarantee of the efficacy of new products or materials, so if the product simply does not fulfil its intended purpose then that is unlikely on its own to trigger cover under the policy. However, there may be cover if the defect in the new material leads to physical damage – either to the defective material itself or to other elements of the property.

It is important, therefore, to understand the distinction between defect and damage.

The test for physical damage is not typically defined within the CAR/ EAR policy, so it will be taken from the insurance law governing the policy. By way of example, the English law test for physical damage requires the following to be present:

(a) A change in the physical condition of the property;
(b) Which has a negative effect on the value or utility of the property.

Taking an example, if a boiler is defectively designed such that it over pressurizes during use and explodes, then there has clearly been a change in the physical condition of the boiler (it has exploded), which has negatively affected the utility of the boiler (it no longer functions). The physical damage test has been satisfied.

However, modifying the example slightly, if the boiler were installed, the defect with the pressure regulation system was discovered and it was taken out of service before it exploded then the physical damage test would not be satisfied. The second part of the test would be satisfied (the boiler can no longer be used) but there has been no physical change.

4.3 London Engineering Group Clauses (LEG Clauses)

As mentioned above, new technology is relatively unproven when compared with products that have been used and refined over a long period of time. Inherent defects in established products are likely to have been ironed out whereas in new technology this is not necessarily the case.

Under a CAR/ EAR policy there will need to be an event of physical damage in order to trigger coverage. Physical damage may be caused by a range of range of factors such as flooding or fire, but insurers must also be aware of the risk of damage caused by defect, which is greater in instances where new materials are utilized. Consider, for example, if a newly designed boiler was installed on a project. If one assumes that the boiler was installed and operated in the conditions it was designed for, but it then overheats and causes physical damage, the proximate cause of this damage might be defective design.

CAR/ EAR policies often contain London Engineering Group Clauses (LEG Clauses) which set out the extent to which the policy will respond in the event of physical damage caused by a defect. There are three LEG clauses which will be briefly analyzed in turn below.

Under LEG 1/96 cover is excluded for physical damage cause by defect in, "workmanship design plan or specification". In the context of a project using prototypical materials this wording is preferable for an insurer. LEG 1/96 will allow an insurer to deny cover outright in the event that physical damage is caused by a defect. As discussed earlier, the risk of defects is higher in new materials as they have not been developed and refined to the same extent, so this wording will serve to reduce an insurer's potential exposure.

LEG 2/96 provides that the insurer will cover consequential damage caused by the defect but not the cost of repairing the defective item itself. If a policy contains a LEG 2/96 clause an underwriter should carefully consider the new materials being used in the project, the potential damage such materials could cause if they prove to be defective and how straightforward or costly any repair might be.

Under LEG 3/96 the insurer is obliged to cover any consequential damage arising from the defect, as well as paying to repair the defect itself. Underwriters should be most wary of this wording. In instances where a highly expensive component part causes significant and widespread damage an insurer's exposure will be much greater.

Many polices contain amended LEG wordings. This is the case in the Munich Re Policy. Special exclusion d) to Section 1 states the Insurers shall not be liable for:

> *"the cost of replacement, repair or rectification of defective material and/or workmanship, but this exclusion shall be limited to the items immediately affected and shall not be deemed to exclude loss of or damage to correctly executed items resulting from an accident due to such defective material and/or workmanship".*

Whilst not clearly identified, this clause operates in a similar way that the LEG 2/96 clause would. As such, it is important that underwriters carefully consider the wordings they are presented with, compare it to standard wordings and assess the extent to which they might be obliged to cover damage caused by defects or the cost of repairing defective parts.

4.4 What is Defective Design?

Another point to consider is what exactly constitutes defective design. This is an important issue as it will determine whether physical damage falls the scope of the defective design clause and the series loss clause. This issue is particularly pertinent in the context of new materials. Often when 'state of the art' products are brought to market they are considered fit for purpose at that time. However, after many years of use unforeseen defects can arise.

Special exclusion c) to Section 1 of the Munich Re Policy states the Insurers shall not be liable for:

> *"loss or damage due to faulty design".*

The key question for an insurer is whether 'faulty design' should be construed as requiring negligence (i.e. the designer made a mistake and should have known better based on the state of knowledge at the time), or whether it is simply enough to demonstrate that the design was not fit for its intended purposes even though this wasn't known at the time of design. Under English law the relevant test is to show that a product was not fit for its intended purpose. However, this standard differs depending on the jurisdiction. As such, insurers should be aware of which materials have been used on the project and how the choice of governing law might impact coverage if physical damage is caused by a defective material or product.

4.5 Serial Losses

Serial losses are common when new technologies or materials are employed on a project. A serial loss clause will provide that where losses or damage occurs due to factors that are directly or indirectly linked, a claim for the losses may be aggregated and treated as one claim. For example, a claim for series loss might arise from:

a. a recurring fault in designing or manufacturing; or
b. repeat use of a type of material or product showing the same defect.

It is often the case that new materials/ products will be installed many times across a project. In the event that a single unit or item of new material suffers/ causes damage, an insurer will have to consider the extent to which the other items of the same type might also be damaged/ have caused further damage.

In the context of a 50 turbine wind farm, for example, hundreds of newly designed corrosion-proof bolts might be installed on each turbine. If an insured submits a claim for damage to one of these bolts, an insurer may be facing a significant accumulation exposure in respect of the entire set of bolts installed across the project. It may not be possible to replace defective parts cheaply or immediately, and replacement could necessitate substantial dismantling and reassembly operations which would require specialist equipment and operators.

Another example is the use of cross laminated timber (CLT). CLT is increasingly common due its benefits in sustainability and structural integrity. CLT even yields a high fire rating when fire retardant is added. However, wooden structures are susceptible to holding moisture, which can be hidden for years. In the event that moisture is discovered in a timber structure it is not always easy to remedy, and the replacement of individual timber units can be difficult. If one unit of CLT is found to have suffered/ caused physical damage due to moisture it is possible that many other units are also damaged. As above, insurers should be aware of such risks and the potential accumulated exposure that could arise.

The extent of an insurer's liability for a series loss will hinge on establishing the cause of the loss and the precise wording of the policy document. In our case the Munich Re policy provides cover for:

> *"Loss or damage due to faulty design (if covered by endorsement), defective material and/or workmanship arising out of the same cause to structures, parts of structures, machines or equipment of the same type shall be indemnified…"*

Wording such as this is somewhat vague and leaves the extent of the loss open to interpretation. The term 'arising out of' suggests that the cause of the damage may be wider than a direct and proximate cause. The wording suggests that a degree of causal connection between the defect and the damage is required, but the extent to which the two must be connected is not clear. Returning to the wind farm example, one might argue that there is a sufficient degree of connection between all the bolts on a single turbine. However, it could also be argued that the clause should apply to all the bolts across the entire farm. Depending on the interpretation there is a huge difference in potential exposure and this is something insurers should be acutely aware of.

A more narrowly worded series loss clause would better protect an insurer against an aggregated loss claim. Other serial loss wordings might include:

(a) "arising from"
(b) "attributable to"
(c) "in connection with"
(d) "resulting from" or
(e) "related to"

Each wording will require the application of a different level of causative link in order to establish what constitutes a series loss. In the event that an insured presents a series loss claim the insurer should carefully scrutinize the circumstances of the loss in order to determine whether the loss falls within the terms of the series loss clause.

We note that in certain sectors, for example insurance regarding renewable energy projects, sophisticated series loss clauses are used to provide a sliding scale of indemnity in the case of serial defects. Considering the risks associated with new materials, insurers may wish to consider using these more sophisticated clauses more widely across their engineering risks.

4.6 Repeated Testing Costs

The issue of repeated testing is closely linked to series loss. Repeated testing costs are the cost of looking for further damage of the same type when damage is initially discovered. Such costs will often be covered under a CAR policy, although no such wording is included in the Munich Re policy. In the context of the wind farm, if one of the corrosion proof bolts suffers damage, the insured will need to assess the extent to which other bolts of the same type are also damaged. If the insured discovers that other items of the same type are damaged, then it will be covered for the cost of this discovery.

It is important that underwriters are aware of this exposure. If one assumes that all of the bolts used on the wind farm in question are damaged in the same way, then the insurer might be obliged to cover not only the cost of the damage itself, but also the cost of discovering and assessing this damage. In the context of a 50 turbine offshore wind farm this discovery cost would be potentially large as it would warrant significant expenditure on specialist operators and equipment.

4.7 Maintenance Periods

Cover under a CAR/EAR policy will not generally end at construction completion. Often there will be a maintenance period, typically of 24 months, during which, under project-related contracts, contractors and suppliers will remain liable to rectify defects or problems arising from the works they have carried out or products they have installed.

There is no specific wording on this issue in the Munich Re policy. Under a CAR/ EAR policy, however, the cover provided during the maintenance period is usually limited to:

a. physical loss or damage caused by faulty or defective workmanship that arises from a cause that occurred prior to the expiry of the project period; and
b. physical loss or damage that arises from a contractor or supplier carrying out their contractual maintenance obligations during the maintenance period.

It is important for underwriters to be aware that this exposure exists, especially in the context of untested materials or products which might be more likely to cause defects during the construction phase.

The best-case scenario for any insurer is a situation in which the post-construction completion maintenance period is the same length as manufacturer or supplier guarantees given under the project. This will mean that the insured will first be entitled to recover losses arising during the maintenance period under the supplier/manufacturer guarantees (if the policy contains a favorably drafted guaranteed loss clause then the insured will be obliged to do so). If, on the other hand, the maintenance period is 24 months but supplier and manufacturer guarantee periods are only 12 months then the potential exposure is larger, as from 12-24 months the insured will only be able to recover under the policy and not under the guarantees.

5 Claims Examples

Material T24 in coal fired Power plants

The increase of the efficiency of coal fired power plants will be achieved by increasing the steam temperature (>600°C) and steam pressure (approx. 300bar). For this reason, Materials were developed and applied in the boilers of new power plants several years ago. One of this Material was T24 (7CrMoVTiB10-10) which was used for the membrane walls at the evaporator in several large power plants across Europe. The advantage of T24 was its creep strength, meaning it did not need to be heat treated after welding. Furthermore, its corrosion stability was expected to be sufficient. Nevertheless, during the testing and commissioning of the first power plants cracks appeared at the welding inside the tubes which triggered steam leakages. The cracks were caused by stress corrosion when getting in contact with high temperature steam. It was assumed to be caused by Hydrogen Induced Stress Corrosions likely resulting from bad welding quality. In many cased the required heat treatment in order to reduce the stress was not carried out.

These cracks resulted in millions of loss costs. Several lawsuits took place to clarify if it is an already existing defect or an insured material damage covered by the EAR policy. The first verdict confirmed that this is an insured loss based on the assumption that the boiler has resisted a pressure test without showing the stress corrosion cracks which did not reflected the final operating conditions. The cracks occurred as the final operating conditions were achieved. Thus, the defect was integral part of the manufacturing process prior to the incorporation of the membrane walls which was not considered by the court.

Fibre optic in offshore wind export cables [14]

The design of AC subsea power cables is well-established and had been used successfully in power interconnectors for many years. When these cables were used in the context of offshore wind farms, however, the design was modified slightly to incorporate a fibre optic cable to allow for transmission of SCADA data. As the fibre optic is smaller and lighter than the power cores, and does not carry electricity, it was not subjected to significant electrical testing.

Several cables suffered power failures after they had been in operation for a number of years. It was determined that the metallic sheath surrounding the fibre optic was generating an induced voltage which, over time, was resulting in the failure of the fibre optic and sometimes the power cores themselves.

The severity and extent of the issue was not immediately apparent, and cables were repaired back to their defective condition, only to fail again later. This is an example of a small change in an existing product causing a very serious increase in the risk profile.

6 Conclusion

New materials and technologies may help achieving higher cost and time savings, material and/or energy efficiency, and a better impact on the environment. Due to the lack of long-term experience, however, new materials and technologies are associated with higher risks from an insurance perspective.

Technology is changing quickly in the engineering and civil engineering sectors, and that new materials and technologies are being brought to market faster than ever. The risk is that with this faster design cycle there is less scope to determine the long-term integrity of the product. Repair costs could be considerable if the incident has not been encountered before and a repair solution has not yet been identified or enacted. On a worst case scenario, if the new material/ technology turns out to be unviable then the entire project could require re-design.

New materials and technology present a risk and opportunity to insurers. The risk to insurers is clear if the cover provided does not reflect the higher chance of damage and repeat damage associated with these new products. However, there is also an opportunity if insurers tailor their products to satisfy the client and appropriately reflect the risk.

The tools available to insurers already exist and are well known. The challenge is in investigating the project at the placement stage and highlighting the new materials. For example, if ultra-high performance concrete is utilized in one aspect of the project then insurers could choose to cover that aspect on a LEG 1 basis whilst having broader defect cover for the other, more traditional, elements of the project. Another useful tool is the series loss clause. This has been the subject of much discussion and development in the context of renewables insurance, where new materials and technologies are particularly common, and we suggest that insurers could benefit from using these clauses more widely in civil engineering and engineering policies.

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