Light and Thin Blast Protection

By Stephan Hauser, Ph.D., P.E. and Larry Abatiell, P.E.

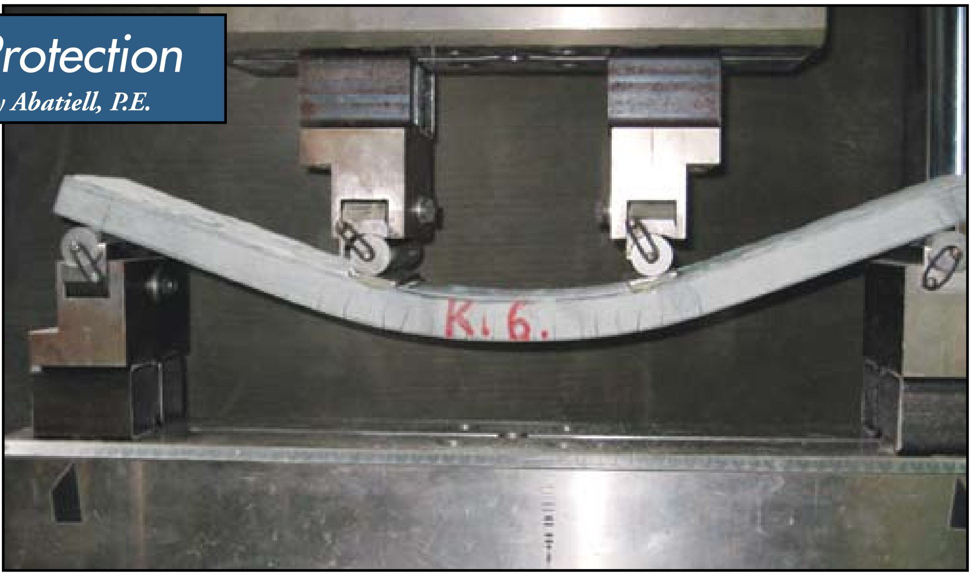
Demand for blast- and ballistic-resistance is increasing, both in existing structures and new construction. Engineers working in both the public and private sector are often forced to make an unpleasant choice between burdening a structure with thick, heavy conventional protective materials, or burdening the budget with costly high-tech materials. In some situations, neither solution is possible within the available space or funding.

A new material called micro-reinforced concrete (MRC) – marketed under the DUCON® brand – presents a solution to this dilemma. It has been found to resist extreme loading using only thin sections, and without budget-breaking expense. Micro-reinforced concrete is a recently invented material, and the development of its broader potential for structural applications is still in its infancy. However, it has already been successfully applied in a series of blast- and ballistic-resistance projects in Europe that feature a variety of engineering, logistical and aesthetic challenges. It has also been used for seismic resistance, an area of design whose loading issues are not dissimilar from the extreme loading associated with explosions.

A New Solution

Micro-reinforced concrete is a composite that reinvents the relationship between the cementitious matrix and steel reinforcement. Its invention was an outgrowth of research done by co-author Dr. Stephan Hauser in the late 1990s at the University of Technology, Darmstadt, Germany on ways to improve SIFCON (Slurry Infiltrated Fiber Concrete). It was found that by substituting 3-dimensional mats of wire mesh for the random fibers used in SIFCON, performance improved markedly. Building on this discovery, optimum mat and slurry designs were developed that produce a material with extremely high performance properties.

The matrix of MRC is a specially formulated, flowable, self-consolidating, high strength mortar made of portland cement, fine aggregate, pozzolanic materials and special proprietary additives. Particle size distribution of the aggregate and cementitious material is engineered to produce a dense, finely textured paste that is virtually impermeable when cured (a property MRC shares with certain other dense, ultra-high performance cementitious materials- see sidenote.) Reinforcement is in the form of mats with multiple layers of fine steel mesh. The mats are completely infiltrated with the cementitious slurry and result in the positioning of aggregate throughout the thickness of the concrete member. A few millimeters of this impermeable mortar provide sufficient concrete cover to protect the steel from corrosion, making it possible to distribute reinforcement virtually throughout the section of concrete.



MRC exhibits ductility more like steel than like concrete.

Impermeability: Testing using the standard European Union water penetration test method on a virgin, uncracked sample of MRC produced no penetration. A sample with cracks was also tested, and it also fell within the limits allowed under the European definition of impenetrability; in fact, it allowed only 10% of the maximum allowable penetration. The inventor's own carbonation depth testing produced zero carbonation, but as of this writing, the test is being re-run for code certification purposes, as is chloride ion penetration testing.

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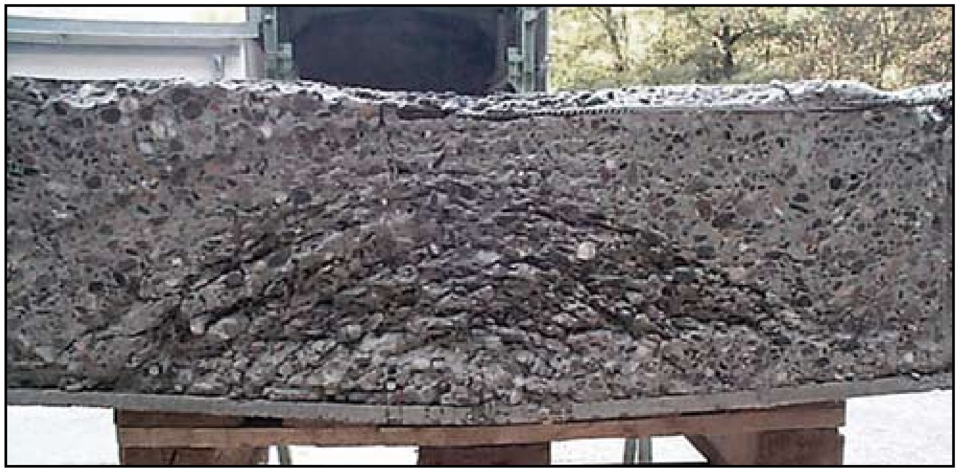
Precast MRC panels are attached to simple steel post supports to form a free-standing blast wall protecting a vulnerable community center.

The composite achieves performance properties not normally associated with concrete: compressive strength up to 23,000 psi, flexural strength up to 11,000 psi, and high ductility. These properties have been experimentally demonstrated through extensive testing, the results of which suggest a wide range of structural and architectural applications. ICC-ES has recently approved AC 373 - *Acceptance Criteria for Precast Reinforced Cementitious Slurry Structural Members*, making MRC an acceptable material for construction in the U.S. Other code approvals and design software solutions for such applications are currently under development.



The top 12 inches of this slab is standard reinforced concrete, subjected to blast loading on the upper surface. Transferred blast energy caused a spall of approximately 75% of the concrete thickness off the bottom of the standard concrete portion, clearly visible as a dome-shaped crack. The 0.6-inch MRC fragmentation-protection layer at the bottom successfully contained this spall.

A highly flowable, self-consolidating cementitious slurry infiltrates the three-dimensional reinforcement mats, curing to an ultra-high strength mortar.

More immediately, the MRC's strength and ductility have already been put to work for resistance to blast shockwaves and fragment (ballistic) penetration. One important factor in these applications is the material's high spall-resistance. When ordinary concrete is subjected to blast loading, impact energy of the shockwave transfers from the impact surface to the opposite surface of the slab, causing the opposite surface to spall. Spalled concrete fragments can become lethal high-velocity projectiles, posing similar dangers to the primary fragments (shrapnel) created by exploded bomb casings. Spalling also reduces the thickness of concrete available to resist penetration by the actual primary fragments. MRC's spall resistance makes it a safer and more efficient basic protective material. It also allows it to be used as a spall-resistant "safety net" in combination with ordinary concrete, both as retrofit overlays and as a combination slab in new construction.

In a variety of test setups, MRC has been shown to provide equivalent blast and ballistic protection with only 30-50% of the thickness that would be required using ordinary reinforced concrete. This makes it a strong choice for retrofit situations where massive weight or extreme thickness cannot be added to existing structures. It is also attractive for new construction, where protection can be achieved with minimal increase in dead load.

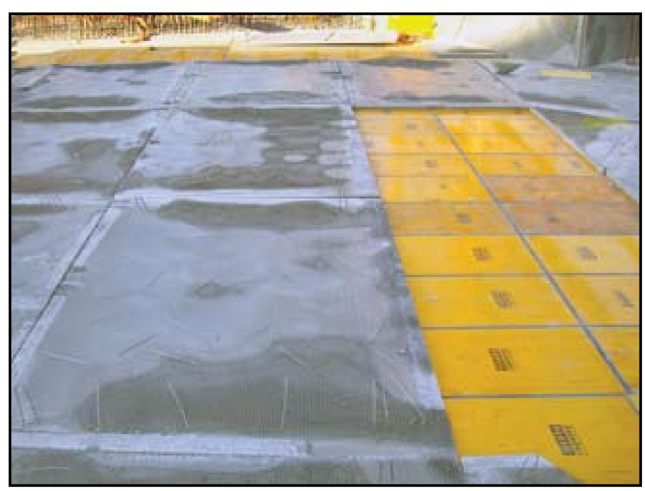
Blast-Resistant Walls

MRC is a patented technology that has been developed over the past 10 years, first by Ducon GmbH, Moerfelden-Walldorf, Germany, working in concert with the prestigious Ernst-Mach Institute, Fraunhofer Institute for High-Speed Dynamics (EMI), Efringen-Kirchen, Germany and the German army, and more recently by Excend Inc, Woodcliff Lake, NJ, the Southwest Research Institute, San Antonio, TX, and Weidlinger Associates, New York, NY. Its earliest uses were in blast resistance applications. One of the first was a container for storing and transporting explosives and munitions. The cylindrical structure is 7 feet indiameter and 8 feet tall, with an MRC wall thickness of 8 inches. It survived an internal test explosion equivalent to 66 pounds of TNT.

Another application was a European consulate that occupied a pre-existing structure. (For security reasons, identifying information about protected buildings and exact protection levels cannot be disclosed.) The building had no previous governmental use and was not designed with security in mind. There was little room to create protective stand-off between the building and the public roadway. (See side-bar: *Basic Security Concepts*). There was also an easily accessible driveway that created a vulnerability to attack along the side of the building.

The driveway problem was solved by applying thin precast MRC panels directly to the side of the building. The same level of protection with ordinary concrete would have been so thick as to partially block the driveway. It would also have been too heavy for the existing wall to support, and would have required an additional footing.

The front of the building was protected with an elegant fence mounted on a low wall. The wall was made of precast MRC, installed partially below grade level. The wall is high enough to deflect direct impact of blast shockwaves and stop fragments from car bombs and other street-level explosives, yet it is not architecturally intrusive. Equivalent



Precast MRC panels are placed over a basement high-security data center. They will be overlaid with a deck of standard concrete that will form the floor of the building's main lobby.

An MRC panel is installed in a European broadcasting center. A publicly accessible parking garage abuts the right wall, creating a vulnerability, but the MRC panels provides both blast absorption and fragmentation protection. The precast panels were lowered into the corridor through a slot cut in the ceiling.

protection in ordinary concrete would have been at least twice as thick and presented a fortress-like appearance, which would have been politically undesirable.

The equipment room of a German broadcasting center was considered vulnerable to attack from an adjacent parking garage. Precast MRC panels were installed in the corridor abutting the garage. They were the full-height of the corridor wall, and were brought into the location by cutting slots through the corridor roof. The thinness of the panels made it possible to provide appropriate protection without appreciably narrowing the corridor.

A threatened community center was protected with a free-standing blast-wall of MRC precast panels mounted to steel posts. Although access to the site was limited, the light weight of MRC panels made installation feasible with a light-duty crane.

Fragmentation Layers

A basement high-security data center was vulnerable to attack from the public lobby overhead. The concrete lobby floor was underlain with a thin fragmentation-protection layer of MRC, a spall "safety-net." Precast

Basic Security Concepts

Blast Mechanism – Shockwave: Explosion is a rapid expansion of gas, producing an air pressure wave (shockwave) that radiates outwards at high velocity. Shockwaves are the most intense at close range, and decrease in relation to the cube of the distance from the center of detonation.

Blast Mechanism – Fragments: The container of the explosive – be it a bomb casing or a steam boiler – is burst by the shockwave. The casing becomes primary fragments (shrapnel) that fly outwards at high velocity. Other objects impacted by the shockwave and shattered are called secondary fragments. Unlike the intensity of the shockwave, the penetrating force of fragments does not decrease appreciably with distance. Building windows and walls that are unable to absorb the blast energy can become secondary fragments.

Stand-Off: The first principal of blast resistance is to create as much distance as possible between the blast and the target, to take advantage of the decrease in shockwave intensity over distance. This is called standoff. The difference between a contact detonation and a few feet of standoff can be crucial.

Secure Perimeter: Limiting access to the target creates standoff. The larger the secure perimeter…the larger the detonation that can be survived.

This consulate is a repurposed building that previously lacked blast resistance. The MRC blast-wall creates a secure perimeter between the building and the public street, and provides blast-protection both by deflecting shockwaves and stopping fragments from street-level car bombs or package bombs.

MRC panels were specially prepared to bond with the standard cast-in-place reinforced concrete deck. It added minimal weight and leveraged the thickness of the deck to make it more effective protection.

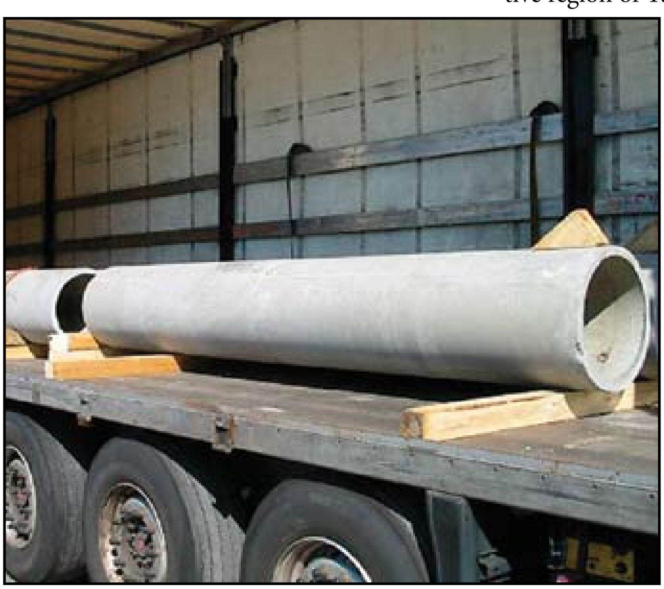
Column Protections

One frequent security challenge is the protection of load-bearing columns in publicly accessible places. Contact detonation of a relatively small explosive charge, such as can be carried in a backpack, can be intense enough to cause failure of a column. As was seen in the attack on the Murrah Federal Building in Oklahoma City, failure of one or a few columns can initiate progressive collapse of the structure.

In the lobby of a European newspaper office building, columns were protected by installing MRC column covers. Tall, precast elements with L-shaped cross-section were mated around the columns in the public lobby. Installation was carried out overnight. Drywall facades were re-installed the following night. The operation never disrupted regular business, and the result was indistinguishable from the original appearance.

In a new high-rise building in Austria, load-bearing columns were cast using forms made of thin MRC tubes. The MRC remained in place after casting, providing blast protection and creating an additional economy by replacing confinement rebar.

Column constraint for seismic resistance was installed in a factory in a seismically active region of Turkey. MRC mats were placed around existing columns. Leakproof forms were attached and MRC slurry was pumped in from the bottom. The constrained columns occupied only a slightly larger footprint than originally, an important consideration in a crowded workspace.



These MRC tubes were used as forms to cast load-bearing columns in the public lobby of a new high-rise building. The forms were left in place to act as blast-protection.

Future Applications

Designers and engineers who have studied MRC are convinced that it has very broad implications for the future of construction. The lengthy code approval process for structural applications is under way, and ICC-ES acceptance has already been achieved. Online design tools are being developed by Weidlinger Associates. Design seminars will be offered across the continent to train engineers in the use of the material.

Already, Charles Thornton, co-founder of the world-renowned design firm of Thornton Tomasetti, is designing a 64-story tower in Dubai that will advance the technology of lift-slab construction. Using lightweight MRC, entire floors with exterior and interior walls will be fully built out at ground level before being raised up to their final elevation. Also planned is the production of MRC "lumber" that can be used like ultra-strength wood.

There is general agreement among those familiar with MRC that its true potential cannot yet be determined. It will take the collective ingenuity and imagination of the design community at large to probe the possibilities and discover the new solutions that will be made possible by this material.

Summary

Micro-reinforced concrete is a new form of reinforced concrete that offers high performance in ways that have been described as "un-concretelike." Its ultra-high compressive strength, combined with flexural and tensile strength that are more like steel, give it effective blast- and ballistic-resistance in thin, lightweight sections. Although still in the infancy of its development as a construction material, it has already been employed for a variety of blast walls and column protections. The same properties that make it an efficient protective material also hold great promise for lightweight, strong, versatile structural and architectural applications.▪

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