Strand rods and high-performance fiber-reinforced cementitious composites: alternative options for seismic retrofit of existing structures

by

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Abstract

A recent increase in the frequency and spatial variety of seismic activities necessitates the need for re-evaluation of existing structures. Many existing structures do not meet the minimum code design criteria should they be impacted by a seismic event. These structures are vulnerable to damages which could result in injuries to occupants or even loss of life. In order to avoid these failures, these structures need to be rehabilitated to provide additional resistance to the lateral effects produced by seismic events.

This report will briefly discuss the necessity of a seismic retrofit and the process in which it can be accomplished. It will then outline two alternative methods of seismic retrofit: strand rods and prefabricated high-performance fiber-reinforced cement composite panels. These methods have a promising future in seismic retrofit due to their ease of use, cost efficiency, and minimal interruption to the continued use of the structure.

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Chapter 1 – Introduction

Seismic activity can be detrimental to the strength and stability of a structure. As a massive amount of energy is suddenly released, dynamic forces can develop in building structures. If not properly designed to account for such forces, the structure can incur irreparable damage and even cause loss of life. In recent years, numerous standards and codes have been developed and published on how to design building structures to adequately withstand earthquakes.

<u>Code Evolution</u>

Historically, seismic design has not always been common practice. The 1906 San Francisco earthquake was a clear indicator that the standard building techniques were inadequate to properly ensure the safety of its occupants. Early in the morning on April 18th, a 7.9 magnitude earthquake ripped through the northern coast of California, extending 270 miles from San Benito county to Humboldt county. In addition to the immediate damage caused, a subsequent fire blazed for the next four days. More than 500 city blocks (over four square miles) were leveled by these events. Some 28,000 buildings were destroyed. Originally, over 700 people were thought to have been killed. The death toll was re-evaluated at a later date and is now believed to have exceeded 3,000 individuals (Encyclopedia Britannica, 2019). It was an unprecedented catastrophe and motivator for change.

At that time, many local municipalities already had building codes in place, however, none of them considered seismic effects (Stanford University, n.d.). Since that event, great strides have been taken to ensure that such a catastrophe is avoided in the future. However, change is a slow process, especially when regarding building codes. The first regulations considering the design of earthquake-resistant buildings did not occur in the United States until 1927 and the regulations were not mandatory for all structures (Fajfar, 2018).

In the 1927 Uniform Building Code (UBC), the wind force resistance was intended to protect buildings from both wind and seismic damage. Even then, it was only recommended for structures greater than 100 feet tall, or taller than three times the building's least dimension (Fajfar, 2018). If a building met this criteria, an additional 30 psf wind load was applied to the building's elevation. It was later reduced to 20 psf and then 15 psf (Fajfar, 2018).

The first mandatory seismic codes in the United States were enacted in California in 1933 (Fajfar, 2018). The first code to relate the seismic coefficient to the flexibility of a building occurred in the City of Los Angeles in 1943 (Fajfar, 2018). In 1956, the City of San Francisco was the first to have a building code that took the natural period of a building into account when determining the seismic design forces (Fajfar, 2018).

In 1959, the first cohesive document addressing seismic design, entitled "Recommended Lateral Force Requirements" was produced. It was the first document to account for the impact of the energy dissipation capacity of structures in the inelastic range (Diebold, Moore, Hale, & Mochizuki, 2008). The document was nicknamed the "Blue Book" and was produced by California structural engineers working as volunteers through the Structural Engineers Association of California (SEAOC) Seismology Committee (Diebold, Moore, Hale, & Mochizuki, 2008). The subsequent commentary was published in 1960. It included the first introduction of the coefficient, K, included in the base shear equation which accounted for the type of building construction.

Due to the publishing of these documents, there was a marked increase in the practice of seismic design in the 1960's to the 1980's (Elsesser, 2004). Even then, it was still only required in certain regions. It was also during that time that requirements related to the detailing of ductile reinforced concrete frames were outlined and accepted (Fajfar, 2018).

In 1971, the San Fernando earthquake provided another clear indication that the provisions needed substantial updating. SEAOC then created the Applied Technology Council (ATC) to carry out research in order to improve existing design practices and codes. The preliminary ATC 3-06 was published in 1967 entitled "Tentative Provisions for the Development of Seismic Regulations in Buildings" (Fajfar, 2018).

It was the first document to incorporate many of the common modern principles of seismic analysis. This document used limit state design instead of allowable stress design, which all the previous codes had used. It also included the introduction of the coefficient, R, the response modification factor which reduces the seismic forces acting on a structure due to the energy dissipation of ductile structures. However, it was not to be used as a code until its practicality was confirmed. Later, the 1978 ATC 3-06 became part of the 1988 UBC and 1988 Blue Book (Diebold, Moore, Hale, & Mochizuki, 2008). The document was later modified as needed to be included in national building codes such as the National Earthquake Hazard Reduction Program (NEHRP).

In addition to the UBC, there were two other building codes being used as well. The BOCA National Building Code (BOCA/NBC), and the Standard Building Code (SBC). Different regions of the United States were using different codes. In general, the BOCA/NBC was typically adopted by the northeastern quarter, the SBC adopted in the southeastern corner, and the UBC adopted in the western half of the U.S. (Ghosh, 2002).

In the mid-1990's an attempt was made to develop a single, unifying model building code for the United States (Ghosh, 2002). The result was that 2000, the International Building Code (IBC) was released. It would come to be the unifying code for the nation. In addition, numerous other codes and standards are often referenced for using in seismic design. The list includes but is not limited to ASCE 7, ACI 318, and AISC Seismic Design Manual.

Codes continue to evolve as more research is done, new technology becomes available, and a better understanding is gained related to how buildings perform during a seismic event. Organizations such as ATC, NEHRP, SEAOC, and the Building Seismic Safety Council (BSSC) continue to participate in the process of developing and updating seismic building codes.

Seismic Hazards

In addition to the necessity of developing building codes that consider seismic design, one of the most noteworthy lessons learned from the 1906 San Francisco earthquake was the correlation between the amount of damage and the underlying geological conditions (USGS).

When a seismic event occurs, there are numerous factors that influence the structural damage. Obviously, the magnitude and location of the earthquake play a role. Shallower earthquakes tend to cause more damage (Chang, 2016). Deeper earthquakes lose energy as they travel to the surface.

The geology and existing soil conditions of the site also influence the amount of damage. Site effects depend on the softness of the soil or rock and the total thickness of sediment above the bedrock (Nolan, 2018). Seismic waves travel faster through hard rock than soft soil. When transitioning from hard to soft earth, their amplitude increases resulting in bigger waves that cause stronger shaking (Nolan, 2018).

Additionally, the composition, layout, height, weight, stiffness, and period of a structure are factors to consider for seismic effects. Resonance is the oscillation that is caused by a seismic wave. During an earthquake, buildings oscillate differently depending on their natural frequency. For example, taller buildings tend to have a longer natural frequency, i.e. they swing back and forth more slowly. The natural frequency of the ground tends to match that of buildings nine stories or taller, making them more susceptible to earthquake damage (FEMA). However, it depends on the waves created by the seismic event. Small buildings are more impacted by high-frequency waves. High rise buildings will be more likely to sustain damage with long period waves.

In terms of configuration, L-shaped, T-shaped, H-shaped, or +-shaped buildings are more susceptible to torsional forces that cause the structures to rotate, causing damage or possible collapse (FEMA).

The regulations that began to address soil effects and other factors were added to the appendix of the Uniform Building Code in 1927. It was the first document to recognize that soil conditions impact the amplification of ground motion (Fajfar, 2018). Once again, the additions to the code were optional, not required. Also, the advances made regarding the understanding of seismic events, their impacts, and how to protect against them do little to improve existing structures designed and constructed without seismic considerations.

According to the United States Geological Survey, the rates of earthquakes with a magnitude greater than 3.0 grew rapidly from 2008-2015 (USGS, 2018). In 2017, the location of recorded earthquakes was more spatially diverse than ever before (USGS, 2018). In fact, earthquakes have the potential to produce significant damage in 42 of the 50 U.S. states at some point in the next 50 years. Seismic hazard maps are now used in building codes as a tool for designers. They provide an approximation of the likelihood of a seismic event impacting a certain structure. The maps are based upon scientific models of potential future earthquakes, attenuation relations, and the geologic site condition (USGS). They are very useful in determining the risk level in specific locations, for both new construction and existing structures.

Seismic Retrofit

The combination of the facts that many existing buildings were not designed for seismic events and that the number of recorded seismic events has been increasing in recent years, it becomes a clear indication that something must be done to mitigate future seismic catastrophes. Numerous documents have been published on the seismic retrofit of existing structures. Specifically, the Federal Emergency Management Agency has published a guide in the Risk Management Series addressing the seismic rehabilitation of buildings (FEMA, 2009). There are unique documents for school buildings, hospital buildings, office buildings, multifamily apartment buildings, retail buildings, and hotel/motel buildings, as well as a general guideline for new and existing buildings. Some of the solutions described are impractical for certain types of existing structures.

Essentially, a building owner has three choices when it comes to seismic rehabilitation. Their first option to do nothing, which is the lowest cost option, but comes with the highest level of risk. A second option is to replace the structure entirely. Full reconstruction is the highest cost, lowest risk option, but is not possible for historically preserved structures. The third option is to rehabilitate the existing structure, either all at once, or incrementally (FEMA, 2009). The third option is in the middle of the other two in terms of both cost and the risk associated with it.

This report introduces two alternative methods for minimally invasive seismic rehabilitation of existing structures. The first is an innovative material called strand rods. A strand rod is an ultra-thin polymer encased carbon-fiber rod, applied to the exterior or interior of structures. The second method is to apply high-performance fiber-reinforced cement composites which can be used to provide additional strength to existing structures through the utilization of prefabricated panels applied at interior joints.

Chapter 2 – Needs and Benefits of Seismic Rehabilitation

The greatest concern for any structural engineer is life safety. It is their professional duty to ensure that structure is stable in the event of unforeseen loading, such as a major earthquake. To achieve this, load and resistance factors are utilized in design; the failures types are identified, analyzed, and accounted for; and the entire structure is examined holistically to determine any areas of weakness. Even if a structure fails, it is designed to do so in a predictable and gradual, in other words, ductile way to ensure the occupants have adequate time to respond to the situation and move to safety.

Current Efforts

As discussed in the previous chapter, seismic design codes are continually being updated. With this constant evolution, what was adequate a decade ago may no longer meet current code. The benefit of this constant updating is that the safety of new structures is continually improving. The drawback is that existing structures do not meet updated criteria. It is recommended that any building constructed prior to 1998 be reevaluated regarding the new codes and requirements, including seismic provisions (Hill, 2008).

Evidence demonstrating the positive impact of updated codes and improved seismic design methods can be seen through examination of the effects of a 7.1 magnitude earthquake that rocked California on July 5, 2019 (USGS, 2019). This major seismic event was the strongest earthquake to hit California in 20 years. The earthquake caused the outbreak of five fires due to broken gas lines, and it resulted in power outages for 28,000 residents. The San Bernardino county fire department reported “minor cracks (in buildings); broken water mains; power lines down; rock slides on certain roads” but no loss of life (Croft & Goyette, 2019). Clearly, the advances in seismic design and California’s updated seismic design codes successfully protected the lives of the residents of that state. Following California's example would be a beneficial strategy to be applied to all states with the potential for seismic damage.

California continues to make efforts to rehabilitate existing structures that are vulnerable to seismic forces. For residential properties, a $3,000 seismic retrofit grant was created for qualifying properties through the Earthquake Brace + Bolt initiative. The funds from these grants are to be used toward retrofits such as bolting the house to its foundation and for adding bracing around the perimeter (California Department of Insurance, 2018). The goal of the initiative is to reduce the number of condemned houses left behind after a seismic event does occur.

For existing commercial buildings, some municipalities in California are passing ordinances that require seismic retrofit. The cities of Los Angeles, San Francisco, and Santa Monica have recently adopted such ordinances. Their goal is to protect the public from seismically vulnerable buildings (Kumar, 2018). Many of these programs provide financial assistance to building owners who must conform with the required renovations.

Benefits

Despite the costs to building owners, seismic retrofits yield several benefits. One immediate benefit is that performing a seismic retrofit increases the marketability and safety of a building. For building owners, the safety of their tenants is their number one priority. The benefit of improving safety is two-fold in that when a tenant feels secure, their occupancy contracts are renewed more often and they are renewed for longer periods (Hill, 2008). Performing a seismic retrofit makes a building more structurally sound, reducing the risk of injury and/or property loss of the tenants thereby reducing the legal/financial liability of the owner.

Sustainability is another advantage of performing a seismic rehabilitation. There is a finite amount of materials available in order to construct buildings. By performing a seismic rehabilitation instead of demolishing and constructing a new structure, the amount of materials required to achieve the end goal is substantially less.

Seismic retrofits can also reduce insurance premiums paid by owners for earthquake coverage in certain regions. Homes that participate in the California Earthquake Brace + Bolt initiative receive discounts of up to 20% on their earthquake insurance premiums (California Department of Insurance, 2018). As previously discussed, the frequency and spatial diversity of earthquakes has increased in recent years. Yet, despite this fact, only 8% of building owners have earthquake insurance coverage (Insurance Information Institute, 2016).

In addition to the previously mentioned benefits, historical preservation is also an advantage. Landmarked sites can be particularly vulnerable to seismic events because, due to their age, they were most likely designed without seismic considerations. Seismic retrofits create many challenges to overcome during the retrofit of these historic structures. Any new seismic retrofit systems must be compatible with the existing structural system. These retrofits should also strive to be reversible, wherever feasible, in order to allow access to repair historic features when needed (Aguilar, 2016).

Weaknesses in Existing Structures

Common deficiencies found in structures designed without seismic considerations include inadequate global strength or stiffness, unstable load path, insufficient diaphragms, or inadequate foundations (Aguilar, 2016). FEMA also notes that configuration, component detailing, and other deficiencies such as adjacent buildings or deterioration of structural materials also impact the seismic vulnerability of a structure. (FEMA, 2006).

Inadequate global strength or stiffness is an issue for many structures designed without a consideration of seismic forces. Global strength is “the lateral strength of the vertically oriented lateral force-resisting system at the effective global yield point" (FEMA, 2006). Global stiffness refers to the stiffness of the entire lateral force resisting system. Both are often controlled by the same existing elements but considered to be separate deficiencies. During a seismic event, a building that is too flexible becomes subject to excessive movement or drift which often leads to extensive damage to exterior and interior walls. Stiffness must be added to reduce the drifts that occur at critical levels (FEMA, 2006).

An unstable load path occurs when there are inadequate connections between lateral force resisting system components, or structural and nonstructural elements of a building. In a structure, both vertical and horizontal lateral force resisting systems contribute to safely transfer lateral forces to the ground. If the forces do not have an effective way to be transferred between elements and to the foundation, it can cause damage.

Diaphragms are the horizontal ties between the vertical elements that resist lateral forces during an earthquake. In many cases, the existing diaphragms are inadequate in shear, bending strength, or stiffness during a seismic event.

Foundation deficiencies can be caused by a variety of reasons such as poor soil conditions, materials and reinforcing used, or unexpected loading conditions. For example, the strength of the cement, the size and type of aggregate used, the type and placement of reinforcement, etc. all play a role in the stability of the foundation. If the foundation is unstable, it consequently impacts the entirety of the structure. Insufficient foundations are often difficult and disruptive to remedy but critical to address.

Configuration irregularities, both in plan and vertical, can adversely impact performance. A torsional response can be created by plan irregularities, placing high demand on the diaphragm. Vertical irregularities create uneven distribution of mass or stiffness between floors and result in a concentration of force or displacement at certain levels.

Most detailing deficiencies occur due to the previous design standard practices. Currently, designers must also consider a system's behavior beyond the nominal strength. A common example is the post-elastic behavior of concrete gravity columns. In the event of significant seismic activity, the deformation capacity may be reached leading to the degradation and possible collapse of the column (FEMA, 2006). The lack of confinement within the gravity column causes a sudden, brittle failure, not a predictable, elastic one.

If an adjacent building is located close to another structure, there may not be adequate room to accommodate both buildings' seismic deformations. It can cause severe damage if the floor levels do not match and the stiff floor framing of one building impacts a more fragile element of the adjacent building (FEMA, 2006). It is more difficult to find a solution to this deficiency due to the likely different ownership and legal issues. However, if both parties are agreeable, the two buildings can be tied together to mitigate this potential threat.

Lastly, the degradation of structural materials can cause some deficiencies in the structure. A condition assessment of the existing materials should be performed to identify potential areas of concern. Different materials have different potential weaknesses. If existing conditions are determined to be degraded, the material will need to be replaced or repaired during the seismic rehabilitation.

While the above described deficiencies are the most common, each structure is unique and comes with its own set of challenges. In addition to being able to solve a number of the aforementioned structural shortcomings, another important advantage of the retrofit methods to be discussed includes the ability to apply the systems to the exterior of the structure, preserving the historical integrity of landmarked sites.

Chapter 3 – Process of Seismic Retrofit

As previously mentioned, FEMA has produced a document (FEMA P-420) titled "Engineering Guideline for Incremental Seismic Rehabilitation." According to the guideline, the process is as follows: due diligence analysis, operator risk reduction standards, initial integration opportunities, seismic screening, seismic evaluation, developing a risk reduction policy, seismic rehabilitation planning for specific buildings, staging seismic rehabilitation increments, budget packaging, financial packaging, and finally seismic rehabilitation project management (FEMA, 2009).

When considering existing buildings, structures can vary widely in size, use, type of construction, condition, and configuration of the building. Therefore, it is difficult to develop a universal methodology for their retrofit as each case is unique. In the case of renovation of a historic building with great significance, these projects are protected by the federal government against permanent alterations that in any way impact the "form and integrity of the historic property" (National Park Service). However, leaving the building unprotected against seismic forces makes the entire structure vulnerable to irreparable damage. These federal restrictions governing the work that can be done create additional challenges that must be addressed by designers when retrofitting on a historically protected site.

Process

The first step of the retrofit process is due diligence analysis. It consists of investors, lenders, and insurance companies identifying potential risks of an investment. The seismic hazard maps are helpful tools in this step of the process. Depending on the determined results, the due diligence analysis can also be used to begin developing a plan for seismic rehabilitation for an existing structure. Operator risk reduction standards and initial integration opportunities are also incorporated within this step. It is essentially a compilation of all the preliminary research necessary to fully understand the scope of the project being undertaken.

The next step is seismic screening which consists of a preliminary analysis of potential seismic deficiencies. This screening is used to determine the seismic vulnerability of the structure. The site itself must also be considered, including existing soil conditions. The seismic evaluation follows and is simply a more detailed confirmation of the possible vulnerabilities noted in the previous step. It is at this point that a detailed account of potential hazards should be completed, and then design work is able to begin.

Next, the incremental seismic rehabilitation plan is developed. The benefit of an incremental rehabilitation plan is that the building can still be occupied and productive while identified deficiencies are addressed. The plan involves designing and prioritizing the rehabilitation measures, identifying the integration opportunities and defining appropriate increments of rehabilitation. For all currently operable structures, an approach must be identified that will minimize disturbances to the occupants while performing the seismic retrofit. This approach may include consideration of possible closures to sections of the building for extended amounts of time to allow the necessary work to occur (Aguilar, 2016).

The primary goal is mitigation of hazards with minimal impact to current occupant operations and their safety. Yet there are important considerations regarding the structure itself, especially if it is a historically protected structure. Care must be taken to minimize the amount of historic material disturbed (National Park Service). The historic features must also be repaired or replaced to restore the project to its pre-existing condition once the seismic rehabilitation is complete.

The defined rehabilitation increments are then further developed into an overall implementation timeline. They must be staged so that once complete, they will collectively meet all performance objectives. It is also required that individually, no one increment, causes the building to be more seismically vulnerable than before work was initiated (FEMA, 2009). The next stage, budget and financial packaging, are then completed along with the incremental seismic rehabilitation plan. The final stage is the project management of the implementation of the rehabilitation plan. This management ensures that the plans, specifications, and quality assurance provisions are properly performed.

The process of seismic retrofit can be adapted across project types on a case by case basis. The steps described above in this section provide a general outline of the procedure to analyze and improve the numerous existing buildings, both historically protected and not, that would benefit from a seismic rehabilitation.

Current Methods

The current methods to rehabilitate deficient lateral force resisting systems vary widely depending on the construction and materials used within a structure. FEMA has also produced a document outlining the “Techniques for the Seismic Rehabilitation of Existing Buildings” (FEMA 547). For each common construction and building type, there are specific recommendations that could mitigate seismic deficiencies.

For timber structures, some recommendations include adding or enhancing a shear wall, adding collector elements, enhancing the anchorage to the foundation, enhancing the cripple wall, or adding a steel moment or braced frame.

For structures with existing steel moment frames, a steel braced frame can be added and connected with the existing frame or the existing steel gravity frame can be converted to a moment frame. Other options are to add a concrete or masonry shear wall, provide collector elements, enhance connection to foundation, strengthen the beam-column moment connection or column splices, or add a steel plate shear wall. Structures with steel braced frames can be strengthened by enhancing the braced frame connection or the strength and ductility of braced frame members.

For a system involving concrete moment frames, an additional steel braced frame, concrete or masonry shear wall, or collector elements can be added. The existing columns can also be enhanced using a fiber-reinforced polymer composite, concrete, or steel overlay. Alternatively, the existing concrete moment frame can be enhanced. For a system utilizing concrete shear walls, a fiber-reinforced polymer composite overlay can also be used. Other options include enhancing the coupling beam or slab and connections between slabs and wall.

For reinforced masonry structures, many of the recommendations are similar to the recommendations for systems using a concrete shear wall. If it is unreinforced masonry, recommendations include bracing or removing the parapet, or adding wall-to diaphragm ties, out-of-plane bracing, or reinforced cores. A concrete or fiber-reinforced polymer composite overlay can also be added to the masonry wall. Other options are to add concrete or masonry shear walls, steel moment frames, crosswalls, supplemental vertical support for the truss or girder, or veneer ties.

Much of the work as noted above can be disruptive to the continued use of the structure. It can also be complicated to make the design cohesive with the existing structure or aesthetically appealing. With the advancement and innovations in material and technology, new seismic retrofit methods are emerging that are less disruptive than those identified above. The two methods to be discussed in this report avoid some of the common problems previously associated with a seismic retrofit. These new methods were chosen for their ease of use, cost efficiency, option for application on historically preserved structures, and minimal interruption to continued use of the structure.

Chapter 4 – CABKOMA Strand Rod

The first method explored is the CABKOMA strand rod. It has been developed for use on existing structures for the purpose of adding additional seismic reinforcement. The product was developed and implemented in Ishikawa, Japan, an area with high seismic activity.

4.1 – Introduction

The CABKOMA strand rod is made of a carbon fiber composite. Thin, oriented carbon fiber strands are used for the interlining. They are covered by an outer layer composed of synthetic and inorganic fibers intended to protect against weathering of the carbon fibers. The combination is then impregnated with thermoplastic resin.

Figure 4.1-1: Section of the CABKOMA Strand Rod.
Reprinted from 'CABKOMA' by Komatsu Matere

It was developed by the Komatsu Seiten Fabric Laboratory in Ishikawa, Japan. It's first application was designed by Kengo Kuma for use on the exterior of Komatsu Seiten's head office building (Overstreet, 2016). The three-story structure is currently used as a workspace, exhibition, and research facility.

Figure 4.1-2: Komatsu Seiten's Head Office with CABKOMA Strand Rods. Reprinted from 'CABKOMA' by Komatsu Matere

According to the company that produces it, the CABKOMA strand rod is the lightest seismic reinforcement system in the world (KOMATSU MATERE Co., Ltd., 2019). It has a high tensile strength, a "delicate but strong structural body," and a superb aesthetic quality. The material has a specific weight of about one-fifth of that of typical steel rebar. In fact, a 160-meter (525 feet) roll of the strand rod weighs only 12 kg (26.5 lbs) (KOMATSU MATERE Co., Ltd., 2019). Yet it still has greater tensile strength per unit area.

Properties		CABKOMA Strand Rod	Rebar
Diameter	mm	5.83	6.00
	in	0.2395	0.2362
Cross-Sectional Area	mm^2	26.7	28.3
	in^2	0.0414	0.0439
Weight	g/m	47.3	222
	lb/ft	0.0318	0.1492
Tensile Strength	kN	38.22	5.67
	kips	8.95	1.27
Tensile Strength per Unit Area	kN/mm^2	1.43	0.20
	ksi	207.4	29.01

Table 4.1-1: Comparison of Size and Strength of Strand Rods vs. Rebar. Recreated from 'CABKOMA' by Komatsu Matere

Figure 4.1-3: Size Comparison of Strand Rods vs. #4 Rebar. Reprinted from 'CABKOMA' by Komatsu Matere

Many sectors utilize the carbon fiber and thermoplastic composite material. The benefits of the material being lighter in weight while still maintaining strength as compared to other materials make it valuable across many industries. For example, the composite has many applications in the nautical and transport trades. Its workability due to the thermoplastic impregnation and the ability to recycle the material are highly advantageous attributes. This composite has been used to make lighter automobiles and aircrafts, reducing their fuel consumption and making their overall design more efficient (Arkema, n.d.). The above figure illustrates the difference in diameter between the two materials while they are still equivalent in terms of strength.

The strand rod also has the potential to add an element of aesthetic appeal to a structure. Typically, seismic reinforcement systems are designed to be disguised within building finishes. The Komatsu Seiten's headquarters is a unique example of how a seismic retrofit reinforcement system can double as an architectural element.

4.2 – Manufacturing Process

The strand rod is described as an interesting mix of old and new technology. It incorporates local techniques of rope braiding to twist the carbon fibers into a strong configuration with cutting-edge hybrid carbon-fiber material (Owano, 2016). The fiber rod “combines together old and new technologies to create a knitted, light, rope-like rod that embodies strong and flexible properties” (Kwok, 2016).

While carbon fiber strands in thermoplastic resin are not a new material composition, the CABKOMA strand rods have a patented method of combining them. Typically, the thermoplastic composite manufacturing process consists of five steps: preforming, heating, impregnation consolidation, cooling, and demolding (Wong, 2017). Following this typical process leads to some questions as to the consistency and strength throughout the material. The main concern occurs during the impregnation consolidation phase. During that time, the composite material is introduced to the thermoplastic using a mixing and fiber agitation process. This results in the axial direction of the reinforced fibers to be randomly oriented. In turn, this causes the strength and elastic modulus to become inconsistent depending on location. Often, the reinforced fibers are broken or cut during agitation, resulting in a decrease in strength of the resultant material.

Strand rods solve these inconsistencies through a precise, detailed, and proven manufacturing process. The materials used are also strictly specified. First, the fiber-reinforced resin material must be a reactive resin, formed by the application of heat or pressure even after curing. There is some flexibility in the size and shape of the resultant material depending upon use. However, it is recommended to have a length to width ratio of greater than five if possible but never less than 1.5. The thickness can range from 0.10 mm to 10 mm. It is recommended to stay within those limits to ensure adequate strength but also to ensure that the fibers can be sufficiently impregnated with the resin (United States Patent No. 20160326323, 2015). It is permissible to have a fiber volume fraction (Vf value) ranging from 20-80%, however a range of 40-60% is most ideal.

The thermoplastic resin can be any of the following types: epoxy, polyamide, acrylic, polyphenylene sulfide, polyvinyl chloride, polyethylene, polypropylene, polyacetal, polycarbonate, polyurethane, polybutylene terephthalate, acrylonitrile butadiene styrene (ABS), modified polyphenylene, phenoxy, polysulfone, polyether sulfone, polyether ketone, polyether ether ketone, or aromatic polyester (United States Patent No. 20160326323, 2015). It is also permissible to combine different types. A linear molecular structure is preferred but not required. Essentially the resin must be reactive with the addition of a curing agent or with the application of heat.

The reinforced fibers can be inorganic, organic, metal, or a combination. Acceptable fibers include carbon fiber, graphitic fiber, silicon carbide fiber, alumina fiber, tungsten carbide fiber, boron fiber, glass fiber, basalt fiber, para-aramid fiber, meta-aramid fiber, ultrahigh molecular weight polyethylene fiber, polyarylate fiber, PBO fiber, PPS fiber, polyimide fiber, fluorine fiber, PVA fiber, stainless steel fiber, or iron fiber (United States Patent No. 20160326323, 2015). Overall, the ideal combination of materials for performance in terms of strength and durability are carbon fibers in a reactive thermoplastic epoxy resin.

Figure 4.2-1: Carbon Fiber Product. Reprinted from ‘Carbon Fibers’ by Teijin.

The thermoplastic resin solution also includes a solvent and curing agent. Options for the solvent includes water, dimethylformamide, toluene, xylene, cyclohexane, methyl acetate, ethyl acetate, butyl acetate, acetone, methyl ethyl ketone, methyl isobutyl ketone, disobutyl ketone, cyclohexanone, methanol, ethanol, butanol, isopropyl alcohol, methyl cellosolve, cellosolve, or anone (United States Patent No. 20160326323, 2015). The curing agent can be a cross-linker, a catalyst, a polymerization initiator, or a polymerization accelerator (United States Patent No. 20160326323, 2015). Additives such as antioxidants, ultraviolet absorbers, pigments, thickeners, emulsifiers, or dispersants are also permitted (United States Patent No. 20160326323, 2015).

Once the selected materials meeting the above criteria are ready for production, the bundles of reinforced fibers are arranged in one direction to ensure the axial direction of each fiber is aligned with the others. Each bundle must include at least 1,000 reinforced fibers but has no upper bound limit (United States Patent No. 20160326323, 2015). As illustrated in Figure 4.1-1, each bundle of fibers is configured around the other bundles utilizing the knowledge gained from local, time-tested braiding techniques to achieve the strongest configuration.

The thermoplastic resin solution is then applied to the reinforced fibers. There are various ways to accomplish this. The first is the dip method in which the bundle of fibers is dipped into the solution. The second method is the dip-nip method in which the fibers are dipped into the solution and then squeezed by equipment, for example a mangle or wringer. There is also the transfer method in which the solution is applied to one surface of the bundle using a kiss roll or a gravure roll.

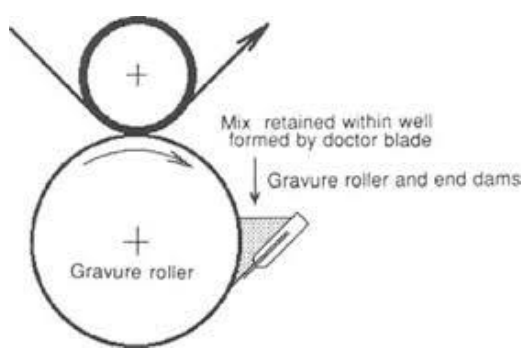


Figure 4.2-2: Example of Gravure Roll. Reprinted from ‘Coating and laminating’ by D.W. Ball

Lastly, the spray method applies the solution as a fine mist sprayed onto the fibers. The dip, transfer, and spray methods are most effective at ensuring the solution is applied deep within the bundle and these methods allow for the excess resin to be removed during the process.

Next, the bundle is dried and then heat treated. Drying and heat treating can also occur at the same time. The drying temperature and heat treatment temperature are dependent upon the thermoplastic resin, curing agent, and solvent used. Once complete, the result is a bundle of reinforced fibers oriented in the same direction within a reactive thermoplastic resin.

For quality control, samples are cut perpendicular to the direction of the reinforced fibers in lengths of 40-50 mm (1.5-2 inches). The cut pieces are analyzed to ensure the resin penetrated to the central region of the bundle of carbon fibers and that the fibers are oriented properly.

The overall result of this process is a material with consistent strength throughout. This method “has provided a molded fiber-reinforced resin body which is superior in the mechanical properties and the uniformity of the properties despite the low volume fraction of reinforced fibers” (United States Patent No. 20160326323, 2015). The resultant molded body with oriented reinforced fibers provides superior performance for impact resistance and fracture toughness. In addition, it has superior workability on site because the thermoplastic resin can be altered into various shapes using heat and pressure. The manufacturing process can also produce various shapes, including but certainly not limited to: a sheet, a plate, a block, or any specific desired shape including rods (United States Patent No. 20160326323, 2015). Being lightweight yet having high strength and durability makes this composite well suited for a wide variety of uses in numerous industries including the automotive, transportation, and construction sectors.

4.3 – Applications

One of the engineering applications of the composite strand rods is seismic reinforcement of buildings. Seismic reinforcement can be achieved using this material through both exterior and interior applications. A strand rod drape is shown on the exterior of a structure in Figure 4.1-1. Use of these rods as shown provide seismic reinforcement by essentially linking the roof level to the foundation level.

Strand rods can be applied as external bracing to structures of various heights and compositions. They help alleviate the stress placed on a building when a seismic event does occur by providing an alternate path for the forces to be transferred to the ground. It is important for the rods to be properly placed and installed to ensure their effectiveness. Below is a detail of how to effectively apply strand rods to the exterior of a structure. In addition, the application configuration allows for the strand rods to be readjusted and tightened should they become less taunt over time.

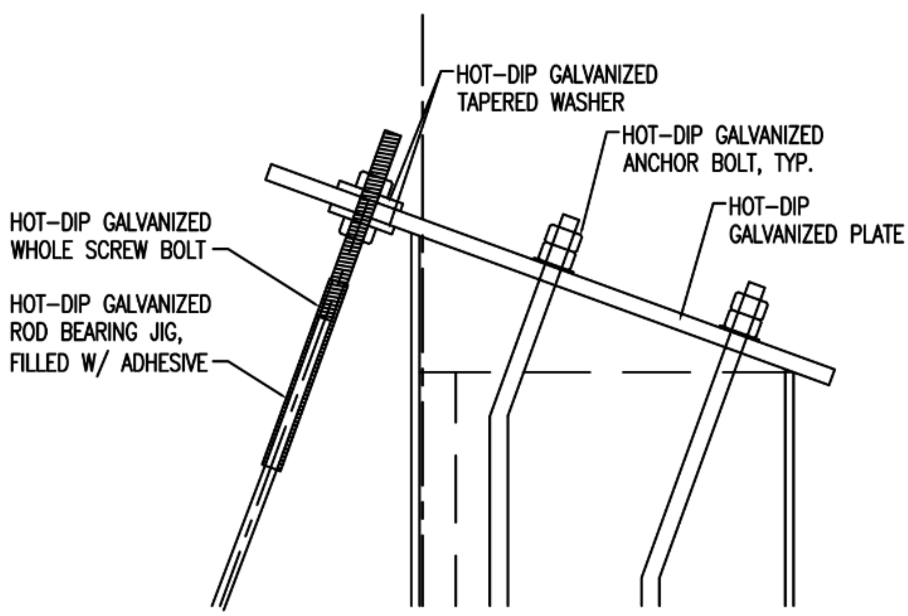
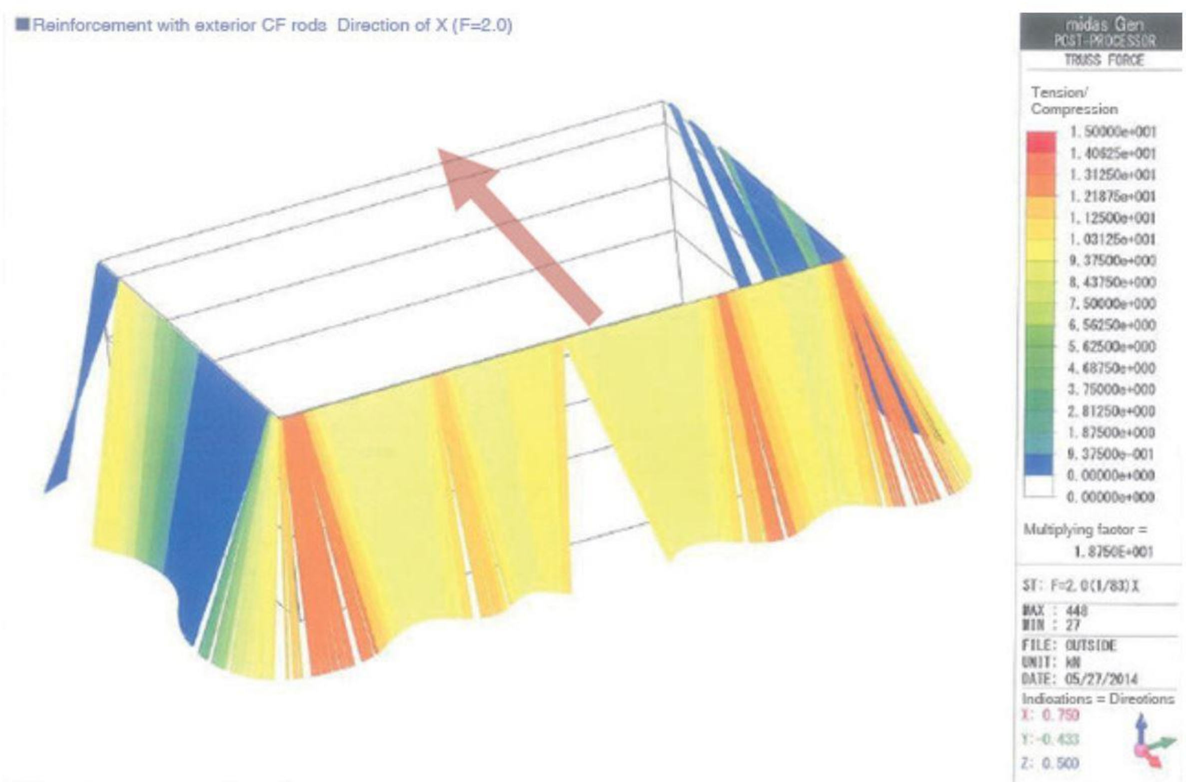


Figure 4.3-1: Application Detail. Recreated from ‘CABKOMA’ by Komatsu Matere.

The purpose of external bracing is to absorb seismic energy and safely transfer it away from the building, mitigating the structural impact of a seismic event. Vertical bracing provides load paths to transfer horizontal (lateral) forces to ground level and provide lateral stability. It also makes it possible to reduce the maximum response story drift angle (Kitajima, Chikui, Ageta, & Yokouchi, 2004). If the building does not sway as much, the likelihood of internal and external structural damage decreases.

The following figures illustrate a finite element analysis, using midas Gen software, of how the strand rods operate in the event of seismic activity.



Tensile strength applied to the rod in the event of an earthquake in the direction of X

Figure 4.3-2: Finite Element Analysis of Exterior Application of Strand Rods.
Reprinted from 'CABKOMA' by Komatsu Matere

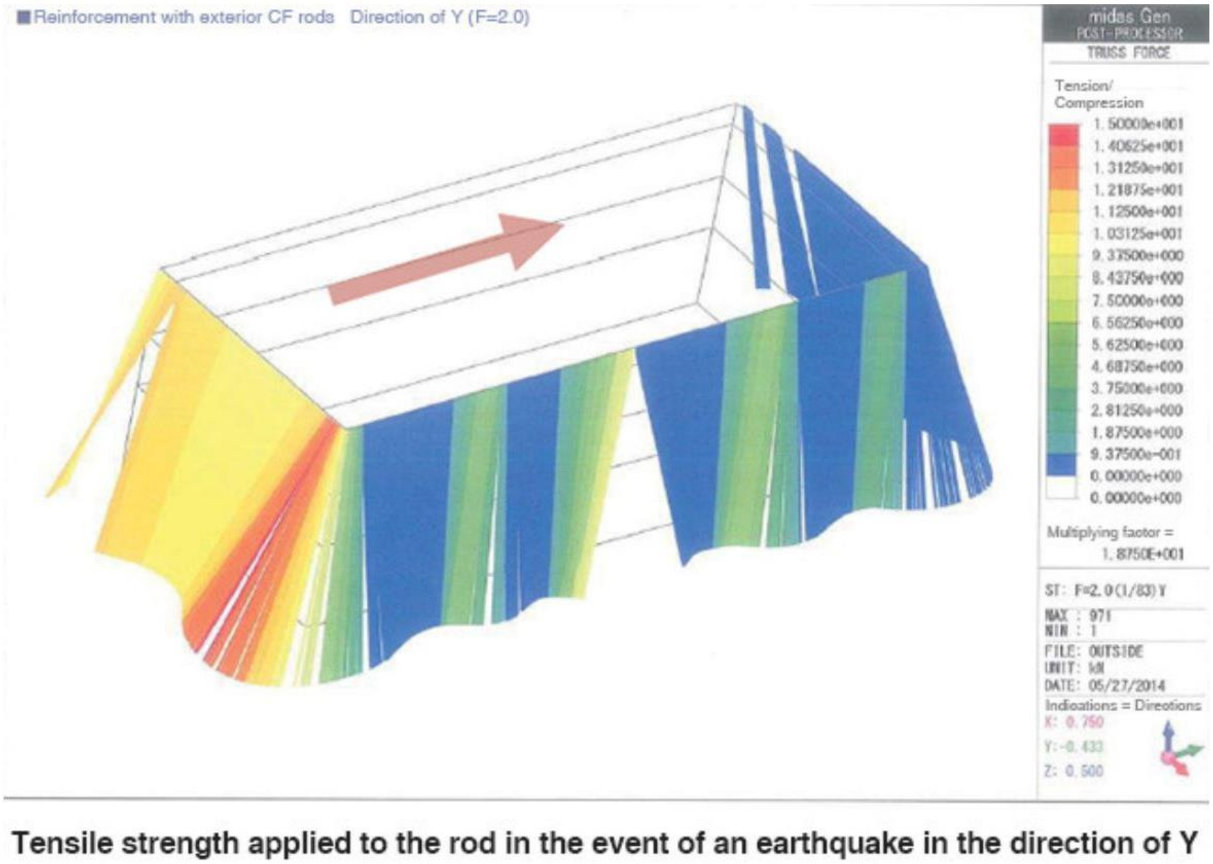


Figure 4.3-3: Finite Element Analysis of Exterior Application of Strand Rods.
Reprinted from 'CABKOMA' by Komatsu Matere

For interior applications, the strand rods can be used in a diagonal mesh pattern to act as a shear wall. A shear wall is used to resist lateral forces parallel to the plane of the wall. Lateral forces caused by wind, seismic activity, or ground settlement create powerful lateral forces, causing members to fail. The shear walls create a rigid vertical diaphragm capable of transferring the lateral loads to the foundation safely. These walls also provide adequate strength and stiffness to control lateral displacements during the event (Skyfi Education Labs Pvt. Ltd., 2016).

Typically, shear walls can cause problems in coordinating with façade design. It is best to use walls without openings to work around. If the design includes numerous windows or other similar features, it can be difficult to find an agreeable location between the engineer and the architect. The use of strand rods in a shear wall is beneficial because it is less bulky than a typical shear wall and provides visibility through the member which still allows for a more open feel in the space.

Figure 4.3-4: Interior Strand Rod Application. Reprinted from ‘CABKOMA’ by Komatsu Matere

The following figure illustrate a finite element analysis of how the strand rods operate in the event of seismic activity.

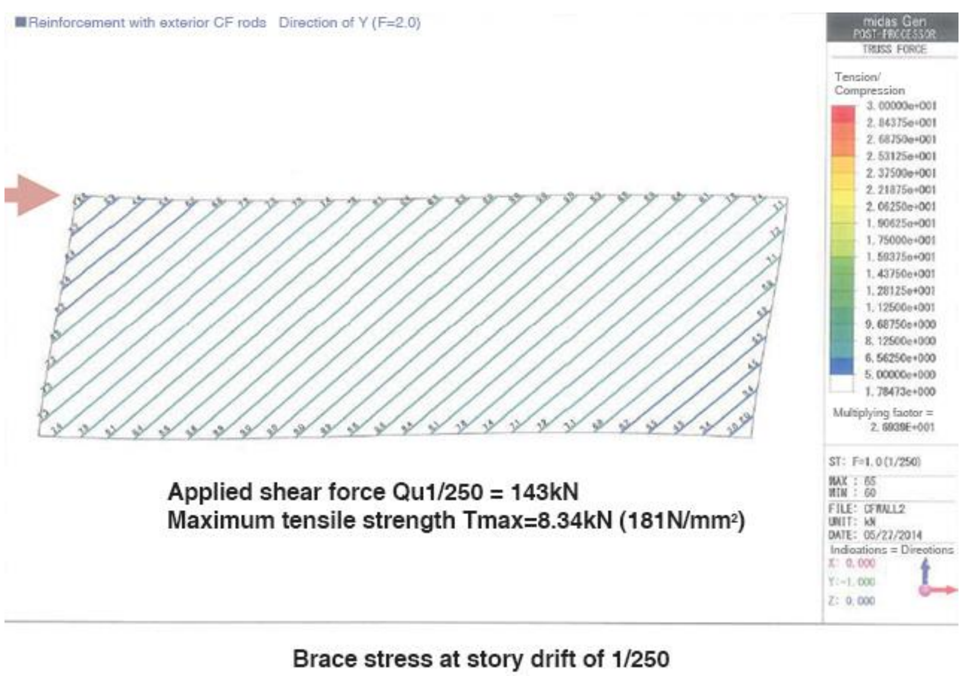


Figure 4.3-5: Finite Element Analysis of Interior Application of Strand Rods. Reprinted from ‘CABKOMA’ by Komatsu Matere

The primary goal of the application is to add additional seismic strength without affecting the existing structure. The reinforcement was planned such that the target reinforcement values would be reached within a story drift of 1/250. Figure 4.3-6 illustrates the strength versus the horizontal deformation and the differences between the strand rods and traditional seismic reinforcement.

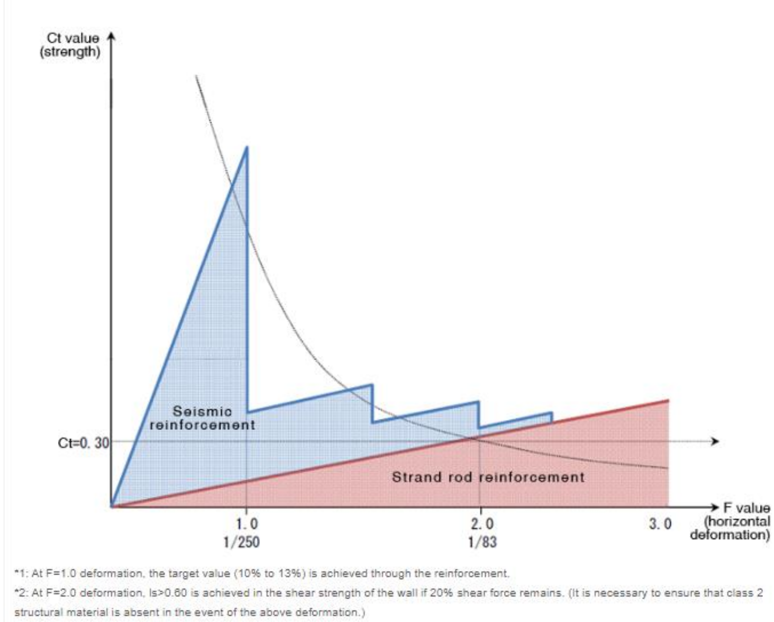


Figure 4.3-6: Strength vs. Horizontal Deformation in Strand Rods and Seismic Reinforcement. Reprinted from 'CABKOMA' by Komatsu Matere

4.4 – Advantages

CABKOMA strand rods have many desirable qualities. In 2018, the material received international recognition from JEC Group for being an innovative new material. JEC Group was established in 1963 and is the largest non-profit composites organization in the world. Their purpose is to promote the recognition and development of composite materials internationally. Strand rods were nominated based upon several key attributes such as: high productivity at low cost, high durability and strength, non-ferrous and rustproof material composition, light weight, windable, and good processability for manufacturing (JEC Group, 2018).

The rod itself is constructed of a thermoplastic resin, meaning that it can be easily bent and worked when heat is applied. This improves its workability on construction sites. This ease of installation feature meets "a great potential need in the building and construction industry" (JEC Group, 2018). This product is not difficult to install, easy to maintain, and extremely durable.

When considering its use as seismic reinforcement, the main advantage is its adaptivity for use in seismic force resisting systems. These rods can be used on a variety of structures constructed from various materials, including timber, concrete, masonry, steel, etc. Traditionally, there have been two effective ways to resist earthquakes (Baker, 2016). The first is to design buildings in such a way that they are not coupled with the ground, allowing the structure to move independently. This can be achieved using seismic base isolators; however, this must be a part of the foundation design from the beginning and is difficult in a retrofit scenario. The second is to a build a structure that can resist the forces that are created. A third option for existing structures is the application of a seismic retrofit.

Traditional retrofits involve additional bracing or adding elements to enhance the existing elements, which can be "troublesome, expensive, not to mention the look isn't particularly aesthetically pleasing" (Lee, 2016). By using the carbon fiber strand rods as an infill shear wall or exterior tie-downs, the "system can transfer the horizontal forces from an earthquake and direct them into the ground, resisting the shaking motion and potentially saving the structure" (Baker, 2016). Plus, it has the added benefit of being lightweight due to the use of carbon fiber, the first use of it in an earthquake-resistance role (Japan Trends, 2015).

In addition, if applied exclusively to the exterior of the structure, there is little to no interruption in the use of the building. The occupants can continue going about their work while the seismic retrofit is being performed outside. The building is continuously functional, making this an economically viable option for the building owners (Kitajima, Chikui, Ageta, & Yokouchi, 2004). If interior work is also required, the installation time is accelerated due to the carbon fiber strand rod's light weight and the thermoplastic nature of the material, which increases its workability.

Aesthetic appeal is another noteworthy benefit. Opinions on how the strand rods visually impact a structure are subjective and may vary widely. However, use of these strand rods is one of the rare cases in which a structural retrofit element can be used to enhance architectural appeal. Typically, the structural elements are hidden or disguised in final finishes. In this instance, these rods provide strength while still providing lightness. This retrofit approach produces additional stability against seismic damage while also achieving a "superb aesthetic quality" (Kuma, 2018).

Another advantage is the product's ability to be used on projects with the intention of preserving historically important structures. Since it is rust proof, it can also be used on important cultural landmarks (JEC Group, 2018). It was designed with the intent to be used on existing structures (Kuma, 2018). It can be "used to protect historical landmarks which might not have been reinforced" (Lee, 2016). In addition, carbon fiber strand rods meet all the requirements outlined by FEMA for the seismic retrofit of existing structures. Use of these rods also follows the guidelines presented for the rehabilitation of historically protected structures.

4.5 – Disadvantages

Strand rods are a relatively new technology, with development begun only recently in 2010 (KOMATSU MATERE Co., Ltd., 2019). The patent was granted in 2015 and the innovation is still developing (United States Patent No. 20160326323, 2015). There are only a handful of structures to date where this technology has been applied. In theory, this technology can be applied in numerous ways across the construction industry. However, the industry is typically slow to adopt new materials and methods until they have proven their value.

Since this material was designed to be used primarily with existing structures, there is little information available at this time regarding how it could be utilized for new construction. A contractor's unfamiliarity with the material may also inhibit their willingness to support using it as a seismic retrofit solution. For example, there are not clear guidelines regarding the allowable construction tolerances for the product yet.

In addition, this technology requires significant computing capability to accomplish the calculations required for properly designing the application methodology necessary to employ these strand rods in a retrofit configuration. According to Kengo Kuma, the architect of the project shown in Figure 4.1-1, there were many difficulties during development. They wanted to keep the overall design light and delicate. Therefore, not only did the rods have to be carefully considered, but the joints as well. "The positioning as well as the facing of the rod, these were all fully calculated and positioned with a computer. It's a structural calculation that can only be accomplished by today's state of the art computers. That's what made it possible" (Kuma, 2018).

The position and angle of each rod must be individually considered. Then the entire structure, including each individual element, is analyzed using finite element analysis. Seismic forces from each direction must also be considered to ensure that the rods have adequate strength to resist such forces.

Another disadvantage is that this new product has yet to be accepted by any codes or standards. A design must comply with the local building code before the use of this product is allowed. There are currently no codes or standards that explicitly outline design guidelines for carbon fiber strand rods. Therefore, performance-based design codes and specifications would have to be used to facilitate their use.

Performance-based design is “the process or methodology used by design professionals to create buildings that protect functionality and the continued availability of services” (FEMA, 2018). The performance-based codes define acceptable levels of risk and a thorough analysis is performed in order to ensure the design is within those levels. The provisions allow for the use of methods and materials not specified in the code, provided that the alternative is approved by the code official.

Lastly, as illustrated in Figure 4.1-1, the use of strand rods slightly increases the building’s footprint. Therefore, it will only be effective for structures that have additional space around them and this system cannot be applied to structures with neighbors immediately adjacent. “Now it seems unlikely that the whole of Japan will begin covering its buildings with this ‘string’ as it would be impractical, not to mention impossible in more urban settings. Instead, it might be more useful in more remote locations where more space is available” (Lee, 2016). Overall, this material has many desirable qualities and is a reasonable option worth consideration for the seismic rehabilitation of many existing structures.

Chapter 5 – High Performance Fiber-Reinforced Cementitious Composites

The second method explored is high performance fiber-reinforced cementitious composites (HPFRCC) prefabricated panel. Recent advancements in the cement industry have made this method a more viable option in a seismic retrofit capacity.

5.1 – Introduction

There are different definitions of fiber-reinforced cement composites. In general, the composite is composed of two main parts, the fiber and the cement matrix. Fibers are added to cement in order to improve the tensile capacity. (Naaman, 2006).

The cement matrix itself may also be considered a composite with several components, including but not limited to, cement, aggregates, additives, and air voids. The principal difference between the cement used in high-performance fiber-reinforced cement composites and typical concrete used for construction is the lack of coarse aggregates. Typically, fine aggregates, such as silica, are used instead. High performance fiber-reinforced cement composites have advanced in recent years due to innovations in production processes, such as self-compacting concrete, which decreases the porosity and increases the uniformity of the mixture (Naaman, 2006).

The fibers are discontinuous and randomly oriented and distributed throughout (Naaman, 2006). There are various options for the fibers. They can be natural organic, natural mineral, or manmade. Their physical and mechanical properties will impact the mixture. For example, the shape, length, diameter, density, surface roughness, chemical stability, flammability, tensile strength, elastic modulus, stiffness, ductility, and elongation all play a part in determining the overall strength and characteristics of the composite (Naaman, 2006).

Figure 5.1-1: Examples of Synthetic Fibers. Reprinted from ‘Ultra High-Performance Fiber-Reinforced Concrete’ by T. Buttignol, J. Souisa, and T. Bittencourt, 2017, p. 961

The fiber and matrix bond to create a compound with superior mechanical properties than each component individually. Fibers used in concrete structures have been found to reduce microcracking and cracking, increase resistance in tension, increase shear and bending strength, and increase ductility and the energy absorption capacity of the structure (Naaman, 2006). Enhancing the bond between the cement and the fibers also restrains spalling and provides additional structural integrity by keeping the reinforcing bars from buckling in a column (Naaman, 2006). To increase the bond, the surface of the fibers can be roughed up or mechanical deformations, such as coils, twists, or hooks can be introduced. Overall, the addition of fibers increases the “damage tolerance” of a structure.

Figure 5.1-2: Examples of Mechanically Deformed Steel Fibers. Reprinted from ‘Ultra High-Performance Fiber-Reinforced Concrete’ by T. Buttignol, J. Souisa, and T. Bittencourt, 2017, p. 961

There are several ways to classify fiber-reinforced composites based on characteristics. Recently, it has been proposed to classify them based on their stress-strain response in tension, i.e., either strain softening or strain hardening. For strain softening, “[crack] localization occurs immediately after first cracking and, with increasing elongation; the stress after first cracking is smaller than that at first cracking” as shown in Figure 5.1-3 (Naaman, 2006). Strain softening is characterized by “a stable crack propagation and a reduction of the tensile strength as a result of a gradual fiber debonding” (Buttignol, Sousa, & Bittencourt, 2017). For strain hardening, “the stress after first cracking increases with strain, and multiple cracking occurs up to the maximum post-cracking stress” also shown in the figure (Naaman, 2006). The finely distributed microcracks before crack localization occurs allowing the material to be used in the non-linear range without loss of performance (Buttignol, Sousa, & Bittencourt, 2017). Once localization occurs, the stress decreases with increasing elongation similar to the strain softening case.

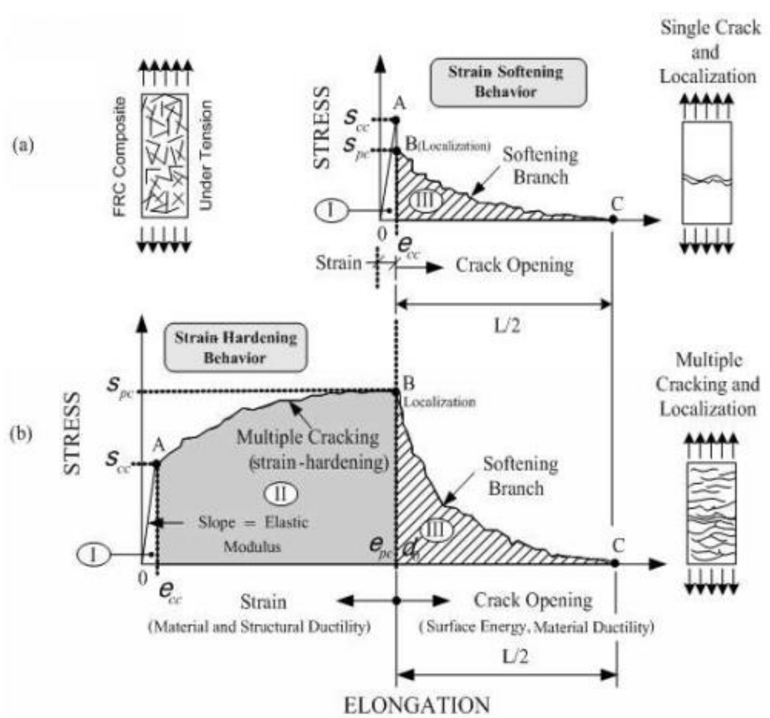


Figure 5.1-3: Stress-Elongation Curves in Tension for Fiber-Reinforced Cement Composites. Reprinted from ‘High-Performance Fiber Reinforced Cement Composites: Classification and Application’ by A. Naaman, p. 392

Overall, this union of fiber and cement creates a composite that outperforms normal and high strength concrete. It has a higher durability, increased bearing capacity, increased ductility, and increased toughness. The stress redistribution prevents the development of cracks, maintaining the materials low permeability (Buttignol, Sousa, & Bittencourt, 2017). As a result, it is possible to use this material for the construction of lighter, more durable, and more efficient and innovative structural elements (Buttignol, Sousa, & Bittencourt, 2017).

5.2 – Manufacturing Process

There is significant variability in the amount of cement, the aggregate sizes and types, fillers, binders, and admixtures in different cement mixes (Buttignol, Sousa, & Bittencourt, 2017). As a result, there are infinite variations of mix designs that produce different characteristics within the composite. Overall, the general process is as follows.

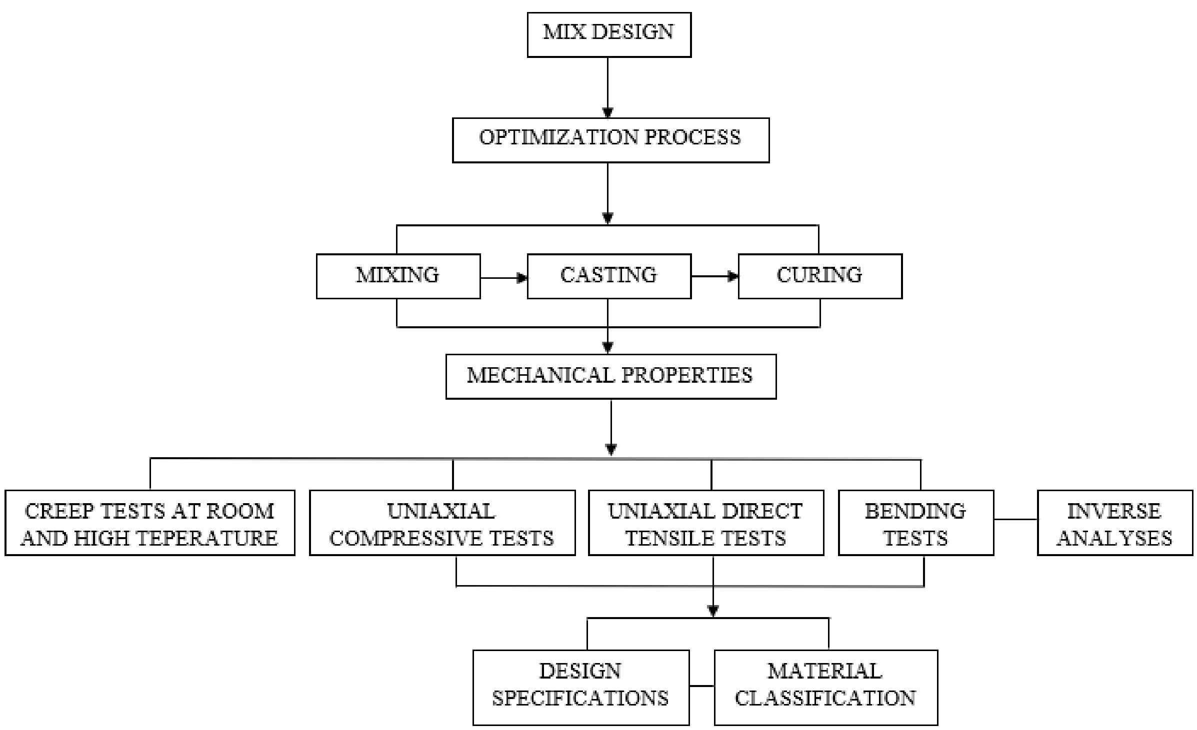


Figure 5.2-1: Fiber-Reinforced Cement Composites Manufacturing Process Flowchart. Recreated from 'Ultra High-Performance Fiber-Reinforced Concrete' by T. Buttignol, J. Souisa, and T. Bittencourt, 2017, p. 959

The optimization phase refers to modifying the mix design in order to achieve the desired results. For example, “an optimization process can reduce concrete porosity and enhance matrix microstructure links, contributing to increasing concrete strength and reduce creep effects” (Buttignol, Sousa, & Bittencourt, 2017). It is an iterative process and refinement will occur after every mix design.

During mixing, the fibers should be dispersed throughout the cement in a way that ensures a good packing density and the avoidance of materials agglomeration. To achieve this, the fine particles, such as binder and sand, should be mixed first. Then the addition of water and chemical admixtures is permissible. The fibers should be incorporated last (Buttignol, Sousa, & Bittencourt, 2017).

The addition of the water during the mixing process is called hydration. It is a thermo-activated process which is impacted by the temperature. The chemical reactions between the cementitious components and the water generate heat, increasing the overall temperature. Many components impact this process including the admixtures and binders in the cement and the water to cement ratio.

After mixing, the composite is placed. It has been empirically shown that pouring the cement from the center produces the best results for strength capacity. The outward flow leads to favorable alignment of the fibers, increasing the number of fibers bridging the cracks and as a result, increasing the strength (Buttignol, Sousa, & Bittencourt, 2017).

After it is placed, the cement is cured. There are numerous options for this process including air curing, steam curing, or tempered steam curing. As the cement cures, microcracking occurs. The cracking engages the fibers, improving the tensile strength of the composite. As the microfibers are activated by the microcracking, the composite behavior is characterized by a long elastic phase (Buttignol, Sousa, & Bittencourt, 2017).

5.3 – Applications

Fiber-reinforced cement composites can be used for a variety of functions. It can be used by itself for light structural elements. It can also be used as a hybrid with other materials for various uses. These include, but are not limited to, seismic reinforcement, blast resistance, offshore structures, long span structures, and fire protection. (Naaman, 2006). This material can be used alongside existing reinforced concrete or steel structures. Finally, fiber-reinforced cement composites can also be used in a repair and rehabilitation capacity, which will be the focus of the following section of this report.

Ideal uses for high-performance cement composites include beam-to-column connections in seismic resistant frames, beam-to-shear wall connections, coupling beams for seismic-cyclic resistance, in-fill damping structural elements, lower end of shear walls, tension zones of reinforced concrete beams, and compression zones of beams and columns (Naaman, 2006). These uses improve the durability and ductility of said elements and can be accomplished during a seismic retrofit.

In order to achieve seismic retrofit using high-performance fiber-reinforced cement composites, prefabricated panels can be used and attached to an existing structure. The panels are bolted on to the existing elements of the lateral force resisting system to provide additional strength. The panels are best utilized in locations with potential weaknesses in their connections, such as at beam-column joints as shown in Figure 5.3-1. For even better performance, panels can be applied to each side of the joint and connected using thru-bolts.

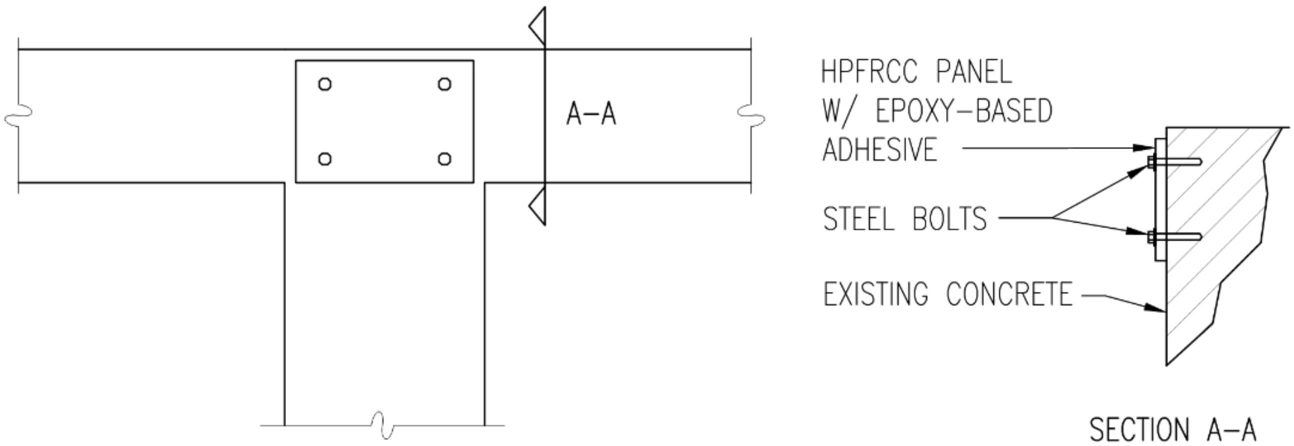


Figure 5.3-1: Application Detail of HPFRCC Panels. Recreated from 'Innovative Techniques for Seismic Retrofit of Reinforced Concrete Joints' by I. Bedirhanoglu, A. Ilki, N. Kumbasar, 2015.

According to the results of research on "High-Performance Fiber-Reinforced Cement Composites: An Alternative for Seismic Design of Structures," it was found that HPFRCC is highly adept to seismic applications. It is "effective in increasing shear strength, displacement capacity, and damage tolerance in members subjected to large inelastic deformations," such as those that would occur during a significant seismic event (Parra-Montesinos, 2005). It was found that high-performance fiber-reinforced cement composites perform well even when little or no steel transverse reinforcement has been utilized in the existing system. These results show promise in applications for unreinforced masonry structures or masonry and concrete structures with inadequate transverse reinforcement.

An experimental study on the "Retrofit of concrete panels with prefabricated HPFRCC plates" was performed to determine the effectiveness of the prefabricated panel method (Bedirhanoglu, Ilki, Incecik, & Kumbasar, 2008). The panels in this experiment were designed and tested specifically to overcome a lack of adequate shear strength in beam-column joints.

The fiber-reinforced cement composite panels were cast in wooden forms and placed on a vibration table to ensure adequate compaction (Bedirhanoglu, Ilki, Incecik, & Kumbasar, 2008). After the curing process, they were then attached to either side of normal concrete test specimens that measured 100 mm thick. The panel was attached using an epoxy-based adhesive and steel bolts as illustrated in Figure 5.3-3. Ordinary Portland cement was used for the concrete test specimens. The resultant concrete had an average compressive strength of 8 MPa and modulus of elasticity of 14000 MPa. The epoxy had a tensile strength of 25 MPa and a compressive strength of 75 MPa (Bedirhanoglu, Ilki, Incecik, & Kumbasar, 2008). Two concrete test specimens were analyzed without the addition of the prefabricated panels to determine the base strength and to highlight the improvement made through the addition of the panels. Different thicknesses of the HPFRCC panels, measuring 20, 30, and 40 mm, were also tested.

Figure 5.3-2: Test Specimens. Reprinted from ‘Retrofit of concrete panels with prefabricated HPFRCC plates’ by I. Bedirhanoglu, A. Ilki, O. Incecik, N. Kumbasar , 2008.

The high-performance fiber-reinforced cementitious composite panels were positioned with 10 mm distance to the edges of the concrete test specimen as shown in Figure 5.3-3. The diameter of the steel bolts used for attachment was 16 mm (5/8 in). This configuration was used in order to simulate a beam-column joint, that is loaded in shear, likely to be found in moment resisting frames.

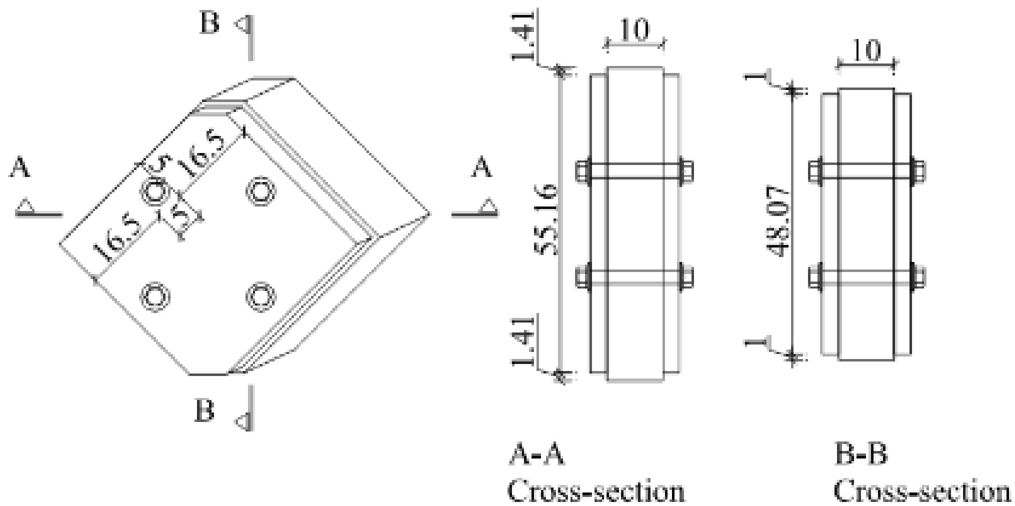


Figure 5.3-3: Attachment of HPFRCC Panels. Reprinted from ‘Retrofit of concrete panels with prefabricated HPFRCC plates’ by I. Bedirhanoglu, A. Ilki, O. Incecik, N. Kumbasar , 2008.

A concentric compressive load was applied to the specimens in the diagonal direction to simulate the shear force in the joint, and the load that caused failure was recorded. The vertical displacements were measured with displacement transducers throughout the test.

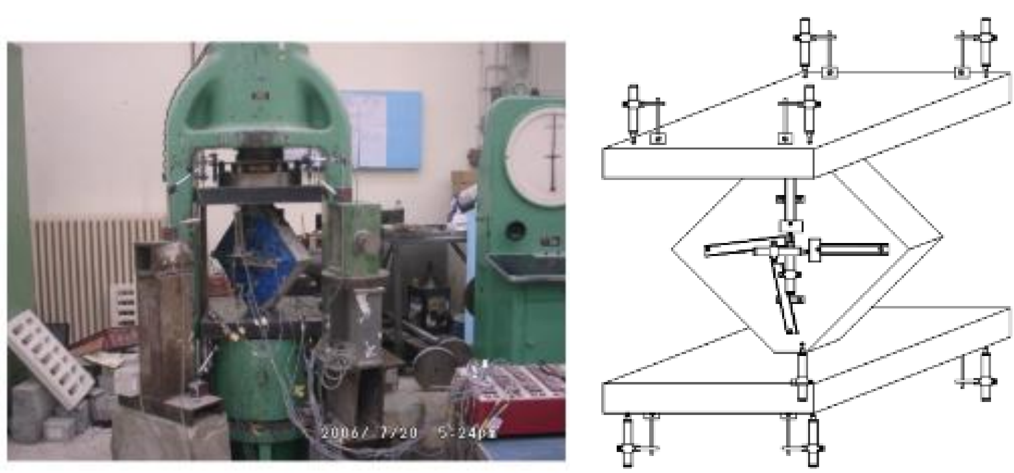


Figure 5.3-4: Loading of Specimens. Reprinted from ‘Retrofit of concrete panels with prefabricated HPFRCC plates’ by I. Bedirhanoglu, A. Ilki, O. Incecik, N. Kumbasar , 2008.

After testing, the results showed an increase in shear strength ranging from 45-150% for the retrofitted specimens (Bedirhanoglu, Ilki, Incecik, & Kumbasar, 2008).

Specimen	Failure mode	Maximum load (kN)	Shear strength (MPa)	Vertical strain at maximum load	Vertical strain at 85% of maximum vertical load on descending branch
DS-O-a	CF	104	1.73	0.0031	0.0032
DS-O-b	CF	113	1.86	0.0030	0.0031
DS-HPFRCC-2	DB1	155	2.60	0.0058	0.0062
DS-HPFRCC-2-A	DB1/CC	166	2.93	0.0113	0.0254
DS-HPFRCC-3	DB1	155	2.73	0.0042	0.0043
DS-HPFRCC-3-A	CC	228	4.02	0.0137	0.0281
DS-HPFRCC-4	DB1	155	2.69	0.0041	0.0043
DS-HPFRCC-4-A	CC	259	4.53	0.0181	0.0230

Table 5.3-1: Test Results of Prefabricated FRCC Panels. Reprinted from 'Retrofit of concrete panels with prefabricated HPFRCC plates' by I. Bedirhanoglu, A. Ilki, O. Incecik, N. Kumbasar , 2008.

The failure mode CF refers to failure at cleavage of panel at its middle vertical axis, DB1 is the loss of bond between the high performance reinforced cement composite panel and the concrete it was applied to, and CC is concrete crushing (Bedirhanoglu, Ilki, Incecik, & Kumbasar, 2008). It is important to note that the thicknesses of the HPFRCC panels were not as important as an adequate anchoring system. The retrofitted specimens also displayed an increased load carrying and displacement capacities as well as enhanced toughness characteristics (Bedirhanoglu, Ilki, Incecik, & Kumbasar, 2008).

The results of this study have shown that prefabricated HPFRCC panels can be used to strengthen existing systems in order to improve the seismic response of a structure and to prevent brittle shear failure at the joints. In a separate experimental study, it was found that the main deficiency of joints in a lateral force resisting system is the slip of beam longitudinal bars combined with shear damage at the joint after large drift ratios (such as 4%) occur (Bedirhanoglu, Ilki, & Kumbasar, 2012). Figure 5.3-5 illustrates the damage incurred.

Figure 5.3-5: Damage due to Shear Loading. Reprinted from 'Innovative Techniques for Seismic Retrofit of RC Joints' by I. Bedirhanoglu, A. Ilki, N. Kumbasar, 2015.

The damaged joints were then retrofitted with high-performance fiber-reinforced cement composite panels. They were bonded over the surface using an epoxy-based adhesive. Subsequent tests showed that the method prevented strength decay due to shear damage at the joint. The retrofitted joints did not show signs of strength degradation even under significantly higher drift ratios (Bedirhanoglu, Ilki, & Kumbasar, 2012).

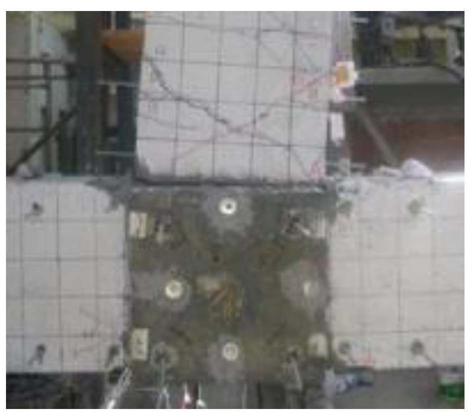


Figure 5.3-6: Damage after HPFRCC Panel Retrofit. Reprinted from 'Innovative Techniques for Seismic Retrofit of RC Joints' by I. Bedirhanoglu, A. Ilki, N. Kumbasar, 2015.

Both studies illustrated that HPFRCC panels are an effective method to strengthen and retrofit existing or damaged structural components for seismic resistance.

5.4 – Advantages

A chain is only as strong as its weakest link. Similarly, the lateral force resisting system is only as strong as its weakest component. Commonly, only a small part of the structure may require strengthening in order to improve the performance of the whole system during a seismic event. The lack of adequate shear strength of beam-column joints can be remedied through the use of prefabricated high performance fiber-reinforced cement composites (Bedirhanoglu, Ilki, Incecik, & Kumbasar, 2008). If the HPFRCC panels are utilized in specific locations of weaknesses, the application will make them highly effective at increasing the lateral force resisting capability of a structure as well as providing an economically justifiable retrofit approach (Naaman, 2006).

Since the HPFRCC modifications are concentrated on specific locations, their installation is less of a disruption to the function of a building as a whole. Utilizing an incremental implementation plan, the structure can continue to perform in its' intended capacity while these upgrades are being completed around the occupants and their ongoing operations.

Prefabrication of the panels yields a more efficient installation requiring less time and further reducing impacts on the building's users. When each panel has already been pre-formed to the specified dimensions necessary for installation and the connection methodology has already been considered, the installation is simply a matter of placing and fastening the panels to the existing structure which ensures seismic rehabilitation can be accomplished in a timely matter.

5.5 – Disadvantages

The manufacturing process for fiber-reinforced cement composites results in a material in which the fibers are randomly oriented. While there are certain methods or practices to minimized discrepancies in material properties, the characteristics of the resultant composite cannot be guaranteed throughout.

In addition, the application of prefabricated HPFRCC panels provides a solution which is somewhat narrow in scope. It is highly beneficial for existing concrete lateral force resisting systems, to strengthen the existing joints. However, if there is no lateral force resisting system in place, there is nothing to strengthen. This solution is less versatile due to the focused nature of application. It can be applied to structures utilizing alternate lateral force resisting systems but there is a lack of research on these methods currently.

Lastly, high-performance fiber-reinforced cement composite panels take time to produce. While field application can be streamlined, each member must be manufactured considering the existing conditions of the structure to which it will be applied. As demonstrated in the manufacturing process, the optimization of the mix design and the time it takes to produce and cure the panels can equate to lengthy production lead time.

Chapter 6 – Conclusion

In a survey regarding the public preferences for the seismic performance of buildings, it was found that a majority of respondents were unaware of the current standards for seismic performance objectives. However, they also responded that it was their expectation for buildings to remain functional or habitable during and after a large earthquake and these respondents were willing to make investments in order to achieve that goal. The research was built on a web-based survey for California and the Central United States, specifically around the New Madrid Seismic Zone, both areas of significant seismic activity. Approximately 80% of respondents believed that seismic performance of buildings is important or very important, even in regions less impacted by seismic activity (University of Colorado, 2016).

The general public is not often aware of all that goes into the design of a structure. However, they do expect the structures to perform in a certain way during seismic events, no matter when the date of the original design and construction occurred.

With the frequency and spatial variety of seismic events increasing in recent years, a wider range of locations have now been identified as being exposed and vulnerable to seismic hazard. Even with modern scientific instrumentation, seismic events are challenging to accurately predict. The location and depth of the earthquake and the surrounding soil conditions are factors that impact the severity of the forces acting on a structure. Additionally, the height, weight, configuration, composition, stiffness, and natural frequency all collectively impact how the lateral forces produced by a seismic event will affect the structure. Without an adequate lateral force resisting system in place, a structure is vulnerable to damage, likely also putting the occupants in danger.

As illustrated by the review of code history, seismic design has not always been common practice. Many existing structures were not designed with adequate consideration of the lateral forces produced by a seismic event acting upon the structure. For the reasons listed above, many structures are in immediate need of practical, cost-effective seismic rehabilitation.

Current practices used to perform seismic retrofits can be interruptive to the continued use of the structure, causing losses in productivity and therefore discouraging some building owners from moving forward with rehabilitation. Fortunately, there are newer, minimally invasive methods that accomplish the seismic rehabilitation with minimal disturbance to the occupants.

The addition of strand rods on the interior or exterior of a structure provide a lightweight seismic reinforcement retrofit solution. Using these rods to create infill shear walls or exterior tie-downs provide resistance to lateral forces incurred by structures during a seismic event. The thermoplastic nature of the composite material increases its workability, allowing for faster installation. The carbon fibers used within the strand rods provides greater strength with less weight.

When applied to the exterior, strand rods slightly increase the footprint of a building. Therefore, adequate room surrounding the building must be present. Strand rods provide design flexibility as they can be used on existing structures of varying composition, age, heights, and configurations.

Alternatively, high-performance fiber-reinforced cementitious composite prefabricated panels can be applied to many structure types. Often, the point of weakness in a lateral force resisting system is the connection between elements. These panels work to strengthen the durability and ductility of beam-to-column and beam-to-shear wall connections within the system. They can also be used in other capacities to strengthen the elements that compose the lateral force resisting system.

This option works best when there is already an existing lateral force resisting system in place where these elements just need additional strength for resisting high lateral forces. Since the panels are prefabricated, the on-site implementation has a shorter timeline when compared to other traditional seismic rehabilitation methods but this option still requires sufficient time for panel manufacturing.

Both retrofit methods discussed in this report are new and still under development. Further research is needed to advance the materials and methods of application. Additional studies can provide deeper insight into the behavior of these materials and to find more efficient ways to apply them. More experimental and analytical data are necessary to codify the methods and to develop design guides that can be utilized by practicing engineers.

Overall, there are methods of seismic rehabilitation that can satisfy the needs of those involved in the process. Using the minimally invasive methods discussed, the occupants are not displaced during the seismic retrofit. Productivity does not cease, and the structure is still able to function as intended. The outcome of the process is that the building owner receives a safer structure, which decreases their risk and increases tenant satisfaction.

Currently, there are a wide variety and large quantity of structures that are in need of a seismic retrofit. The materials and methods discussed in this report have the ability to be applied to structures of various shapes and compositions including historically landmarked properties. The versatility, constructability, and optimized installation timeline make these methods viable options that warrant consideration as retrofit solutions for structures located in seismically risky regions.

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