CHAPTER 1
Introduction

1.1 Background

Masonry is one of the earliest artifacts invented by man to meet his shelter need. Mud/adobe, stone, and burnt clay bricks have been extensively used in the ancient times and are still in practice all over the world. The masonry consists of two different materials; brick unit and mortar. The common masonry units are stones, mud/adobe bricks, concrete blocks, burnt-clay bricks, and calcium silicate bricks. The earliest masonry structures were constructed using mud/adobe, and stone bricks. The Indus valley civilization, which flourished from about 3000 BC to 1600 BC made prolific use of burnt bricks in the South Asian subcontinent [1]. Mud bricks and stones were also used during this period. In the 16th century, brick work became very decorative and was used for construction of beautiful temples in Tamilnadu, India. In 18th century, the Industrial revolution in the England led to improvement in brunt bricks making by use of extrusion process and continuous kiln. Concrete bricks were introduced in mid of 18th century. Now hollow concrete bricks are used for reinforced masonry construction. During ancient period mortar was used in the form of mud, clay, bitumen or clay-straw mix. Few thousand years ago, Egyptians used calcined gypsum as a mortar while the Greeks and Romans added lime, water and crushed stone or bricks to make mortar [2]. The Romans found that lime mortar did not harden under water, then they started mixing volcanic ash in the lime what became known as pozzolanic cement [3]. The name pozzolanic is derived from the village of Pozzuoli near Vesuvius where the volcanic ash was extracted. The modern cement (Portland cement) was invented by Joseph Aspdin in England in 1824. After that time, Portland cement mortar has proceeded till today by the invention of new chemical and mineral admixtures.

After more than 6000 years, masonry is still used as a construction material in most of the countries due to its advantages such as good heat insulation properties, high compressive strength, good soundness, easy availability, durability, and the low cost. The appeal of masonry structures for their aesthetic beauty, user comfortability, and closeness to nature have attracted many for masonry buildings. Other uses of masonry structure are in partition walls, retaining walls, arches, dams, and columns or piers, etc. Masonry is also used in building for cladding and roofing. Some of the world's famous monuments are built with masonry structures. The Hanging Garden; the Great wall of China (the largest man made object on earth); the Hagia Sophia and the Taj Mahal in India are some of the examples of renowned masonry structures.

1.2 Need of Strengthening and Retrofitting

The masonry structures are well known for their simplicity in construction and economy compared to steel and reinforced concrete structures. Masonry structures represent a large portion of the residential masonry building and historical monuments in the world. From ancient time to present, there are magnificent examples of masonry construction that would be very difficult and expensive to duplicate today even with our advanced design skills, modern materials, and machines. These monuments represent the identity of the culture, country, region, and artistic values and hence preservations of these structures are very important. Archaeological survey of India has reported that there are at present more than 3650 ancient monuments and archaeological sites in the nation [2]. These old structures have not been designed for earthquake loads; masonry walls of the building were principally designed to resist gravity loads. Moreover, a large number of masonry houses exist all over the world. Anand [4] reported that the masonry house in India constitutes 84.7 % of the total housing units as per data of Indian census 2001. However, the strength and ductility of these brittle brick masonry structures are limited and susceptible to collapse without significant warning especially under earthquake loading situation. The human casualties and socio-economic problems along with damage and collapse of masonry structures occurred due to earthquakes. A large number of human casualties occurred during the past earthquakes due to the failure of unreinforced masonry structures. More than 15 lakh people have lost their lives due to collapse of the building during the earthquake in last 100 years, all over the world. In 1976, approximately 2.4 lakh people lost their lives due to an earthquake in China which was the worst death toll from an earthquake in the past century [5]. The masonry structures have performed poorly during the Maharstrastra earthquake in 1993 and Bhuj earthquake (2001) which caused more than 10000 deaths [6]. More recently in 2015, numerous masonry structures partially or completely collapsed during the Nepal earthquake resulting in approximately 8000 fatalities [7]. Therefore, moderate to strong earthquakes can destroy complete villages or cities resulting in massive human casualties and extensive property losses. Hence, retrofitting of these structures and improving their strength is significant and vital. The strengthening and retrofitting of existing structures is required due to many reasons such as lack of stiffness, strength, durability, and ductility. Apart from earthquake requirement, masonry structures need strengthening due to general deterioration. Deterioration of these masonry structures might be due to ageing, corrosion, poor maintenance, poor initial design or construction. Consequently, the demand for strengthening and retrofitting of these buildings has become increasingly stronger in the last few years. Moreover, based on new design codes most of the existing structures need to be upgraded [8]. For example, the building evaluations have shown that approximately 96 % of masonry building need to be retrofitted. It is also observed that retrofitting makes a building 30% more efficient than existing one. In this way environmental protection can also be achieved via retrofitting rather than constructing new structures [9]. Thereby, the development of an effective and affordable method for strengthening and retrofitting of masonry elements is needed.

1.3 Conventional Methods for Retrofitting/Strengthening of Masonry Structures

There are several conventional techniques to strengthen and for retrofitting of the masonry structures. Few of the techniques which are being adopted for strengthening and retrofitting of masonry structures are discussed in this section.

1.3.1 Surface treatment

The surface treatment is a common method which has largely been developed through experience. The surface treatment incorporates different techniques such as Gunite or Shotcrete, Reinforced plaster, and Ferrocement. All of these techniques have to be found very effective for masonry exterior and architectural or historical appearance of the structures.

Shotcrete: It is a covering method of masonry walls reinforced with steel rods and steel mesh with sprayed concrete. The thickness of a shotcrete depends upon the seismic demand and generally, the overlay thickness is provided at least 60 mm. Many researchers have studied the advantages and disadvantages of shotcrete method [10-15]. Shotcrete (Fig 1.1) is very effective for increasing the flexural and shear load carrying capacity of the retrofitted walls. The mesh used for shotcrete helps to restrict the cracking in masonry units and improved the inelastic deformation capacity. However, shotcrete is expensive because of considerable materials and special workers are involved with placement.

Fig. 1.1 Applying Shotcrete [10]

Reinforced plaster: A thin layer of cement mortar applied over steel reinforcement can be used for retrofitting [16]. The steel reinforcement can be arranged as diagonal bars or as a vertical and horizontal mesh. The improved strength depends on the cement mortar strength, strengthening layer thickness, the degree of damage, the reinforcement quantity and its bonding with the masonry wall. The major advantage of the reinforced plaster is the ease of the construction effort because it requires very little surface preparation and skilled labor [17].

Ferro-cement: It is getting more attention because of its advantages such as light-weight, ductile, water tightness, ease in construction and maintenance. It consists of closely spaced multiple layers of fine rods mesh with reinforcement ratio of 3-8% completely embedded in a high strength (15-30 MPa) cement mortar layer (10- 50 mm thickness) [10]. A typical mortar mix consists of 1-part cement: 1.5-3 parts sand with approximately 0.4 w/c ratio. The strength of the mortar can be improved by adding low-cost fiber. Ferro-cement is an orthotropic composite material [18]. The mechanical properties of Ferro-cement are depending on mesh amount, type, and orientation of the reinforcement. The disadvantage of this technique is very labor intensive which makes it expensive for industrial applications in the western world. Thus it is mainly used in developing countries where labor cost is low. In addition, threats to degradation (rust) of the steel components is a possibility if air voids are left in the original construction which makes the system to fail [19].

1.3.2 Bamboo reinforcement

This technique is simple enough to understand and can be easily applied without any prior special expertise. This retrofitting technique enhances the seismic capacity of adobe masonry building. It consists of vertical and horizontal bamboo reinforcement tie with chicken wire mesh and a ring beam. It has been shown that adobe masonry building retrofitted by this system increases the collapse time of structure whereas it has little capacity to prevent cracking at low-intensity ground motions [20]. The advantages of this method are low cost and no need of special workers required. Limitation of this technique is that the bamboo has poor fire-resistance and it can be damage by insect and fungi.

1.3.3 Stitching & grout/epoxy injection

This technique is one of the most widely used strengthening methods of masonry structures, as it does not alter the aesthetic architectural features of the existing building. This method involves injecting grout or epoxy into the walls in order to fill voids or crack of the building. Grouting can be done manually, under pressure, by gravity, and through the vacuum. The main purpose of injections is to restore the original integrity of the retrofitted masonry wall and to fill the voids and cracks, which are present in the masonry due to chemical and physical deterioration. For injection, epoxy resin is used for relatively small cracks (less than 2 mm wide); while, cement based grout is considered more appropriate for filling of larger cracks, voids and empty collar joint in masonry walls [21-22]. Schuller et al. [22] used a cement-based grout (Portland cement with expansive admixture and w/c ratio of 0.75) to inject 0.08 mm wide cracks. In addition to grouting, existing larger cracks can be stitched together using steel ties and mortar. This technique gained a popularity because of minimal cost, material availability, ease of implementation. Indian Standard (IS) 13935:1993 [23] has discussed in detail the grouting technique for masonry structures. Eurocode 8 [24] and Federal Emergency Management Agency (FEMA) 273 [25] also recognize the grout injections technique for the strengthening of unreinforced masonry (URM) walls. Limitation of grouting technique is that it cannot be relied on as far as the improving or making a new connection between orthogonal walls is concerned [2].

1.3.4 Center core method

Center core method is an advanced method for strengthening of unreinforced masonry structures. The method is a nondestructive method which could be achieved without evacuation of the structures. The method is useful for historical buildings to preserve the architectural aspect of the structures and intervention can be carried externally. In the center core system, grouted core placed in the center of an existing masonry wall and a continuous vertical hole is drilled from the top to basement of the wall. Then, the reinforced steel bars are embedded in the holes and cement grout will be poured to create bond strength between wall and bars. The diameter of the core was depending upon the thickness of wall and the required retrofitting strength. However, the spacing between the successive cores along the length of walls depends upon the seismic demand and existing capacity of the masonry walls [2]. Generally, the diameter of the vertical core is taken between the range of 50-125 mm from the center of the wall at regular intervals of about 900 to 1500 mm apart. The advantage of this technique is the minimal site and interior disturbance and no disfiguring of the internal or external fabric to accomplish safe resistance to future ground shaking [15]. However, the main disadvantage of center core system is given by the fact that high tech equipment, highly skilled labor, and stringent quality control are required. Moreover, the technique tends to create zones with common varying stiffness and strengthened properties [15].

1.3.5 Post tensioning

This technique has been extensively used to improve the tensile and flexural capacity of URM walls. For strengthening of masonry wall, this method is applied by drilling vertical core from top of the masonry walls and then inserting prestressed reinforcement along the vertical member. The prestressed steel bars is designed to take all the tensile stresses associated with the expected lateral loads. In this method, the compressive strength of the masonry is involved to counteract the tensile stresses resulting from lateral loads. This technique has an advantage that it does not alter the appearance of the structure which is important for historical structures. However, this method has been somewhat costly. Moreover, the biggest drawbacks of the method are that external connections and straps might affect the architectural aspect of the structures and post tensioning reinforcement being external are exposed to corrosion.

1.3.6 Confinement

Confinement strengthening technique one of the most widely used for masonry structures in Asia and Latin America. In China, the confinement is used in new masonry structures as well as retrofitting of existing masonry structures. However, it is difficult to construct such confinement in the existing masonry structures. This method involves introducing the reinforced masonry tie columns which confine the walls at all corners and intersections. The reinforced tie columns should be connected with a tie beam along the walls at floor level to make this confinement more effective. Karantoni and Faradis [26] shows that tie columns without tie beams do not have a significant improvement of walls behavior. However, this method improves the in-plane deformability and energy dissipation of a masonry structure. The confinement in existing structures have improved the flexural strength, shear strength and ductility of the masonry walls. Limitation of confinement method in retrofitting is that it requires a large number of laborers.

The conventional retrofitting/strengthening patterns are not showing durable performance and long life. Usage of non-corrodible, high strength and ductile materials for the strengthening of brick masonry structures seem to be a potential solution. Hence, it is essential to use such high performance materials for strengthening and retrofitting the brick masonry structures. Use of fiber reinforced polymer (FRP) bars/fabrics and ductile fiber reinforced cementitious composite (DFRCC) is expected to give maximum strength along with ultra-high ductility and durable structures with little maintenance requirements. Details of these strengthening materials, i.e., FRP and DFRCC are discussed in the next sections.

1.4 Fiber Reinforced Polymer (FRP)

In the following sub-sections, details of FRP material characteristics and application are presented.

1.4.1 History of FRP materials

Incorporation of fiber reinforced polymer (FRP) composite technology into the industrial world was introduced during the late nineties. The first known FRP product is a hull boat manufactured during mid-1930 which was the part of a manufacturing project using a fiber glass fabric and polyester resin [27]. During and after World War II, the FRP composite products were exploited in aerospace industries for making of aircrafts. The production and use of carbon fiber began in late 1950 with pursuit of improved ablative material for rockets [28]. At the same time, Aramid fibers were being produced and appeared first under the trade name of Nomex by DuPont [29]. The FRP industries finally matured in late 1970 when polymer productions increased in comparison to that of steel making FRP the universal material that it is today. In 1984, the use of FRP composites for strengthening of reinforced concrete (RC) structures was first investigated at the Swiss Federal laboratory where tests on RC beams strengthened with CFRP plates were performed [30]. In recent years, the applications of FRP composite in constructions have seen rapidly growing around the world in terms of both research activities and practical purpose. Indeed, many have evoked FRP an excellent composite as a new generation of constructions materials following concrete and steel.

1.4.2 FRP composite

FRP composites are defined as a polymer matrix, either thermoset or thermoplastic, that is reinforced with a fiber to provide a discernible reinforcing function in one or more directions. FRP composites are anisotropic (properties vary with the direction), whereas steel or aluminum are isotropic (uniform properties in all directions). The performance of any composite depends on the material of which they are made, and the interaction between the materials (fibers and matrix) [27]. The mechanical properties of the FRP depend upon the arrangement of the primary load-bearing portion of the reinforcing fibers.

(a) Reinforcing fibers

Fibers are the principally load-bearing component of any FRP products. Fibers are pre-assembled into various forms to make the fabrication of composite products. Discontinuous fibers are generally used to make low-cost composite products such as non-woven mats. Fibers, roving, and filaments yarns are generally representing parallel bundles of continuous filaments. The fibers bundles may be used directly in composite fabrications such as by pultrusion process or filament winding to produce bars, or they may be further converted to other reinforced forms such as prepregs, fabrics, and sheets [31]. Fibers can be both natural and synthetic. However, synthetic fibers are commercially used. Most commercial fibers used in the application of civil engineering are glass, carbon, and aramid. Typical mechanical properties of fibers are given in Table 1.1. There are three main sources for the production of carbon fibers, namely, Pitch, Polyacrylonitrile and Raylon [32]. These are manufactured at a processing temperature of around 1000-1500°C. The fibers are classified as high modulus and low modulus fibers based on the fiber microstructure. The fibers with high modulus and low modulus can be identify with value of modulus around 200 GPa and 50 GPa, respectively.

In comparison to carbon fibers, glass fibers are economical and can have strength in a specific direction according to fiber orientation. The main ingredients which constitutes glass fiber are silica (50-70 %), aluminum, calcium carbonate, iron. The glass fibers are classified as E glass, S-Glass or C-glass based on their ingredients composition present in their microstructures. As the surface of glass fiber is very active, thus they are susceptible to damage while handling.

The aramid fibers are a class of strong synthetic fibers. The chemical composition of fibers is poly-para-phenylene- terephthalamide (PPD-T). The aromatic ring in the PPD-T gives high thermal stability to the fibers. These fibers are 50% stronger than E glass. These fibers can be degraded by the action of strong acids and bases, but are unaffected by most of the solvents.

Table 1.1 Typical properties of fiber materials [33]

Property	E-Glass	Carbon	Aramid
Tensile strength (MPa)	2350-4600	2600-3600	2800-4100
Elastic modulus (GPa)	73-88	200-400	70-190
Strain at failure (%)	2.5-4.5	0.6-1.5	2.0-4.0
Density (g/cm^3)	2.6	1.7-1.9	1.4

(b) Resin matrix

The term matrix used in the context of FRP reinforcements is analogous to the term concrete in reinforced structures. The role of matrix in the FRP composite is to bind the fibers in the desired locations; transfer the load to the fibers and protect them from environmental damages. Three different types of resins i.e., Epoxy, Polyester, and Vinyl-esters are most commonly used in the production of FRP composite [27]. Epoxy resin is most widely used in the composite part, structures, and concrete repair. A major benefit of epoxy resin is its lower shrinkage in comparison to polyester resin. Polyester resins are produced by condensation polymerization of the dicarboxylic acid and difunctional alcohols (glycols). Polyesters are versatile because of their capacity to be modified or tailored during the building of the polymer chain. Polyester resins have been found very efficient in all the segments of composite industries. Vinyl-ester resins were developed to combine the advantages of epoxy resins with those of unsaturated polyester resins. These resins are produced by reacting epoxy resin with acrylic or methacrylic acid. This provides as an unsaturated site, much like that produced in polyester resin when maleic anhydride is used. Typical mechanical properties of resin matrix are given in Table 1.2.

1.4.3 Structural applications of FRP materials

There are many applications of FRP materials in Civil engineering field. However, the applications are classified into two broad divisions: (a) Applications of FRP materials for new constructions, (b) Retrofitting and strengthening of structures using FRP materials. Architects have also discovered the many applications for which FRP can be used such as siding/cladding, roofing, flooring, and partitions.

Table 1.2 Typical properties of resin matrix [33]

Property	**Epoxy**	**Polyester**	**Vinyl-ester**
Tensile strength (MPa)	60-80	20-70	68-82
Elastic modulus (GPa)	2-4	2-3	3.5
Strain at failure (%)	1-8	1-5	3-4
Density (g/cm^3)	1.2-1.3	1.2-1.3	1.12-1.16
Glass transition temperature (°C)	100-270	70-120	102-150

(a) Application of FRP materials for new constructions

FRP composite materials have demonstrated great potential in construction industries. FRP bars and tendons are widely used for the construction of all flexural members and more specifically bridge decks and bridge girders. Structures such as bridges built completely with FRP composites have demonstrated exceptional durability and effective resistance to the effect of environmental exposure. Bridge street bridge [34] situated in Southfield, Michigan, USA is one of the famous vehicular bridge made of FRP prestressing external post-tensioning tendons and FRP bars. The first design guidelines in the world for FRP reinforced concrete building structures were established in Japan in 1993. Guide for designs and constructions of structural concrete reinforced with FRP bars (ACI 440.1R-06) [35], Prestressing concrete structures with FRP tendons (ACI 440.4R-04) [34], Guidelines for design of concrete structure using FRP material (JSCE Standard,1996) [36], Externally bonded FRP reinforcement for RC structures (FIB 9.3 Task Group, 2001) [37], and ISIS Canada design manuals [38] published in 2001 are the some of the popular design guidelines available for the applications of FRP materials for new constructions. In India, however, no design guidelines are available for FRP materials and constructions.

(b) Retrofitting and strengthening of structures using FRP materials

One of the most common use of FRP, involves the retrofitting and strengthening of damaged or deteriorating structures such as beams, girder, slab, columns, and frames. The FRP materials have shown great potential in replacing the steel reinforcement as a retrofit material because of their advantages such as lightweight, high tensile strength, non-corrodible characteristics, suitable to curved and rough surface, flexible and easy application, less disturbance to occupants during retrofitting work. FRP composites can be used in different forms of strengthening such as FRP wrapping, FRP laminates, FRP prestressing, and FRP bars in near surface mounted. Assessment of the effectiveness of FRP composite as retrofitting or strengthening alternative for masonry structures is required to be carried out experimentally.

In 2010, the American Concrete Institute (ACI) published a new standard ACI 440.7R-10 [39] entitled "Guide for the design and construction of externally bonded fiber-reinforced systems for strengthening unreinforced masonry system." This article provides an overview of the ACI design procedures for in-plane and out-of-plane strengthening of URM wall systems. It also provides two example case studies to further detail the design processes of the new standard in an effort to further disseminate the design approach.

1.5 Engineered Cementitious Composite (ECC)

Even though there were a number of investigations conducted on fiber reinforced concrete/composites before the year 1990, the Engineered Cementitious Composite (ECC) material came into existence only in the early nineties. In the year 1992, Li and Leung [40] studied the steady-state and multiple cracking of short random fibers in the brittle composite. In this study, conditions for steady-state and multiple cracking were found which can embody all micro mechanical properties to composite performance. These micro-mechanical principles have become the theory behind the ECC technology. Further, the pseudo strain hardening behavior and translation of material behavior to structural behavior were demonstrated.

ECC is a cement based composite which contains discontinuous short polymeric fibers featuring high ductility and strain hardening behavior based upon micromechanics. Micro-mechanics mean that the mechanical interaction between fiber, matrix, and interface are taken into account by a micro-mechanical model which relates these constituent properties to composite response [32]. ECC exhibits tensile strain hardening with multiple micro-cracking during the inelastic deformation unlike the conventional fiber reinforced composite (Fig. 1.2). ECC has high ductile properties after the first crack and due to this property, it is also known as Ductile Fiber Reinforced Composite (DFRCC). ECC can be developed with a variety of polymeric fibers such as polyethylene fiber (PE), polyvinyl alcohol (PVA), and polyester fibers [41]. Most investigations so far, have been carried out on polyvinyl alcohol (PVA) and polyethylene (PE) fibers for making of ECC. There is a difference in basic micro-mechanics of these two fibers. The PE fibers are hydrophobic and do not make any bond with cement matrix but PVA fibers are hydrophilic and makes the bond with cement matrix [32]. Li et al. [42] initially used the high modulus PE fiber to produce the ECC, then, Kanda et al. [43] studied the behavior of PVA-ECC which has shown good agreement. Since the cost of high modulus of PE fibers is 6 to 7 times higher than PVA fibers, researchers started using PVA fibers instead of PE fibers to produce ECC. Most of the researchers [41] had used oiled PVA fiber (oil coating to the surface of fiber) because unoiled PVA fiber may get ruptured in a cementitious matrix due to the strong chemical bonding to cement hydrates [41].

1.5.1 Behavior of ECC

The uniaxial tensile behavior of Fiber Reinforced Concrete (FRC) exhibits the quassi-brittle failure that is, after the first tensile crack, tension softening will occur followed by a continuously widening crack [45]. Many of the modern high-performance fiber reinforced cementitious composite also fall under this category. The conventional FRC exhibits the pseudo strain hardening behavior with large fiber volume content (8-15%). Unlike conventional FRC, ECC exhibits the pseudo strain hardening behavior under tensile loading with low fiber volume. A summary of the differences between ECC, FRC and other common HPRCC are shown in Table 1.3. Typical stress-strain curves of ECC is shown in Fig. 1.3. In Region 1, the composite is deforming linearly elastic and no crack occurs through the thickness. In region 2, multiple cracking occurs and the strain increases with additional cracks while the crack width remains constant. In region 3, multiple cracking is completed and further straining results in direct loading of fibers. In region 4, pull out or rupture of fibers occurs. Li and Wu [46] analyzed the various conditions for pseudo strain hardening of short and random oriented fibers with cementitious composites. From that, it is clear that pseudo strain hardening is based on crack mechanics. The short crack limit is associated with the first crack strength which is crack size dependent, whereas the long crack limit is achieved the higher pseudo strain hardening, the interface bond between fiber and matrix has to be designed for high absorbed energy [32].

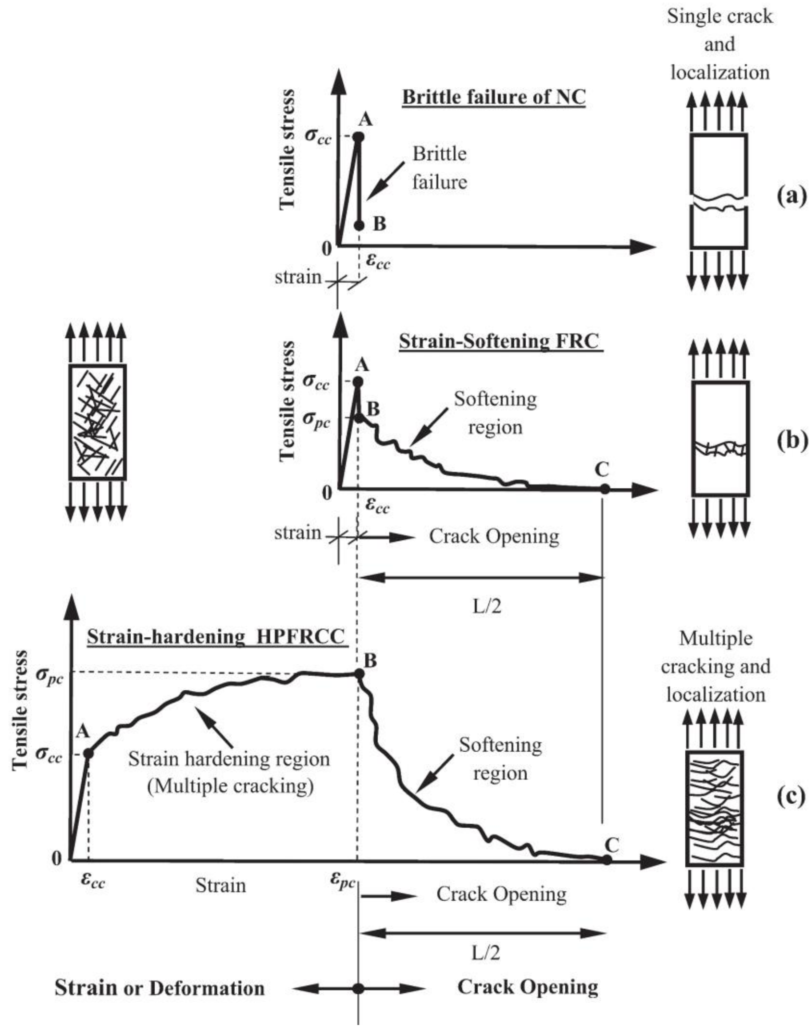

Fig. 1.2 Typical tensile stress–strain or deformation relation up to failure of: (a) normal concrete (NC); (b) Fiber Reinforced Concrete (FRC); and (c) High Performance Fiber Reinforced Cementitious Composites (HPFRCC) [44]

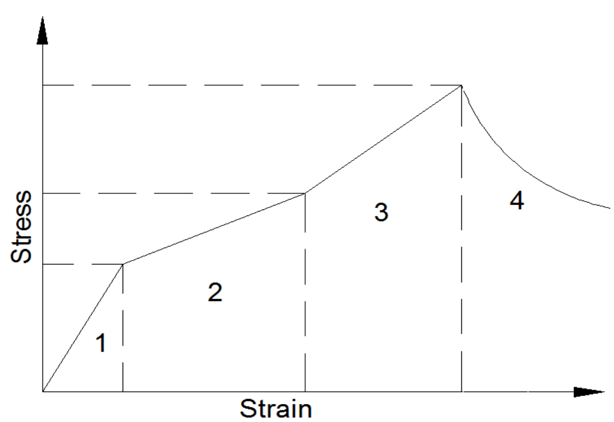

Fig. 1.3 Typical tensile stress-strain curve of ECC [32]

Table 1.3 Comparison between FRC, other HPFRCC, and ECC [32]

Properties	FRC	Other HPFRCC	ECC
Design methodology	Not available	Generally high fiber volume fraction is used (7-20 %)	Micromechanics based design methodology which uses less fiber volume fraction to reduce the process.
Matrix	Generally coarse aggregates are used	Generally fine aggregates are used	Very fine silica sand/powder is used to control the matrix toughness.
Fiber	Any type; fiber volume fraction usually less than 2% ; The diameter of the fiber will be 500 microns	Mostly steel fibers are used. Fiber volume fraction usually greater than 5 %; The diameter of the fiber will be 500 microns	Typically, polymer fibers are used. Generally, fiber volume fraction will be less than or equal to 2 %; The diameter of fiber will be less than 50 microns
Interface	Not controlled	Not controlled	Chemical and frictional bonds are normally controlled.
Mechanical properties in tension	Strain-softening	Strain-softening	Strain-hardening
Tensile strain	0.1%	<1.5%	>2% (typical)
Crack width	Unlimited	Typically several hundred microns, unlimited beyond 1.5% strain	Typically less than 100 microns during strain-hardening

1.5.2 Applications of ECC

ECC has been considered as promising material for the wide range of applications including new constructions, structure repair, seismic activity resistance, impacts and blast resistance, and high strain capacity behavior. ECC have been used in lots of structural applications in Japan, Australia, Korea, and the USA [47]. These include:

- The 95 m height Glorio Roppongi high rise apartment building in Tokyo contains a total 54 ECC coupling beams (2 per storey) intended to mitigate earthquake damage. The properties of ECC such as high energy absorption, high damage tolerance, and ability to deform under shear, provide it superior properties in seismic resistance applications when compared to ordinary concrete. Similar structures include the 41-story Nabeaure

Yokohama tower situated in the Harbor town of Japan, Yokohama containing four coupling beams per floor.

- The Mihara Bridge in Hokkaido, Japan approximately 1 km long was opened to traffic in 2005. For the construction of road bed, it contains nearly 800 m^3 of ECC material with steel reinforcement. Due to ECC properties (tensile ductility and crack control behavior) led to 40 % reduction in material used during construction.
- Another 225 mm thick ECC bridge joint deck slab on interstate highway # 94 in Michigan, USA was completed in 2005 [48]. The slab consumed about 30 m^3 of ECC material which was transported using standard trucks from batching plant. Due to the unique mechanical properties of ECC, this deck consumed less material than a proposed deck made of ordinary concrete. After 4 years of monitoring, performance remained undiminished.
- Ellsworth road bridge over US-23 was repaired using self-consolidating and high early strength ECC. The ECC has achieved the compressive strength of 23.59 ± 1.40 MPa in 4 hours and 55.59 ± 2.17 MPa in 28 days which allow the quick reopening the bridge to traffic. ECC has shown superior long-term durability in field conditions compared to typical concrete repair materials.
- In 2003, the Mitaka dam near Hiroshima, Japan was repaired using ECC. The surface of this 60 years old dam was severely damaged and showing evidence of cracks, spalling and some water leakage. The surface was repaired using 20 mm thick layer of ECC which was applied by spraying over 600 m^2 area.
- Another, an earth retaining wall in Gifu, Japan was repaired using ECC in 2003. Ordinary concrete has not been used due to a severity of cracking in the original structure, which would have caused reflective cracking. ECC was used to minimize this danger and after one year only micro cracks of tolerable width were observed.

1.6 Research Significance

The research presented herein describes a methodology for the retrofitting and strengthening of masonry sub-assemblages using FRP and ECC. This methodology can be used for masonry structures that have been damaged due to significant flexural loading or structures that are substandard and need to be strengthened. As compared to traditional retrofitting/strengthening method, this new technique is considerably most effective as well as less intrusive.

1.7 Scope and Objective of the Present Investigations

Masonry structures, which are deficient in original design, can be improved by strengthening of the structures. The strengthening consists of enhancing the strength of existing masonry structures with the aim to increase its load carrying capacity and ductility. The scope of the work includes a study on the effect of strengthening of masonry elements such as beams and walls using FRP and ECC in terms of their load carrying capacity and ductility.

The scope of the work involves experimental investigations to examine the structural behavior of masonry beams and walls strengthened with FRP and ECC along with the material characterizations of strengthening materials. It also involves analytical investigations to study the flexural response of masonry beams and walls strengthened by ECC sheet.

The objectives of the present work are:

1. To experimentally determine the mechanical characteristics of Masonry, Engineered Cementitious Composite (ECC) and Fiber Reinforced Polymers (FRP).
2. Experimental investigations to study the flexural response of strengthened masonry beams and walls with ECC and FRP sheets.
3. Numerical investigation of ECC strengthened masonry beams and walls using FEM based software (ABAQUS) and validation with experimental results.
4. To experimentally and numerically examine the effect of opening on the flexural response of ECC strengthened masonry walls.
5. Development of design charts to find the flexural strength of masonry walls strengthened with ECC.

1.8 Thesis Contributions

There are several conventional techniques available as described in Section 1.3 for retrofitting and strengthening of the masonry structures. These conventional methods are not showing durable performance and long life. Usage of non-corrodible, high strength and ductile materials for the strengthening of masonry structures seem to be a potential solution. This thesis explores new technique for retrofitting and strengthening of masonry structures by use of high performance materials such as FRP and ECC. The effect of these strengthening materials (i.e., FRP and ECC) on the flexural response of masonry beams are investigated. The masonry beams are made in different ways with cement mortar and ECC as bed joint to examine the effect of ECC with replacement of cement mortar. The masonry beams are strengthened with different strengthening patterns to find the specific approach of strengthening. Further, the effectiveness of precast ECC sheets on strengthening of masonry beams and walls in flexural are studied. Additionally, the effect of cement mortar and epoxy as adhesive agent for bonding of ECC sheet with masonry beams is examined. The technique developed herein for strengthening of masonry beams and walls with precast ECC sheet has shown better performance in terms of load carrying capacity and ductility. This thesis also contributed in development of design charts for evaluating the flexural strength of masonry walls strengthened with ECC sheet. Moreover, the effect of openings on the flexural strength of ECC strengthened masonry walls has also been studied.

1.9 Organization of Thesis

This thesis is divided into 7 chapters in order to explore the above-mentioned objectives. Details of the next six chapters are given below.

Chapter 2 presents a literature review highlighting the details of this research work carried out to study the strengthened behavior of masonry structural elements such as beams, columns, and walls with FRP and ECC.

Chapter 3 describes the material characterization of masonry and its constituents (brick and mortar) along with the material behavior of strengthening materials i.e., ECC and FRP.

Chapter 4 presents the experimental investigations carried out for the flexural response of strengthened masonry beams with FRP and ECC.

Chapter 5 deals with the experimental investigations on out-of-plane response of strengthened masonry walls using FRP and ECC.

Chapter 6 discusses the finite element based numerical modeling on masonry beams and walls strengthened with ECC sheet.

Chapter 7 deals with summary, overall conclusions and future scope of the work.

Appendix-1 present the cost estimation of strengthening materials used in this study.