THE VACUUM INFUSION MOLDING PROCESS FOR STRENGTHENING CONCRETE STRUCTURES

Adel Hammami[1,a], Abdullah Alshamsi[2] and Saeed Hareeb[1]

1. Department of Mechanical Engineering, 2. Department of Civil Engineering
College of Engineering, United Arab Emirates University, P.O. Box 17555,
Al-Ain, United Arab Emirates

ABSTRACT

The issue of upgrading and repair of existing civil engineering infrastructure has been one of great importance for over a decade. Deterioration of bridge decks, beams, girders and columns, buildings, parking structures and others may be attributed to several factors such as ageing, environmentally induced degradation, poor initial design and/or construction and lack of maintenance. In many cases, retrofit and rehabilitation by conventional means is very costly since it calls for specialized equipment and the shutdown of the structure during repair. As an example, current costs associated with the fabrication of bridge decks are 4 –5 times that of conventional reinforced concrete decks, thus placing great importance on the development of cost-effective processes such as the vacuum infusion molding process. In this paper, results of an ongoing research program aimed at investigating alternative methods for strengthening and repairing concrete structures will be presented. Assessments of two different schemes of the vacuum infusion molding process are performed. Experimental results show than the use of an infusion mesh can be more efficient that the use of a groove network, in terms of rate of infusion. However, structural performance are comparable and are superior to panels produced using hand lamination. It is clear that by using the vacuum infusion as a strengthening technique, a substantial reduction in defect formation will occur. However, additional work is needed in order to meet the industry requirements regarding the development of more affordable reinforcements and resins suitable for large structures and a low cost market.

Keywords: Vacuum infusion, concrete structure, infusion mesh, permeability.

1.INTRODUCTION

In the US and across the world, decaying structures are becoming a major economic burden, especially with the newly observed trend towards reducing expenditure on infrastructure projects. For example, an estimated 35% of all bridges on the federal inventory are judged to be structurally deficient or functionally obsolete and require repair, strengthening, widening or replacement [1]. In addition to increasing or changing traffic demands, common deficiencies include, among others:

(1) Deck deterioration due to wear, deicing salts, temperature gradients and freeze thaw cycles, etc.,
(2) Scour at bridge substructures in flowing water;
(3) Corrosion of structural steel members;
(4) Corrosion of steel reinforcements in structural concrete;
(5) Problems associated with dynamic response under wind or earthquake conditions, and
(6) Deterioration of materials.

These deficiencies are not isolated to bridge and other transportation related structures alone, but are endemic to the built environment, ranging from residential housing to pipelines used for the distribution of water, and industrial structures [2].

Owing to their outstanding properties such as lightweight; design freedom and resistance to corrosion, fiber reinforced composites are emerging as an excellent material for upgrading and strengthening concrete structures. The factors driving this technology are several, but

[a] To whom correspondence should be addressed.

perhaps the most relevant one is ease of installation, in the repair/upgrade arena as well as in new construction [3].

The key advantages of fiber reinforced composites, such as free-form and tailored design characteristics, strength–to-weight and stiffness-to-weight ratios which significantly exceed those of conventional civil engineering materials, high fatigue resistance, and a high degree of inertness to chemical and environmental factors, are often lost in high materials and manufacturing costs, particularly in direct comparison with conventional structural materials such as steel and concrete. However, the recent downturn in defense spending and the resulting need for new markets has spurred renewed efforts to reduce the costs of both raw materials and manufacturing processes, making highly feasible the use of composites in civil infrastructure on a competitive basis.

Composite materials for the strengthening of civil engineering structures are available today mainly in the form of:

- Thin unidirectional strips (with thickness in the order of 1 mm) made by pultrusion and normally bonded to the external face of the structure.
- Fabrics impregnated with resin and wrapped around the structure.

It must, however, be mentioned that composites do suffer from some disadvantages [2], primary among them being:

(a) higher initial materials costs,
(b) lack of familiarity in most areas (outside aerospace related application areas);
(c) lack of comprehensive standards and design guidelines at present, and
(d) need for an integrated materials-process-design structure in product development, which entails a critical change in paradigm.

In addition, other factors might challenge the fully-fledged acceptance of these materials as an addition to the palette of civil engineering materials alongside metals, timber and concrete. Chief among these are the need for new or modified versions of fibers, resins and sizings designed for the civil infrastructure environment, the lack of complete data sets and understanding of the long term durability and response of the constituent (fiber, matrix and filler) materials and the composite, and a lack of a comprehensive set of design guidelines and standards.

The wet lay-up process is perhaps the most currently used and gives the maximum flexibility for field application, and is probably also the cheapest alternative. However, it presents the most variability, and necessitates the use of excessive resin, and could result in the wrinkling or shear deformation of the fabric used, decreasing its designed strengthening efficiency. It could also causes a potential health problem when using resin systems containing styrene monomer, i.e., vinyl ester, since the latter cannot be controlled while the resin is cured. Also the process carries with it the intrinsic entrapment of air voids, and the resulting potential for deterioration with time.

A promising new manufacturing technology known as vacuum infusion molding process [4,6] is gaining acceptance among composite parts manufacturers since it involves low tooling costs and allows complete elimination of volatile organic compounds (V.O.C).

The process is similar to the resin transfer molding process; however, in the vacuum infusion technique, a polymeric film, often referred to as vacuum bag, replaces the stiff mold cover. The film is sealed against the lower half of the mold, at the periphery. Air expelled from the mold cavity results in the compaction of the reinforcement by the atmospheric pressure present on the outer side of the polymeric film. Finally, resin impregnates the mold cavity, usually through a resin distribution channel (see Figure 1).

The resin infusion process allows for the lay-up of fabric preforms with specific local tailoring of the reinforcement architecture, without dependence on expensive tooling or the need for a large outlay for capital equipment. The process provides significant flexibility for the incorporation of cores and inserts, as well as for the prefabrication of modular perform elements that can be assembled prior to the infusion step.

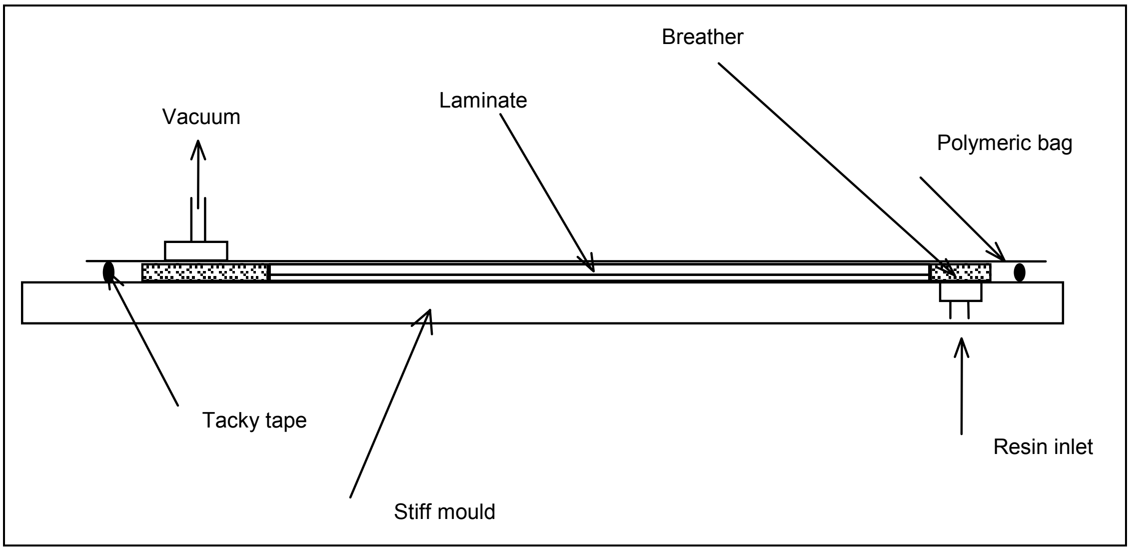


Figure 1 Schematic of the vacuum infusion set-up.

Although this technology has been the subject of extensive research in the last few years [7-9] and is now emerging as a viable and proven technique for composite manufacturing, especially for large structures, implementation of this technology for concrete repair and strengthening is not obvious, since additional work is needed to address the effect of different process parameters, for instance concrete surface preparation, the maximum applied pressure and how to accommodate surfaces of rough textures or with complicated geometries [10].

2. MATERIALS AND METHODS

Flat square concrete panels were prepared having an edge length of 600 mm and a thickness of 40 mm. The panels were reinforced with a steel grid made of a 6 mm diameter steel bars spaced 150 mm center to center. Straight grooves on the surface of two of these flat panels were prepared at the fresh concrete stage. These grooves were 5 mm deep spaced at 20mm. Sand blasting with a very coarse metallic brush was applied to two panels to create a rough surface to allow for a fast resin impregnation and to increase the bond between the composite layers and the concrete panel.

Unidirectional glass fabric having a surface density of 913 g/m^2 was used. The glass fabric was cut into bands having a width of 30 cm and a length of 50 cm. The resin used was an epoxy primer normally used in strengthening concrete structures. This resin (based on manufactures data sheet) is made up of two constituents: the base and the curing agent. The base has a viscosity of 3500 cP and the curing agent has a viscosity of 180 cP. When mixed together, their pot life is close to 90 min and the viscosity of the mix is around 800 cP, which is low enough to perform the infusion.

A disposable high permeable layer (Aerovac systems), having a net structure was also added to the stack and used as an infusion mesh. This high permeable layer was constructed from high-density polyethylene (HDPE). The product is manufactured in a diamond mesh pattern with a pitch of 4 mm between each strand.

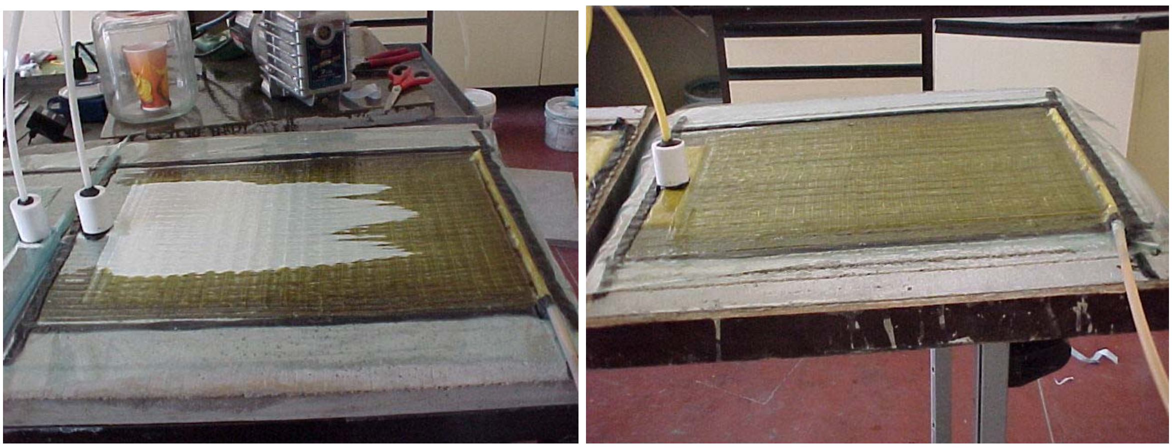
Infusion experiments were performed using a stack containing four layers of unidirectional glass fibers. The vacuum infusion set-up, which is shown in Figure 1, consists of an aluminum table on top of which the fabric is laid down and covered with a heat stabilized polymeric bag that possesses excellent elongation and heat ageing characteristics (CAPRAN 518, blown nylon 6 film from Aerovac systems). A sealant tape is used to seal the polymeric bag to the table, and then vacuum is applied to withdraw the air encapsulated within the mold cavity.

Three different infusion schemes were investigated. The first scheme consists in the use of the infusion mesh as a high permeable layer. The second scheme consists in using the grooved and textured panels. Finally, rugged surface was used for the third scheme. It is worth mentioning that when using the infusion mesh, the latter was placed in the middle of the stack. Then, it was placed on the top of the stack just below the polymeric bag. Furthermore, the surface of the concrete panel was initially covered with the same resin used for infusion. Besides vacuum infusion, hand laminated panels were also prepared having the same number of layers and the same impregnating resin for benchmarking.

3. RESULTS AND DISCUSSION

Eight concrete panels were prepared using the three different infusion schemes in addition to two samples made by hand lamination. Starting with the scheme using the rugged surface, it was difficult to complete the filling of the panels. Many reasons could be attributed for the non-success of this scheme. First of all, it was difficult to maintain vacuum throughout the panel due to the surface texture, thus resulting in possible leaking areas. Second the reinforcement being used has a large surface density, which when vacuum is applied, results in a relatively high fiber, thus slowing down the resin impregnation in the transverse direction.

For the scheme using grooves in Figure 2, resin starts by filling out the grooves, then the space between the grooves. In this case, infusion was completed within 60 min. Flow phenomena can be considered as a three stage flow [3] consisting of: (a) one-dimensional flow inside the grooves and, since the permeability in the grooves can effectively be estimated to be between 300,000 and 450,000 Darcy, the latter will control the filling time; (b) flow in the through thickness direction, here the reinforcement structure will have a major role in controlling this type of flow. In this case the reinforcement being used has a large surface density (913 g/m^2), thus it will restrict the flow; (c) in-plane flow in areas between the grooves. Here the spacing is an important processing parameter. In this work, these two parameters were selected randomly and no analytical analysis was performed to optimize the depth and spacing of the grooves.



(a) (b)

Figure 2. Infusion of the concrete panels using the grooves: (a) preliminary filling of the grooves, (b) infusion completed.

For the infusion scheme using the high infusion mesh, infusion was completed using two scenarios for the positioning of this mesh inside the reinforcement. In the first scenario, the infusion mesh was positioned in the middle of the reinforcement stack. In this case, infusion was completed within 50 min and the flow can be considered as a two-stage flow: first, a rapid flow in the mesh followed by a through thickness flow in the reinforcement. Here also the structure of the reinforcement will be responsible for the complete infusion of the panel, as shown in Figure 3.

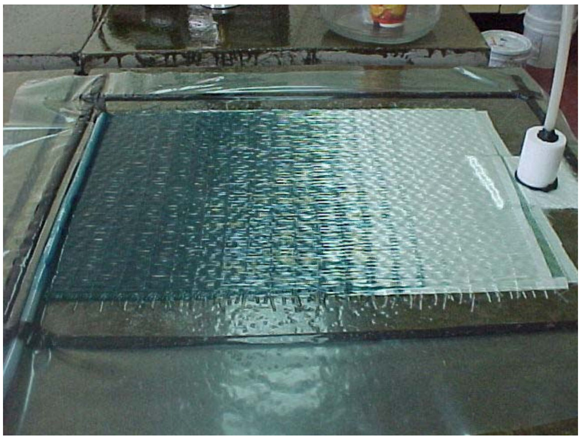
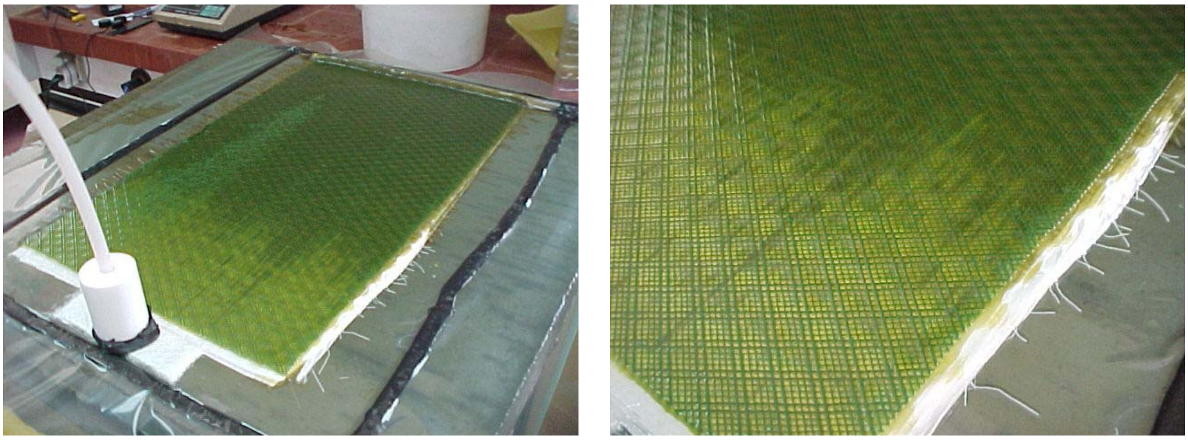


Figure 3. Infusion of the concrete panel using the infusion mesh (mesh positioned in the middle of the reinforcement stack).

In the second scenario, the infusion mesh was placed on top of the reinforcement stack, as shown in Figure 4. Infusion was completed within 45 min and the flow here can also be considered as a two-stage flow: first a rapid flow and filling of the infusion mesh, followed by a through thickness impregnation in the reinforcement (Figure 4-b).



(a) (b)

Figure 4. Flow patterns in the infusion mesh: (a) rapid flow; (b) through thickness impregnation.

According to the infusion results, the infusion mesh should be positioned on top of the reinforcement in order to reduce the filling time. Although the permeability of this type of mesh was not measured before, similar devices known for enhancing the filling stage have a permeability ranging between 2500 and 5000 Darcy [3]. Assuming a similar value for the infusion mesh being used in this work, it is low compared to the permeability measured in the grooves, which is anticipated to result in lower infusion time.

An explanation for this low performance could be attributed to both the structure of the reinforcement and the grooves themselves. Regarding the reinforcement, the latter has two different values for permeability depending on whether it is measured along the fibers (in-plane permeability) or perpendicular to the fibers (transverse permeability) and normally the value for transverse permeability is an order of magnitude lower than the in-plane permeability. Accordingly, once the grooves are filled, the resin will fill the space between the grooves and the latter will determine to what extent the filling can be accelerated. Although when using the infusion mesh on top of the reinforcement we are in presence of the same filling pattern (transverse permeability), however the distance to be traveled by the resin is much shorter: 4 mm compared to 10, which is the mid-distance between two consecutives grooves.

It is also important to mention that the grooves were made while the concrete was fresh. The latter once cured is subject to shrinkage, which may result in a non-uniform width for the groove channel, thus disturbing the filling of the groove itself.

Concrete panels strengthened using the different infusion schemes in addition to panels strengthened using hand lamination were subject to flexural fracture testing using a three point bending testing set-up (Figure 5). A two-fold objective was sought from this testing: first identifying which application method will yield higher fracture resistance; and second, how fracture initiates in the strengthened panels and whether the latter is affected by the application procedure.

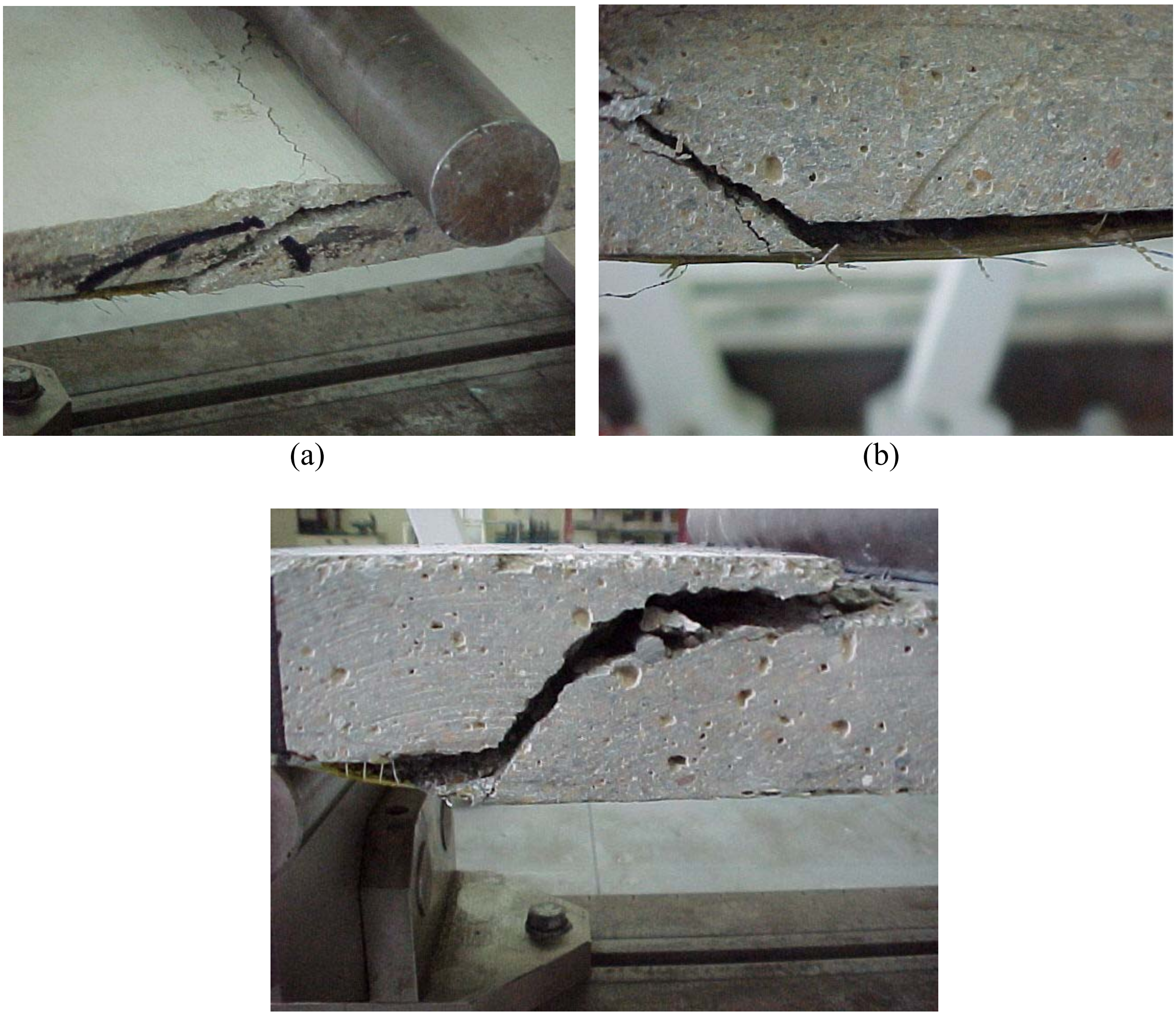
According to the average results shown in Table 1, concrete panels strengthened using either the infusion mesh or the grooves show higher fracture loads and lower deflection (39 KN, 5 mm) than concrete panels strengthened using the hand lamination method (35 KN, 5.8 mm). It is clear that using infusion molding as a strengthening technique will yield a component with a more uniform laminate resulting from a better resin distribution and a substantial reduction in the voids that may occur during hand lamination.

Table 1. Average for flexural fracture testing

Application procedure	**Maximum load (KN)**	**Deflection (mm)**
Hand lamination	35.1	5.84
Infusion using grooves	39.1	5.37
Infusion using infusion mesh (on top of the stack)	39.8	4.86
Infusion using infusion mesh (middle)	32	6.04

Concrete failure was initiated at the interface between the concrete and the composite stack, thus indicating that the quality of this interface will be responsible for the long term performance of the strengthened panel. Consequently by using the vacuum infusion as a strengthening method, it is expected to achieve a good adhesion between the composite laminate and the concrete panel.

The infusion mesh used here was integrated to the laminate on a permanent basis and no real difference regarding the maximum load sustained by the concrete panels was observed. However, since the latter is made of HDPE, its long term performance is subject to its durability, especially if the mesh was placed on top of the reinforcement.



(a) (b)

(c)

Figure 5. Testing of the strengthened concrete panels : (a) fracture initiation; (b) debonding of the composite layers and (c) complete fracture.

4. Conclusion

The objective of this work was to investigate the use of the vacuum infusion molding technique as a strengthening method for concrete structures. Several concrete panels were infused using different infusion schemes.

From the results, it can be concluded that the vacuum infusion can be considered as a viable route for strengthening and repairing concrete structures and this apply for the two infusion schemes. However, additional work is needed in order to reach the same level of performance achieved by this method and normally encountered when manufacturing composite parts.

For instance, it is clear that current epoxy resins and reinforcements are developed for hand lamination. Epoxy resins systems having high viscosities and heavy fabrics are the current norm. Consequently, it is urgent to develop new resins systems, even though attempts are made to introduce vinyl ester as a possible replacement for epoxy resins.

Optimizing the spacing and the depth of the grooves may result in shorter infusion time. However, for a typical strengthening situation, it is not easy and sometimes not economical to proceed with the grooves. Accordingly, using either an infusion mesh or reinforcement with a high permeability is probably the most economical route. Thus it is important to accommodate the existing infusion mesh and fabrics of high permeability in order to be used in civil structures.

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