DAMAGE, INSPECTION, MONITORING AND MAINTENANCE OF STRUCTURES STRENGTHENED WITH FRP MATERIALS

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Abstract: *Extensive research on the use of FRP elements in the strengthening of reinforced concrete has been carried out in recent years. Application of these materials nowadays is very common, and it's behaviour in exploitation well known. However, due to mechanical properties of FRP materials, its durability characteristics and tendencies to fail in brittle manner, the need for continuous monitoring, gathering and analysing conditions data is ever present. All this resulted in improved experimental techniques for close monitoring of strengthened structures. In this paper, authors indicate the importance of inspection and maintenance of structures strengthened with FRP materials as externally bonded reinforcement sheets, laminates, bars and tendons, and show methods to build in health monitoring systems for subsequent field inspections.*

Key words: *FRP materials, monitoring, inspection, maintenance, durability*

1. INTRODUCTION

Fibre reinforced polymers (FRP) have been used successfully over the past several decades worldwide. In many occasions, this type of reinforcement is used as an externally bonded reinforcement. This means that during service life, it is more or less exposed to various environmental influences which may cause material deteoriation. FRP material deterioration may begin due to one or combination of the following:

- Mechanical influences (stresses, repeated impacts, fatigue, erosion, abrasion, etc.),
- Chemical influences (water, various solvents, oils, acids, alkali, etc.),
- Radiation (including sunlight),
- Heat (high temperature or temperature fluctuations),
- Biological influence (bacteria, fungi, insects, etc.).

When influenced by these factors, crazing, dirt retention or the loss of gel coat can be observed, but apart from aesthetic appearance, these visual changes do not affect the structural performance of the reinforced structure. FRP are designed to meet challenges of the environment during service life. Hence, FRP materials can often survive individual treats, but can succumb to a combination of aforementioned influences.

There are three key factors which can determine the end of life of a reinforcement material:

1. It must remain safe to use despite of the stresses or environmental influences for decades,
2. It has to be inexpensive for maintenance,
3. It must continue to meet the structural and aesthetic performance requirements.

FRP has the ability to be repaired or even replaced more easily than other materials, which makes them very attractive choice for strengthening and extending service life of concrete, steel, wooden or masonry structures.

Aesthetic impairments can be improved by the occasional use of mild cleaning agent and the application of a special formulated wax, designed for FRP upkeep. Still, incorrect maintenance

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of FRP structure can deleteriously affect the durability of FRP material, thus causing intentional damage. Intentional damage can also occur when FRP components are cut or drilled during installation. Unintentional damage, however, can be caused by:

- Accidental impact,
- Unexpected excessive loading,
- Long-term environmental exposure.

2. INSPECTION

After several decades in service, the initial properties of a component will have changed, even in absence of obvious mechanical damage. Therefore, it is customary to perform inspections and note these changes in properties with time as a measure of the extent of deterioration in retention percentage.

General, routine inspection is performed by visual observation. Sometimes, the changes are more obvious than mere colour change. There may be gross cracking or swelling, but sometimes there can be no visible signs of deterioration. Changes can, in such cases, be apparent only when advanced diagnostic equipment is used, such as thermography, acoustic emission equipment, ultrasonic instrumentation etc. This is a detailed inspection and testing.

An additional sample of the strengthening fibre is usually bonded to the structure away from the strengthened region for inspection and testing during service life. Additionally, or alternatively, samples of FRP laminates can be bonded to short beams later stored in the vicinity of the strengthened structure. These samples can later in time be tested as part of the inspection regime. To aid inspection, some or all of the samples should not be covered with protective layers. They should thus indicate a lower bound of performance than the strengthened structure if tested. Also, regular testing can include traditional pull-off tests to determine tensile strength, or conventional structural loading testing.

Test data and observations gathered this way are used to assess any damage to the structural integrity of the strengthened system. The assessment report can also include a recommendation for repairing any deficiencies and preventing recurrence of degradation.

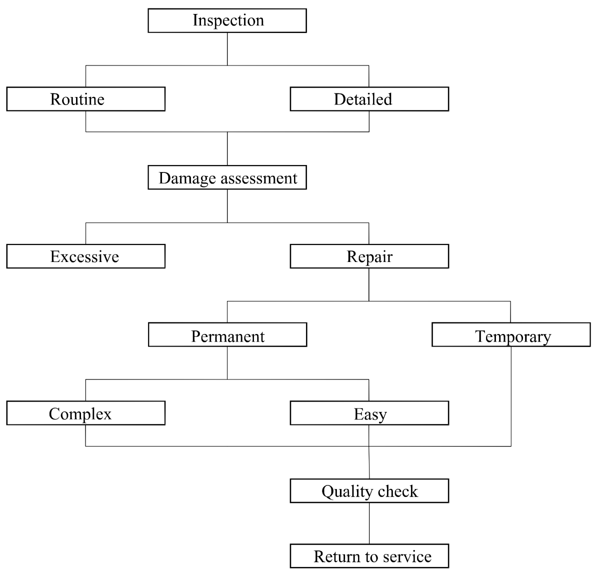

Figure 1: Flow chart for composite inspection and repair

Routine visual inspection should look for the signs of crazing, cracking or delamination, for local damage (caused by impact or abrasion for instance) and deterioration of the structure itself (additional cracking or corrosion). Where the FRP has been covered with protective layer, inspection of this layer should indicate the possibility of the composite being damaged. In this case, protective layer should not be removed, unless absolutely necessary, for thus may cause unintentional damage to the fibre composite. Identification and warning labels indicating presence of FRP reinforcement, placed on the structure upon FRP installation, should be checked and if damaged or missing, replaced. This is especially important is any work is planed to be done on the construction that may damage the FRP reinforcement.

Check list for routine inspection should consist of the following questions:

- Is the FRP wet?
- Are there any signs of visual damage to the FRP? (Impact damage, exposure of fibres, surface cracks, colour changes, etc.)
- Has any cleaning been carried out since the last inspection?
- Has any coating or paint been applied since the last inspection?

Detailed inspection is usually carried out by non-destructive methods such as simple hammer tapping on the reinforcement, thus determining by sound if any debonding has occurred during service life. Thermography is a bit more complex and expensive, but also more accurate non-destructive way of testing the FRP material. However, there are no currently known non-destructive methods to best determine current condition of the adhesive. For this purpose, pull-off tests are the most inexpensive and easiest tests, and should be performed on a regular basis on the control specimens kept in the vicinity of the strengthened structure. Other instruments for the purposes of testing during service life may also be installed either at the time of the assessment (for example to measure strains due to live loading of the structure), or at the time of the actual strengthening process. In case significant changes to the expected ones are observed, it will be necessary to identify their origin (whether it is in the FRP reinforcement such as its delamination, or in the original structure like additional cracking of concrete, for example), and act accordingly with a remedial action required.
Intervals between inspections are recommended along with the design guidelines by American Concrete Institute (ACI) [1], International federation for concrete (FIB) [3] and Concrete Society Council (CSC) [2].
CSC in [2] also suggests that detailed inspections should be carried out more frequently in the first few years after installation, in order to give the owner of the structure confidence that the strengthening has been carried out satisfactorily.

Type of structure:	**Routine inspection:**	**Detailed inspection:**
Bridge	Every year.	At least every six years
Building	Every year.	At change of occupancy. At change of use. When performing structural work or refurbishment. At least every ten years.
Other	Depends on the use of the structure (ideally every year).	Depends on the use of the structure. At least every ten years.

Table 1: Recommended inspection intervals

Check list for detailed inspection should consist of the following questions:

- Is there any internal damage? (Determining by surface tapping and other non-destructive methods of testing.)
- Has there been any change of use or change in environmental conditions?

- Is the structure still meeting the mechanical performance requirements? (Assessment made by a qualified engineer.)

3. DAMAGE AND ITS EFFECT ON DURABILITY AND PERFORMANCE

Mechanical

Mechanical durability is easily achieved in FRP materials [4] since fibres that are load barring are very durable, but deterioration of the matrix which transfers the load between fibres, can have an indirect impact on mechanical properties of the entire material. A soft matrix is easily eroded or scratched, thus leaving fibres susceptible to weathering, exposed.
Collision with a small object can cause impact damage to the material, hardly or even not visible with the naked eye, but can result in delamination, matrix cracking, fibre debonding, and in severe cases, fibre rupture. The possibility of on-site-repair is often in these cases a very favourable option for maintenance of FRP materials.
As for toughness of the matrix, two main methods have been used to improve its characteristics. One is adding small quantities (approximately 10% by weight), of impact modifiers (rubbers or thermoplastics) before fabrication of the FRP material. And the second is inserting energy-absorbing (elastomeric) layers between the reinforcing plies.
Fatigue “life” is usually measured as the number of cycles prior to failure for a given applied load. Degradation of some structures is often associated with cyclic and dynamic loading which can be mechanical, thermal or chemical. Longevity of FRP materials can be predicted with some degree of confidence based on the research data. Still, research continues on a global basis in order to better understand the fatigue behaviour of FRP materials and enable better prediction of structures service life that are designed for extended service conditions.
Joints that are necessary, especially in large structures, can also be a weak point of FRP external reinforcement, whether they are adhesively bonded or mechanically fastened. Therefore, joints should be easily accessible for inspection and replacement or repair. Adhesive joints in FRP structures are capable of achieving higher strength than mechanically fastened ones, and may be preferred for that reason. Their durability depends more on the flexibility and toughness of the resin used in the adhesive than on the FRP material itself. Adhesive joints strength can be predicted by performing a stress-strain analysis and applying an appropriate failure criterion. As for mechanically fastened joints, their advantage can be that they can be disconnected and replaced easily if needed. Mechanical joints fail in tensile, shear and bending modes of failure. If made of metal, they have to be protected against corrosion, but use of materials such as stainless steel is also common and cost effective.

Chemical

FRP materials are known to absorb water to some extent. Glass or carbon FRP materials absorb water slowly, and glass fibres are often given “finishes” such as silane surface coatings to prevent this absorption. Where absorption does occur, moisture migrates through the resin and eventually reaches fibre-resin interfaces. In the interface is a strong one, no separation of fibre from the resin will occur, but still, reduction in strength can be observed.
Some resins are very susceptible to boiling water, but not to cold one. Other resins may be unaffected at temperatures within their normal range of use. Still, the combination of absorbed moisture and temperature fluctuations can cause cracking and other types of damage. Thick laminates are much less susceptible than the thin ones in a given time period and this explains the durability of many early FRP structures. Despite these reported effects of moisture, careful selection of material and component design can overcome any potential problem. Thus, it is important to specify the correct resin formulation for the particular application. Also, cutting and drilling on site is strongly discouraged since it exposes both fibre and resin, which can affect the absorption properties of the FRP material.

A surprising number of FRP applications involve occasional or prolonged contact with chemicals other than water. Many FRP materials are placed in contact with detergents, cleaning solvents, acids, alkali etc. Resistance of FRP material to highly reactive chemicals is good, which explains their widespread use when reinforcing the structures where chemical processes are conducted and where any other affordable material, capable of withstanding the harsh environment conditions, is hard to find. Still, powerful oxidising agents, strong caustic alkalis, bromine and wet chlorine pose severe problems for general-purpose resins. In such cases, consultation with the manufacturer of the FRP material and good selection in design can avoid problems with possible chemical influence.
If FRP laminate is subjected simultaneously to a mechanical stress and chemical environment, environmental stress cracking (ESC) can occur. ESC is a term which describes the failure mechanism caused by rapid and brittle crack propagation. FRP can be subjected to only small quantities of the chemical or solvent and for duration period that varies from near instantaneous to very long timescales. Still, ESC failure can happen suddenly and with catastrophic consequences. Usually, ESC mechanism is evident from the characteristic planar fracture surfaces which can be spotted during inspections.

Weathering
FRP polymers show good resistance to weathering. However, this is greatly based on their formulation. Resins vary in their ability to withstand outdoor use for long periods of time. The effect of outdoor use on FRP laminates, such as glass/polyester or carbon/epoxy materials, are confined only to the surface and do not often involve a serious treat to structural integrity, unless there is a reduction in strength due to surface cracking.
The mainly cosmetic effects involve:

1. *Fading and darkening*
   Colour fading or darkening without loss of gloss can be due to the use of unstable pigments or pigment combinations which change colour after exposure. This can be avoided by the appropriate choice of pigment.
2. *Yellowing*
   Yellowing is due usually to the darkening of the base gelcoat resin. This can be avoided by using a resin more resistant to UV rays and better UV absorbers, and by assuring good cure of the resin.
3. *Blooming*
   Blooming is caused by migration of an incompatible pigment or additive to the surface of a gelcoat to give a matt, faded appearance. Bloom can be removed by polishing, but this is only a short-term solution. Better choice of the pigment should overcome this problem.
4. *Loss of gloss and chalking*
   The effect of chalking and loss of gloss is usually caused by erosion of the surface layer of the gelcoat due to chemical or mechanical damage, or the combination of both. In such cases, the colour appears to have whitened due to the diffused reflection of the light from the matt surface. The erosion of gelcoat after years of service can bring about the eventual mechanical failure of the laminate by exposing the reinforcement underneath. However, the loss of gloss or the chalking effect, do not present an immediate disappearance of the gelcoat, which normally lasts for many years.

Climate effects can also influence the FRP. Hence, FRP reinforcements are designed to meet specific climatic conditions, however severe.

Temperature
Maximum temperatures for the use of FRP materials are governed by two main factors- the resin’s glass transition temperature and the temperature at which chemical decomposition starts

to become significant. Decomposition temperatures are seldom reached in service life. Also, strength, yield stress and modulus all decline with increasing temperature. Most resins have only a limited ability to withstand high temperatures. High-temperature resins are available with superior heat resistance, but can be expensive. The fibres are generally stable materials and can withstand a higher temperature than any commercial resin.
Effects of high temperature can include:

1. Chemical decomposition of the resin by heat alone.
2. Reduction in modulus, strength and their properties at high temperatures.
3. Acceleration of other degradation processes (such as those of chemicals or radiation).
4. Damaging effects of thermal expansion and thermal mismatch between two materials with different expansion coefficients. Debonding being one of the possible consequences.
5. Thermal shock after series of rapid temperature changes that causes cracking.
6. Repeated rapid heating of FRP materials that have previously absorbed moisture or solvents causes various forms of damage to the material.
7. Fire exposure

Fire performance of FRP material is as much essential design criterion as modulus or yield stress. Resins themselves do not burn. They will rapidly lose dimensional and mechanical integrity when heated above either glass transition temperature or melting temperature. The poor thermal conductivity of most resins and consequently of most FRP materials, means that under high radiant heat, high surface temperatures are soon reached and degradation becomes rapid. Most organic resins will rapidly degrade with the evolution of volatiles at temperatures between 300 and 400^{o}C. Attempts to reduce or eliminate the tendency to burn can involve careful choice of resin and of the nature and physical form of the reinforcement, but main emphasis is usually on adding special additives to the resin composition.

4. MAINTENANCE AND REPAIR

FRP materials need little or no maintenance during service life. However, repairs are made during installation and during service life, due to service exposure or accidental damage). During installation, sawing, drilling, routing and other procedures necessary to accomplish installation can damage the resin surface and expose the reinforcement fibres, thus seriously affecting the performance properties of the FRP system. The exposed new surface must be sealed with a resin-rich layer using resins or paints. A general rule is to use the sealant material of the same type as the component being repaired. Manufacturer’s instructions must be strictly followed in order to provide an optimum repair. Also, to ensure proper repair, residual dust or other debris resulting from the installation procedure must be thoroughly removed before commencing the repair operation.
The decision to do the repair work needed due to service exposure or accidental damage during service life of a structure is based on the extent of repair needed to restore the original performance of the FRP. Other considerations are repair costs, accessibility of the damage and the availability of the suitable repair materials.
Best practice repair sequence for surface exposure and accidental damage consists of the following steps:

1. Inspect and asses damage
   - visual and instrumental techniques
2. Asses the repair options
   - use as is and do nothing
   - repair existing component
   - scrap and replace component
3. Carry out the repair work

- remove damaged material
- treat contaminated material
- prepare repair area
- complete FRP repair

4. Inspect repair for quality
5. Restore surface finish

<u>Types of repair</u>

According to flow chart given in figure 1, there are three types of repair:

1. Easy repair

Damage is small or does not affect structural integrity of the component. Repair is purely cosmetic and can be carried out to protect and decorate the surface. It does not restore any strength and is used only where strength is unimportant. Due to high shrinkage of the repair material, cosmetics repairs may start to crack after a relatively short time in service.

2. Complex repair

These are needed when damage is extensive and structural performance of the FRP material has to be restored. The best choice of materials would be to use the original fibres, fabrics and matrix resin, if possible. But if not, an alternative should be considered carefully. The proposed repair scheme should meet all the original design requirements for the structure.

3. Temporary repair

When small areas of damage which do not threaten the integrity or mechanical properties of the component have been detected, simple patch repairs can be carried out. These are made with minimum preparation, to protect the FRP component until a permanent repair can be made. Temporary repairs should be subject to regular inspections.

<u>Repair techniques</u>

1. Coating

If it is only a surface scratch or abrasion, the repair may simply involve coating the area with a resin-rich coating.

2. Patch repair

The thickness of the original laminate is made up using filler plies and the repair materials are bonded to the surface of the laminate. The edges of the repair patch should be tapered and all plies should have rounded corners. The patch repair attempts to replace the damaged area in the FRP laminate exactly, restoring it as much as possible to its original. Thus, the number of plies and its orientations, have to match that of the original structure. The repaired structure is typically about 60-80% as strong as the original undamaged structure [5].

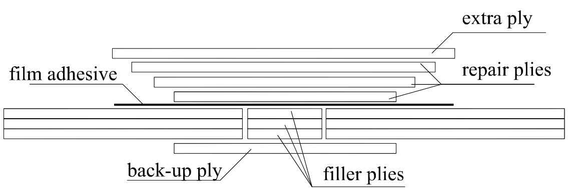

Figure 2: Patch repair of non-structural component

<u>Advantages:</u>

- quick and simple to do
- requires minimum preparation

<u>Disadvantages:</u>

- repaired laminate is thicker and heavier than the original
- careful surface preparation needed in order to get good adhesion

3. *Tapered or scarf repair*

An area around the hole is sanded to expose section of each ply in the laminate. It is important to know the number of plies in the FRP and to establish the ply orientations. Sometimes a filler ply is added to produce a flatter surface.

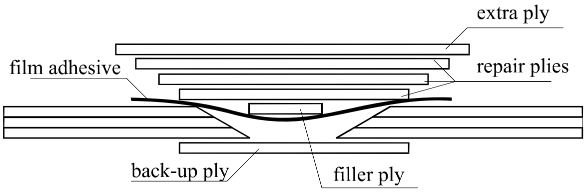

Figure 3: Scarf repair of a structural component

Advantages:

4. only slightly thicker than the original
5. each repair ply overlaps the ply that is repaired, giving a straighter, longer load path
6. good bonds can be achieved on the freshly exposed surfaces

Disadvantages:

7. time consuming
8. high level of skill needed in order to achieve good repair
9. *Step sanded repair*

Stepping is an alternative method to scarfing for removing material in preparation for applying a repair patch. In stepping, the overall angle is achieved by removing a precise area of material per ply of FRP. The laminate is sanded down so that a flat band of each layer is exposed, producing a stepped finish. Stepping leaves abrupt edges and butt joints in each repaired ply. It is also hard to do without cutting through and damaging the underlying plies.

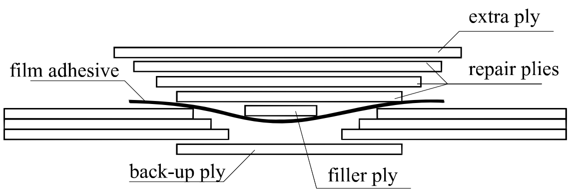

Figure 4: Step repair of a structural component

Advantages:

10. only slightly thicker than the original
11. each repair ply overlaps the ply that is repaired, giving a straighter, longer load path
12. good bonds can be achieved on the freshly exposed surfaces

Disadvantages:

13. extremely difficult to do

5. CONCLUSION

Long-term durability and performance in service are key benefits in the application of FRP materials. As with all structural elements, in order to obtain this, there is a need to check the FRP composite strengthening system as part of the regular inspection and monitoring of the structure. When areas of damaged composite materials are identified, they may be repaired by various techniques mentioned in this paper.

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