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RINFORZO DI STRUTTURE METALLICHE MEDIANTE FRP: PANORAMICA DELLA UK PRACTICE

STRENGTHENING METALLIC STRUCTURES USING EXTERNALLY- BONDED FRP: AN OVERVIEW OF UK PRACTICE

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SOMMARIO

Il rinforzo di strutture metalliche mediante incollaggio di fibre-reinforced polymers (FRPs) è una tecnica che si sta rapidamente diffondendo. Permette di mantenere la funzionalità di strutture interessate dalla corrosione, fatica, danneggiate o dove è richiesto un cambio d'uso. Molte delle applicazioni con FRP su strutture metalliche è avvenuta in Inghilterra, dove un numero di ponti ed edifici di ghisa e acciaio sono stati rinforzati. In questo lavoro si fornisce una panoramica generale della tecnica, con alcuni esempi di strutture metalliche rinforzate mediante FRP e un'indicazione delle tematiche critiche che richiedono ulteriore ricerca. Si è fatto riferimento al report CIRIA C595, che descrive la best-practice in UK, e che è stata pubblicata nel Febbraio 2004.

ABSTRACT

Strengthening metallic structures using externally-bonded fibre-reinforced polymers (FRPs) is a young and rapidly developing technique. It allows extension of the lives of structures that are deficient due to corrosion, fatigue, damage, or where a change in use is required. Many of the applications of FRP to metallic structures have been in the UK, where a number of cast-iron and steel bridges and buildings have been strengthened. This paper gives a general overview of the technique, with some examples of metallic structures strengthened using FRP and an exploration of the critical issues that require addressing. Reference is made to the recently completed CIRIA report C595, which describes current best-practice in the UK, and which was published in February 2004.

INTRODUCTION

Fibre-reinforced polymer (FRP) materials are particularly suited to strengthening and repairing existing structures, and there have been widespread applications to concrete buildings and bridges. They are also being increasingly used to extend the life of metallic infrastructure. FRP, bonded to the external surface of an existing metallic structure, can be used to provide an increase in strength and stiffness, replace material lost by damage or corrosion, extend the structure's fatigue life, or allow a change in the structure's use. These various applications of FRP to metallic structures are generally referred to as 'strengthening', although this may not be the primary purpose of the intervention.

To date, the largest number of metallic structures to which FRP has been applied has been in the UK. This paper provides an overview of FRP strengthening for metallic structures from the UK perspective. The current best-practice in this rapidly-developing technique is described.

FRP-STRENGTHENED METALLIC STRUCTURES IN THE UK

The Historical Context

Figure 1 shows how metallic materials and structures developed in the UK, starting with cast iron at the end of the 18th century and wrought iron in the middle of the 19th century. Carbon steel was first produced at the end of the 19th century, and has been continuously developed ever since.

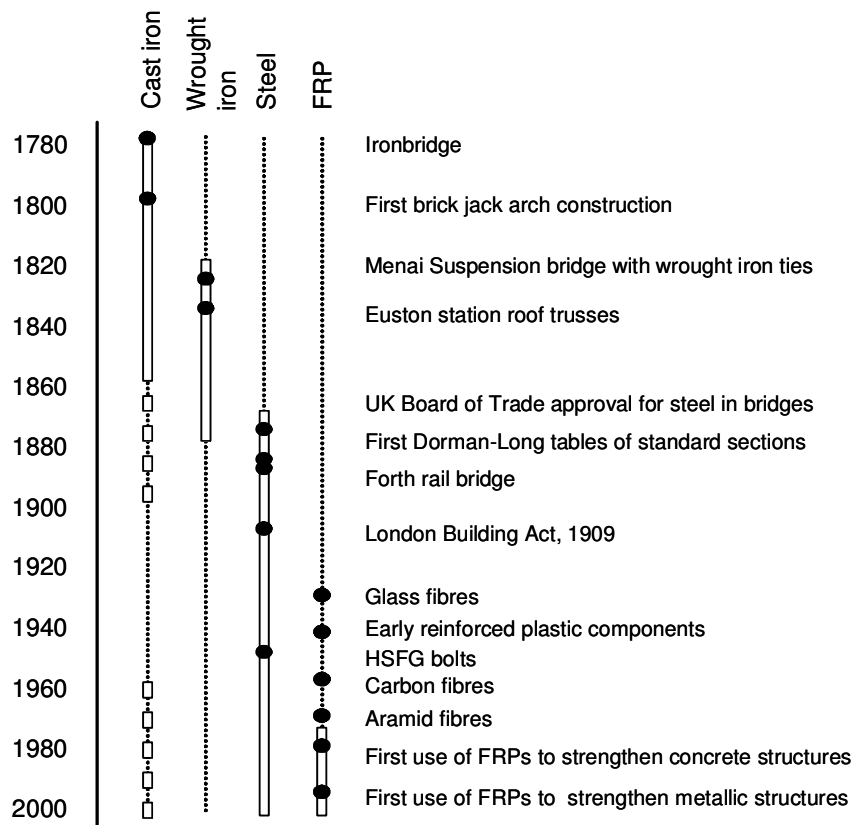


Fig. 1. The development of metallic structures and FRP strengthening techniques.

The development of structural forms has been intimately linked with advances in material technology. The use of cast iron was limited by its brittleness in tension, resulting in arch bridges that utilise the metal in compression; stocky, asymmetric beams; and often combined with brick jack-arches. Wrought iron is ductile, but plates were limited in size and beams had to be fabricated by riveting together a number of plates. Modern steel, however, is available in rolled sections of virtually any length, can be welded, and can be connected using high-strength friction-grip bolts.

The development of metallic structures has consequently left a wide range of both metallic materials and metallic structural forms, any of which might require strengthening.

Examples of FRP strengthening

The development of FRP materials is also shown in figure 1. The initial development of FRP strengthening techniques focused on concrete structures, with the well-known first application of FRP strengthening to the concrete Ibach viaduct in 1991. The extension of the technique to metallic structures has been a more recent development, with the first application of FRP as structural strengthening in 1996.



King Street Bridge, Mold



Shadwell station struts, London Underground



Tickford Bridge, Newport Pagnell



The Boots Building, Nottingham

Fig. 2. Examples of UK metallic structures strengthened using FRP

A range of metallic structures have been successfully strengthened using FRPs in the UK, examples of which are shown in figure 2. (A comprehensive list can be found in reference

1). King Street Bridge has cast iron beams supporting brick jack arch infill, and this was strengthened using pultruded CFRP plates. Cast iron struts at Shadwell station on the London Underground were strengthened by in-situ resin infusion of dry carbon fibres. Partially pre-impregnated CFRP was used to strengthen the cast iron spandrel rings of Tickford Bridge, and pre-impregnated CFRP was used to strengthen a curved steel beam in the Boots Building. Wrought iron structures have not yet been strengthened due to the lack of research knowledge on the influence of wrought iron's laminar structure. However, investigations into the feasibility of strengthening wrought iron are reported by Moy, Clark & Clarke.²

DESIGN & PRACTICE GUIDANCE

Two Design & Practice Guides have recently been written on the basis of UK experience in strengthening metallic structures using FRP:-

- *FRP composites – Life extension and strengthening of metallic structures*³
- C595, *Strengthening Metallic Structures using Externally-Bonded Fibre-Reinforced-Polymers*¹

Various documents provide guidance that is partially relevant to the topic. The following are UK documents, but there will usually be national equivalents:-

- TR-55, *Design guidance for strengthening concrete structures using fibre composite materials*⁴
- TR-57, *Strengthening concrete structures with fibre composite materials: acceptance, inspection and monitoring*⁵
- CIRIA C564, *Fibre-reinforced polymer composites in construction*⁶
- *Structural Design of Polymer Composites: Eurocomp Design Code and Handbook*⁷
- *Guide to the structural use of adhesives*⁸

Report C595 describes the best-practice at the time of writing. However, it should be noted that this is not a design *code*, but provides design *guidance*. It recognises that this is a rapidly developing technique in which a number of areas require further research.

Overview of CIRIA Report C595

The remainder of this paper will outline some of the critical issues when strengthening metallic structures using FRP, by reference to report C595.

C595 aims to be a single source of information on strengthening metallic structures using externally-bonded FRP. It is aimed at a wide audience: clients and owners of structures, installation contractors, design consultants, and materials suppliers and manufacturers. Consequently the report covers a broad range of material, as summarised in Figure 3.

The structure of the report reflects the four principal stages of an FRP strengthening project: consideration of the materials involved the design of a strengthening scheme, the installation of the FRP strengthening, and operation of the strengthened structure.

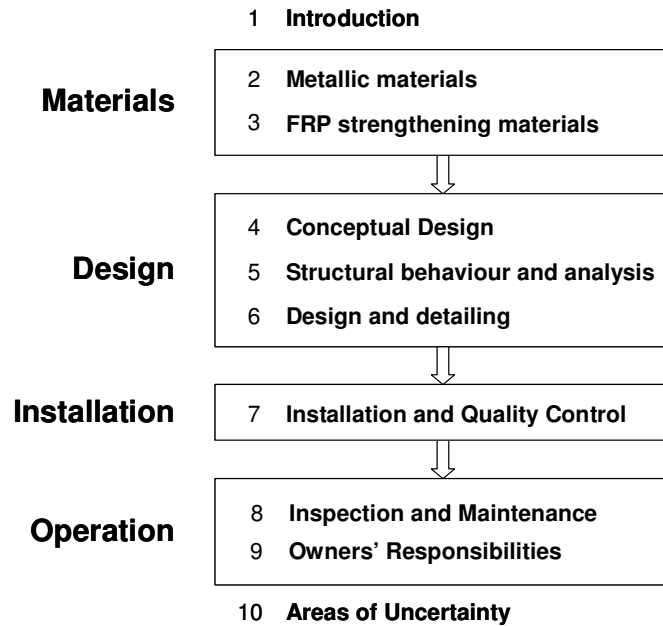


Fig. 3. The structure of report C595

Materials

The examples given in figure 2 illustrate the diversity of metallic materials and structures that can be strengthened. This diversity is only matched by the number of different FRP materials and applications methods that can be used for strengthening them.

Carbon FRP is usually used to strengthen metallic structures, as efficient strengthening requires a material with a high modulus. Aramid FRP might be used where a non-conducting fibre is desirable, and glass FRPs may be used in combination with carbon FRP (for example around connection details). The bonding component of the system is usually an epoxy adhesive. Where carbon fibres are used, a non-conducting glass or vinylester mat is usually incorporated into the adhesive layer to guard against galvanic corrosion.

The FRP can be either *preformed*, or formed *in-situ*. If an FRP component is preformed for later bonding to a structure, the distinction between the FRP and adhesive components is well defined. If the FRP is formed in-situ, however, the bonding adhesive is also used to impregnate dry fibres to form the fibre-reinforced-polymer, and there is no clear distinction between the bonding adhesive and the FRP matrix material.

Conceptual Design

Figure 4 shows some of the possible aims of FRP strengthening. Although the term '*Strengthening*' implies the application of FRP material to improve a structure's strength, it is not always an increase in load capacity that is primarily sought. Often, an increase in stiffness is required (possibly to increase the buckling capacity of a member). The fatigue life of a metallic structure can be increased by using prestressed FRP to close cracks that initiate at stress concentrations such as rivet holes.

Of particular importance with brittle, cast iron structures are the permanent tensile stresses present at the time of strengthening, which can represent a significant proportion of the tensile strength of the material. Prestressing the FRP allows a portion of the permanent tensile stress to be transferred from the cast iron to the FRP material, but requires special

anchorage arrangements. If the strengthening is not prestressed, it needs to have a high modulus to be effective (e.g. ultra-high modulus CFRP).

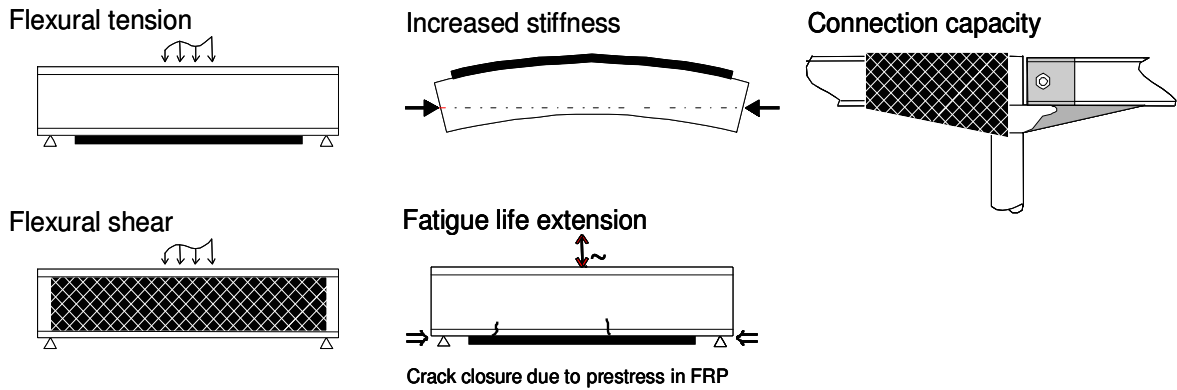


Fig. 4. Applications of FRP to extend the life of metallic structures

Steel structures are ductile and hence a lower modulus, non-prestressed FRP can be used, provided that the system is capable of accommodating stress redistribution when the steel yields. FRP can also be used to increase both the global and local buckling capacities of modern thin-walled steel sections.

Good quality wrought iron is also ductile, but may be laminated (as already noted). Strengthening wrought iron members will often be constrained by the locations of the rivets used to fabricate a member from individual plates.

Detailed Design and Analysis

The framework for detailed design is illustrated in figure 5. The inputs to this process include the existing structure, materials, design parameters (such as the partial factors), and environmental actions (such as temperature, moisture conditions). These inputs are used to determine the quantity of strengthening material required, and to check the capacity of the adhesive joint. Dynamic and fatigue effects are also examined where relevant, and the design is finalised by suitable detailing, including fire protection if necessary.

Structural Analysis of a flexural strengthening scheme must consider two components of the strengthening system in particular:-

- the FRP reinforcing material,
- the adhesive joint.

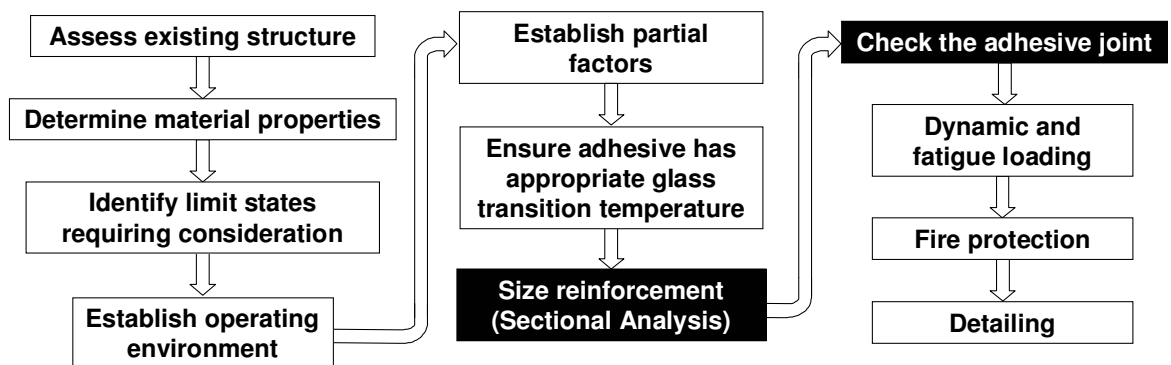


Fig. 5. Overview of the design process

Sizing the FRP reinforcing material

A sectional analysis is used to determine the minimum cross-sectional area of FRP material required to achieve the specified strength or stiffness of the strengthened section. The analysis must take into account the stress in the structure at the time that the strengthening is applied, and is based upon the conventional assumption of flexural stress analysis, that plane sections remain plane. Due to the existence of initial stresses and strains in the unstrengthened member, the analysis must be carried out on a stage by stage basis.

The strengthened member must be able to carry not just the imposed loads, but must also be checked for temperature effects. The coefficients of thermal expansion of the FRP and the metal can be very different, so that very significant restrained thermal stresses develop within the section and across the adhesive joint. The effects of differential thermal expansion can govern the capacity of the strengthened member.

Analysis of the adhesive joint

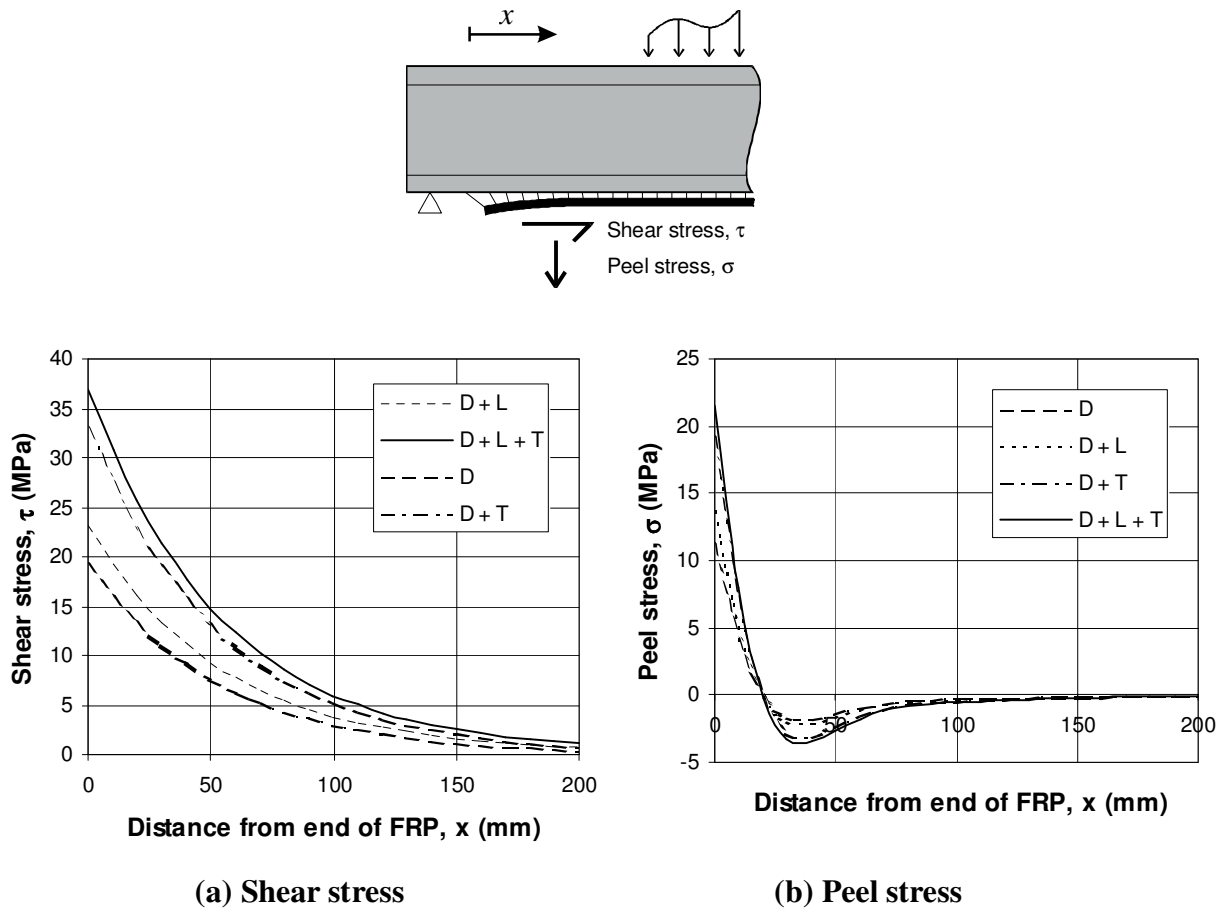
The strength analysis of adhesive joints is not a familiar technique to many structural engineers. Concentrations of shear and through-thickness (peel) stress occur across an adhesive joint adjacent to geometric discontinuities, such as the end of the strengthening plate, at a defect in the adhesive layer, or at a crack in the metallic substrate.

The current best-practice for analysing adhesive joints is to use a linear-elastic analysis to determine the distributions of shear stress and peel stress along the beam. A variety of linear-elastic bond analyses have been presented by various researchers.^{9,10,11} The guidance in C595 uses the method presented in reference 12.

Figure 6 gives example distributions of shear and peel stress along an adhesive joint for combinations of dead, live and temperature load cases, applied to a typical cast iron beam with prestressed CFRP strengthening. (Full details of this example can be found in reference 1). This figure illustrates the significance of temperature effects in adhesive joint analysis. Under dead load alone (D), the peak shear stress is 20N/mm^2 . This increases to 23N/mm^2 under dead and live load (D+L), but a much more significant 33N/mm^2 under dead and temperature load (D+T). Clearly the adhesive stresses due to temperature changes can be large compared to those due to the action of live load.

If the peak combined adhesive stress predicted by the analysis exceeds the strength of the adhesive joint, methods for reducing the peak adhesive stress must be sought. These might include relocating the end of the strengthening plate to a less highly stressed region of the member, or changing the width of the strengthening plate, or changing the geometry of the strengthening near the end of the plate. However, if a tapered plate or adhesive fillet is used to reduce the magnitude of the stress concentration, it is possible that a small amount of damage to the adhesive could lead to unstable debonding of the plate.

An elastic bond analysis is a visual design method which practising engineers are comfortable with. However, it has a number of shortcomings, for example, the adhesive is not an ideal elastic material and the analysis does not consider bond defects. C595 recommends the development of fracture-mechanics based approaches to bond analysis; although it was not possible to develop these sufficiently as part of the project.



D = Dead load (present at time of strengthening), including prestress
 L = Live load
 T = Temperature

Fig. 6. Shear stress and peel stress distributions in a typical adhesive joint for different load cases.

Installation

A high quality installation is essential for an externally-bonded FRP strengthening system, in order for it to perform as required and not fail prematurely. The complete installation process is summarised in Figure 7, including test procedures to provide assurances that the strengthening has been correctly installed. Careful planning of the strengthening works, provision of the correct equipment and environment for strengthening, and in particular adequate training of all personnel involved are vital to achieve the required quality of installation.

Operation

The operational aspects are of particular interest to the owners of structures, and can be split into:

- (a) inspection and maintenance requirements;
- (b) procurement and management issues.

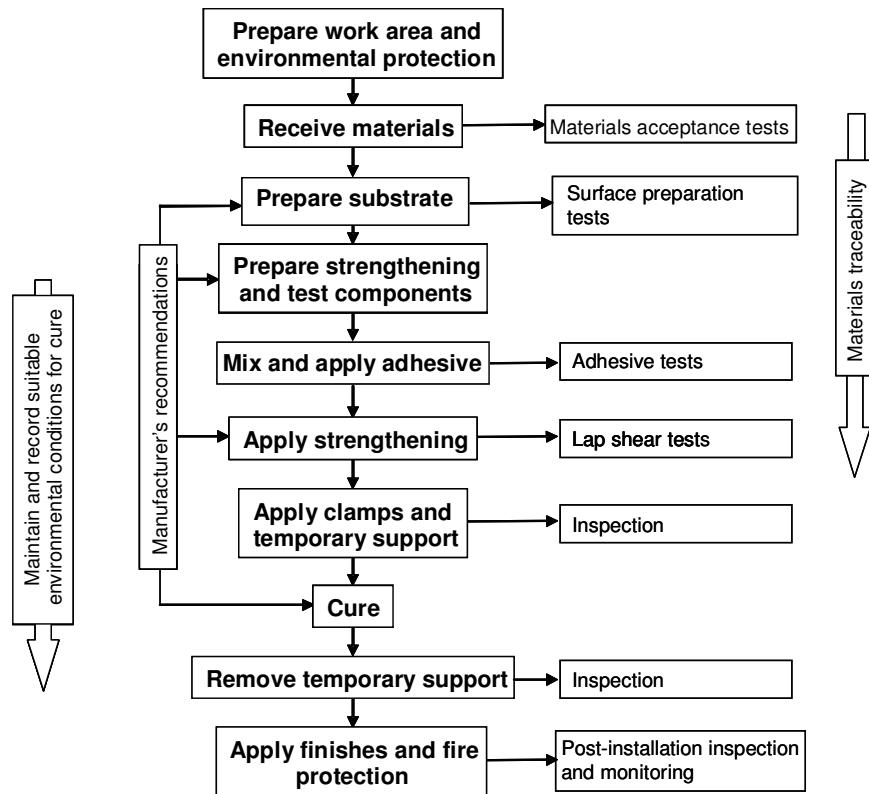


Fig. 7. The installation process for FRP strengthening

The procurement of an FRP strengthening scheme starts with a structural assessment, which establishes to what extent strengthening work is required. Procurement proceeds through conceptual and detailed design, installation, inspection and acceptance of the completed works, and maintenance of the strengthened structure. The decision to use FRP strengthening will depend on an economic assessment (in which savings due to ease of installation are often found to outweigh higher material costs). The environmental impact of the strengthening method and the implications of using FRP strengthening on heritage structures must also be considered.

Like any construction scheme, an FRP strengthening project requires inspection immediately after the work is carried out and at regular intervals during the structure's service life. The inspection and maintenance regime for the strengthened structure will typically involved annual inspections at first, relaxed to longer inspection periods after the first few years. The inspection engineer must be aware of the significance of specific defects within an FRP strengthening scheme, for example:

- defects in the adhesive layer, particularly at the end of a plate;
- crazing of the FRP matrix adhesive;
- galvanic corrosion of the metallic substrate;
- impact damage;
- mechanical fasteners attached through the FRP.

Non destructive test (NDT) methods can be used as part of an inspection, but no single NDT method is likely to provide information on all defects present, and currently available methods of NDT inspection of FRP-strengthened structures are still under development.

CONCLUDING REMARKS

This paper has presented a brief overview of metallic structures strengthened using FRP in the UK. Nevertheless, it has illustrated the diversity of structures to which the technique can be applied. It has also drawn attention to the principal issues to be considered, including an adequate understanding of the materials involved, the importance of the adhesive joint, the effects of temperature on the strengthened section, the importance of a high quality installation, and regular inspection of the strengthened structure.

ACKNOWLEDGEMENTS

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