STRENGTHENING CHOICES FOR THE REPAIR & RETROFIT OF CONCRETE BRIDGE STRUCTURES WITH FRP

J. M. Eyre  
(Graduate Structural Engineer, Costain Ltd, Maidenhead, UK)

T. J. Ibell  
(Professor of Civil & Architectural Engineering, University of Bath, Bath, UK)

A. Nanni  
(Jones Professor of Civil Engineering, University of Missouri-Rolla, Rolla, MO, USA)

ABSTRACT
At present there exist numerous, approved documents and guidelines across Europe, the US, Japan and Canada, giving detailed information on the various applications available that provide for the strengthening of concrete structures with Fibre Reinforced Polymers (FRP). Such guidelines offer a detailed overview of the principles involved in the design of strengthening for deficient beams, columns and slabs, but do not offer codified approaches for individual materials and techniques, or the necessary specialist bridge related criteria. The information and understanding gained from this study is intended for use in directing the generic approach to future FRP design strategies, through the unification of material, system & installation procedure selection and inspection & monitoring regimes.

Software has been developed by the authors to provide a rule-based, logic-programmed ‘FRP Strengthening System – Selection Toolkit’ defining the extent of required superstructure strengthening following diagnosis and recommendation for pre-installation treatment of the defects and degradation established from analysis of assessment and inspection results. The design process protocol incorporated in the software, consciously targets the concerns of largely inexperienced engineers in this field, particularly those of graduate level training, whilst also attempting to meet the knowledge demands of the Project Engineer or Department of Transportation Investigating Official, responsible for compilation of a preliminary strengthening scheme proposal, for later submission to tender.

KEYWORDS
Fibre Reinforced Polymer, Strengthening, Expert-system, Selection-criteria, Diagnosis.

1. INTRODUCTION

The failings of many of the guidelines, from the extensive range of those produced by the major European (Concrete Society Technical Report 55, Fib TG9.3 Committee 2001), US (ACI 440.2R-02) and Canadian Research committees/ national bodies, in providing truly useable and practical design assistance is in the provision of information relating to practical cases of ‘whole’ bridge or building strengthening/repair or retrofit. Particularly lacking are guidelines for the undertaking of adequate specification detailing.

Understandably, the industry still remains highly sceptical of new technologies, which further limits the take-up of FRP solutions. Most significantly because degradation cannot be fully anticipated and the associated risk is borne by clients, they are becoming increasingly aware of the durability and maintenance implications of the solutions they adopt. Experience with steel plate bonding and more than 20 years of use of carbon fibre in highly stressed applications for the aviation and automotive industries, has provided accepted criteria for comparable FRP techniques. Adhesives, for instance, have been shown to be equally effective for use with FRP in construction as in the above areas. Ultimately, the limitation of repair lies in the fatigue life of the embedded reinforcement and thus the success of externally bonded FRP relies on its ability to increase the stress range of the reinforcement.
2. AIMS & OBJECTIVES

If FRP techniques are to receive continued use and development, reliable performance of demonstration schemes must be assured and maintained. The foremost objective of this research work was therefore, to develop a design process protocol for the selection of suitable strengthening systems, for the retrofit of structurally defective and/or deteriorating concrete bridges. This objective has been reached through the production of a series of decision-tree’s/flow diagrams which are presented as design aids, along with a rule-based, logic-programmed, Expert-system, (referred to as the ‘Toolkit’ throughout this report where appropriate) titled; ‘FRP Strengthening System – Selection Toolkit’, covering the following phases of selection and repair:

- **Deterioration and degradation processes** – Damage and crack analysis for selection of associated repair or protective treatment.
- **Strengthening option selection and elimination** – Balanced assessment of the merits or limitations of FRP over more traditional counterpart solutions, such as bonded steel plate, increased section size or additional prestress.
- **Structural re-calculation** – Analysis of the requirements for enhanced capacity – in shear, flexure, axial strengthening and/or ductility.
- **FRP material and system technique choice** – Suitability of material type. Namely carbon, aramid or glass, with epoxy, vinylester or polyester laminating resins/adhesives. Appropriate methods of application, principally wet-lay-up sheet, pre-cured plate or Near Surface Mounted reinforcement.
- **Structural Design** – Rule-based sequencing for shear, flexural, axial-strengthening or ductility retrofit. Extension of above phases, to include lengths, laps and splices, layering and the required geometry on the surface of the structure. Criteria for the selection of pre-stressed and mechanically anchored FRP are included to allow exploration for their suitability as appropriate solutions for less conventional defects. Flexibility is however in-built for future extension.

Cost is arguably one of the most influential factors when assessing the advantages of alternative methods and schemes. Detailed costing however is difficult to provide impartially and can become quickly outdated in a highly changeable environment, where new technology is continually emerging. For the benefit of preliminary design clarification, final unit costs are provided, developed from an accumulation of typical material-supply, labour and inclusive construction costs, for each of the phases of development highlighted above. Design costs cannot be accurately predicted under the scope of this work and thus are not included in the final cost report.

Work to tailor the expert system to cater directly for the needs of the Project Engineer, was also carried out after close consultation with MoDOT (Missouri Department of Transportation) area engineers, responsible for the Rolla precincts. Efforts have been made to manipulate criteria for selection throughout each stage, with refinements made to the Toolkits’ user-form ordering, questioning and where appropriate, linking procedures and recommendations with MoDOT documentation for standard detailing, ‘Special Job Provisions’ and contractual requirements.

3. DEGRADATION DIAGNOSIS

The design of strengthening systems for concrete structures is largely achieved through the application of externally bonded reinforcement (abbreviated to EBR where appropriate). Such design is usually carried out as an iterative process of generation, evaluation and modification of trial and error solutions. In such early stages of development of composite technology, there exists little comprehensive guidance for use by inexperienced engineers for preliminary design clarification, final unit costs are provided, developed from an accumulation of typical material-supply, labour and inclusive construction costs, for each of the phases of development highlighted above. Design costs cannot be accurately predicted under the scope of this work and thus are not included in the final cost report.

The most important use of the ‘FRP Strengthening System – Selection Toolkit’ is to initiate appropriate thinking and direct/control preliminary design rationale and the generic approach. Overall, the suitability of a candidate bridge superstructure for flexural, shear or axial strengthening, is gauged, having provided an evaluation of the extent of the required strengthening and the sequential impacts of chosen options relating to construction, manpower, material and cost resources. The software does not attempt to prescribe a fixed solution to every eventuality at this stage, but does provide important and fundamental design considerations and practicality issues, specific to local and global conditions, environment and loading. The intention is for the programme to receive continued update to account for future modification and refinement to analysis approaches and as techniques and technologies advance.
Various alternative protective and partially curative techniques may be used to combat each form of chemical attack, based on the severity of their effects and the location and the nature of strengthening required. For diagnosis of observed defects and/or subsequent selection of appropriate remedial and compatible crack treatment; ‘Pre-Installation Treatment 1,2 &3’, ‘Weaknesses’, ‘Cracks’ and ‘Substrate’ of the ‘FRP Strengthening System - Selection Toolkit’ should be consulted. Questioning on the user-forms in the software, associated with the a foregoing categories, corresponds to the stages of pre-installation treatment investigation and requires responses to establish the overall scheme priorities and limitations, progressively refined throughout each stage of treatment selection. Additionally the environmental and existing structural criteria is defined through responses to the ‘Degradation Diagnosis’ phase of questioning, giving options and reasoning for the potential environmental, chemical and mechanical defects present.

4. SELECTION

The knowledge base of the ‘Toolkit’ consists of two main knowledge modules pertaining to diagnosis & selection (‘Pre-installation Treatment’) and preliminary design (‘FRP Strengthening’). Diagnostic information is stored in a spreadsheet format, database search being undertaken through ‘If and Then’ ruling and ‘lookup’ systems, written in Visual Basic. The benefit of relative simplicity in this form of data handling is in the ability for all routes through the program to be predefined by the author once a workable decision tree has been established. Problems of changes of the state of the variables with time are not of concern to this stage.

Taking the example of ‘System’ selection, a decision tree/network was used to create an Excel spreadsheet by compiling a rudimentary series of questions, asked in the associated user-form, to delineate the overall geometry, structure and construction methods used, but also to ensure compatibility with the previously selected repair, preparation and pre-installation conditions. Further questioning is designed to determine whether a bond or contact critical repair is necessary and hence what the stress-strain behaviour, eventual failure mode and ductility requirements are likely to be. ‘System’ options of Plate (Pre-cured Laminate), NSM or Sheet are subsequently progressively eliminated with applicable reasoning, based on their performance under the strengthening constraints presented. The results obtained at this point are entirely qualitative, with built in subjective preference by the single domain author. It is quite possible that substantial differences may be encountered in the rule base for different experts and indeed facilities are provided, encouraging customary changes to be made, through the ‘expert inclusions’ option at the base of each user-form.

5. STRUCTURAL ANALYSIS

Numerical calculations are now necessitated, some of which require iteration, whilst others require the solution of sets of equations. Again built on decision flow/ network diagrams, responses to most questioning and execution sequences are limited to ‘True’ and ‘False’, facilitating a rapid breakdown of the intricacies of design and division of the various routes to completion. Manufacturer’s data is input by the user, allowing for testing and analysis with contemporary material solutions. The final result is an economical cross-section, which satisfies the design criteria. Responses given on user-forms called from the main-menu orientation page are written directly to the corresponding spreadsheet/ flow chart in the Excel platform, activating the execution of subsequent stages of calculation within the worksheet. Solutions and limits are then returned via message box captions to the screen or via the final report textboxes, giving details of the final system.

Where seemingly complex or involved questions arise and are queried, or guidelines are sought for a series of such questions by clicking on the available ‘checkbox’, numerous quick reference checklists have been compiled which offer elaborations on the type of response demanded, or underlying nature of the conditions attempting to be configured. Similarly where numerical input values are called for, options are given where possible, via a ‘see chart’ button function, which links the user to the worksheets corresponding to the calculation being undertaken, this option allows for more accurate initial estimations, however optimisation may be achieved through continual trail and error for all design parameters if complications arise.

American and British guidance is separated for the strengthening design stages, owing to the sometimes very different principles adopted. The highly prescriptive approach used in ACI-440.2R-02 generates a very concise program routine that has been adapted and applied to TR55 guidance by making alterations to the order of design development officially recommended. Mixing the views held in the separate codes, or differential schools of thought indiscriminately would almost certainly result in major shortcomings and inconsistencies.
6. COST ESTIMATION

The level of cost control included within the selection ‘Toolkit’ at this stage concentrates on the initial costs of repair. Included within this categorisation are; material, labour (supervisors, skilled and unskilled) and UK Highways Agency recommendations for start-up and preliminary design costs. It is argued that the single event repair, using correctly designed and constructed FRP systems together with the negligible probability of failure, results in near insignificant repair cost.

\[
C_{\text{repair}} = \sum_{i=1}^{n} (1 - P_f(t_{r,i})) C_{\text{maintenance}}(t_{r,i}) \frac{1}{(1 + r)^{t_{r,i}}}
\]


The limited level of allowable strengthening or repair of structures with FRP, demanding an ultimately service-sustainable structural capacity following potential FRP failure, additionally eliminates failure costs of the consequences of injury or loss of life from bridge damage. It is also argued that, particularly in the US, where repair under live loading is permitted with nominal speed restrictions, user costs are minor factors of ultimate life cycle pricing. Hence:

\[
W = B_{\text{lifecycle}} - C_{\text{lifecycle}} \quad \rightarrow \quad C_{\text{lifecycle}} = C_{\text{initial}} + C_{\text{repair}} + C_{\text{user}} + C_{\text{failure}}
\]

\[
B_{\text{lifecycle}} = \text{Benefit that can be gained from existing bridge after rehabilitation}
\]

The final cost report, at this stage ultimately follows the recommendations generated through project RI 02-022, ‘Cost-Effectiveness Analysis of FRP Strengthening’. Firstly a cost per square foot is extracted, based on a budget estimated per bridge span. Unit costs for material, labour, preparation and concrete repair are respectively adjusted by a corresponding ‘factor ratio’ equated to the; amount of FRP material for element in question divisible by the gross amount of material applied across the entire span.

7. CONCLUSIONS, POTENTIAL & FURTHER WORK

Preliminary design, involves the overall structural form of the artefact, satisfying a few key design constraints. This early stage of the design process for repair and retrofit works, is perhaps more closely linked with the conceptual design of a new structure, but is largely based around the adoption of key decisions, based on the criteria to be satisfied at the detailed design stage. As such, an expert system and the particular method chosen for the ‘Toolkit’ is entirely appropriate for providing a platform for integration of these related stages.

With the help of the ‘Toolkit’, design should now evolve with choices being made in a logical sequence. Where a stage in the design process is reached, requiring a complete analysis to be carried out, the expert designer will do this with the expectation that the structure is safe. The potential of the ‘Toolkit’ as a Value-Engineering tool and device used for ‘Early-warning’ of project shortcomings, is also significant, in providing advanced notification of potential or consequential constructional, technical or resourcing conflicts.

8. REFERENCES


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