# STRENGTHENING OF TUNNEL SUPPORTS USING CARBON FIBRE COMPOSITES

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**SUMMARY:**

A research programme into the strengthening and life extension of tunnel supports using carbon fibre composites is presented. Details are given of a CFRP beam that will be used to relieve the load on the existing tunnel support and also provide an alternative load path to support the loads above the tunnel. The progressive damage non-linear finite element analysis of the beam is explained as is the static and fatigue testing of the beam. A complementary test programme of coupon testing to examine the degradation of CFRP in aggressive conditions is also briefly described. It is shown that the technology developed is applicable to other infrastructure applications.

**KEYWORDS:**

Construction; Infrastructure; Strengthening; Life Extension; Carbon Fibre Composite; Strength and Durability; Design Guide.

## INTRODUCTION

Much of the London underground railway system was constructed during the second half of the nineteenth century. This was the heyday of railway expansion and the engineers of that time made full use of the materials available to them. Some of the lines, such as the Circle and District, were constructed relatively close to the surface. The traditional form of construction in this situation was cut and cover. The tunnel was excavated from the surface and the walls and invert were lined with brick. The tunnel was the covered with fill material supported by cast iron beams, spaced typically at 2.4m, spanning between the brick walls, typical spans being 8m. The gaps between the beams were closed using brick jack arches. Figure 1 shows the form of construction.

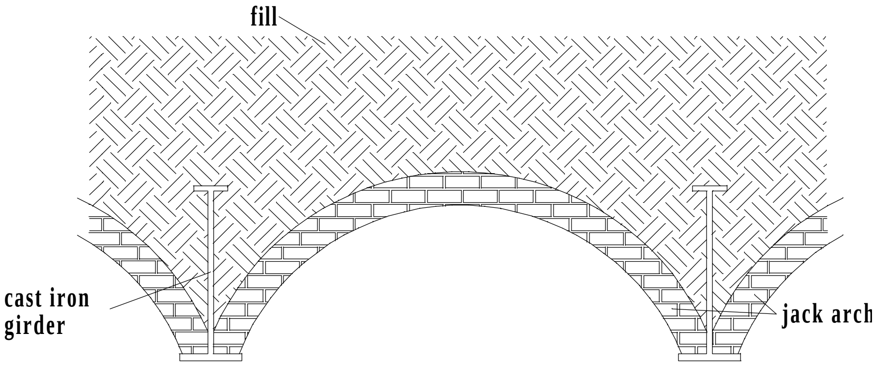


Figure 1: Cut and cover tunnel support structure

Over the intervening years two problems have arisen. Firstly, there has been development of the city above ground. New buildings, new roads and much heavier traffic have resulted in significant increases in the loading on the tunnel support structure. Secondly, the cast iron has aged over the life of the tunnel, in many cases over a hundred years. The conditions in the tunnels can be aggressive, so that the cast iron may be corroded. Cast iron of that age may have a weakened structure or may have significant casting inclusions that will reduce its strength. Because of these problems London Underground Limited (LUL) has a requirement to strengthen these tunnel support structures, but must do so without closing the tunnel to traffic except for short periods overnight.

This requirement presents an opportunity for the use of carbon fibre composite in civil engineering construction. This paper describes the research programme that is being carried out to justify the use of carbon fibre for a strengthening scheme that will have a design life of 100 years. Although the research is aimed at a particular situation the technology involved will have a wide range of applications in construction. Hence the other objective of the research is to develop and disseminate a Design Guide for the use of carbon fibre composites in construction.

## OUTLINE OF THE STRENGTHENING SCHEME

There are two parts to the scheme, as shown in figure 2. The first is to strengthen the cast iron beams by bonding carbon fibre to the tension flange using the RIFT (Resin Infusion under Flexible Tooling) method developed by Devonport Marine Limited (DML) [1]. The second is to provide an alternative load path that will relieve the load on the cast iron beams and replace them if they should fail. This is achieved by the use of a carbon fibre composite beam that is shaped to fit between the beams, underneath the jack arches. In order to relieve the load on the cast iron grout will be pumped under pressure between the jack arch and the carbon beam.

Usually the material cost of the carbon fibre beam, in comparison to a steel solution, would be prohibitive. In this case there are other factors which significantly affect the overall cost. Access to the tunnels is difficult and possession of the tunnel is limited to a short period in the early hours of each morning. The lightness of the carbon fibre means that the strengthening beams can be manhandled into the tunnel and installed without specialist equipment. Thus the total cost of the carbon fibre scheme is competitive with that of the steel alternative.

Although the use of fibre reinforced plastics is commonplace in aerospace and shipbuilding, it is a novel material for the very conservative construction industry. It is necessary to prove that they have adequate strength, in the short and long term, and durability to meet the design

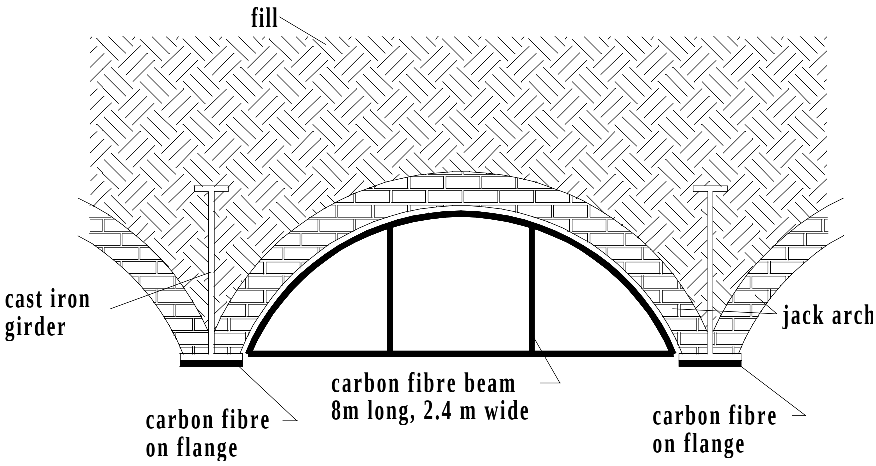


Figure 2: CFRP strengthening scheme

requirements. Two research projects have been commissioned to achieve this. One is investigating the strengthening of the cast iron, the other is concerned with the carbon fibre beam. This paper will concentrate on the latter.

The remainder of the paper will describe the finite element analysis of the carbon fibre beam, fabrication of the beam and the various tests that are being carried out. These involve static and fatigue tests on nearly full-scale carbon beams and small-scale tests on coupons exposed to a variety of aggressive environments, to simulate ageing of the carbon.

## CARBON BEAM DESIGN AND CONSTRUCTION

A near full-scale beam has been designed for structural testing; the beam is 7.6m long with an effective span of 7.4m, it is 1.5m wide and 0.6m deep. Most of the bending strength and stiffness is in the shell spar cap and the 'U'shaped spar; the remainder of the structure is needed to take up the shape of the brick jack arch. This consists of unidirectional and quadraxial carbon fibre fabric to resist longitudinal bending and shear stresses. A small amount of glass fibre has been used to protect the carbon from local damage. In certain parts of the beam sandwich construction has been employed using cores of Belcobalsa wood or foam. The unidirectional fibres are high modulus carbon and the quadraxial fabric is high strength carbon. Typical material properties are given in Table 1.

The curved shell spar cap and the 'U' shaped spar were cast in separate single operations using the RIFT technique. The 7.5m long units were cast in about one hour using specially formulated epoxy resin. The intention is to eventually cast the complete beam in a single operation. The epoxy cures at room temperature and reaches near full strength after a few days. The final stages are to connect the shell spar cap, spar and transverse ribs using adhesive. At an early stage the manufacturing processes were proved using glass fibre members. It was found that the moulds had to be very stiff in order to minimise imperfections that had to be overcome at the connection stage. Plate 1 shows the spar member being cast.

Table 1: Details of materials properties

| Property | Unidirectional High Modulus Carbon | Quadraxial High Strength Carbon | Belcobalsa |
|---|---|---|---|
| $E_1$ (Mpa) | 310000 | 46000 | 2661 |
| $E_2$ (Mpa) | 5900 | 46000 | 2661 |
| $G_{12}$ (Mpa) | 3800 | 19000 | 152 |
| $G_{13}$ (Mpa) | 3800 | 19000 | 152 |
| $G_{23}$ (Mpa) | 3800 | 19000 | 152 |
| $\nu_{12}$ | 0.3 | 0.31 | 0.3 |
| $\sigma_{1t}$ | 1157 | 596 | 9.5 |
| $\sigma_{1c}$ | 346 | 420 | 8.8 |
| $\sigma_{2t}$ | 24 | 596 | 9.5 |
| $\sigma_{2c}$ | 40 | 420 | 8.8 |
| $\tau_{12}$ | 20 | 210 | 2.3 |

Plate 1: Casting of ‘U’ shaped spar

## FINITE ELEMENT ANALYSIS

The beam has been modelled using the ABAQUS finite element package. Symmetry about the longitudinal and transverse centrelines was utilised to minimise the mesh. All the components were modelled using the 8-node quadrilateral (S8R), doubly curved thick shell element for layered composites, with reduced integration to prevent shear locking. Figure 4 shows the mesh used.

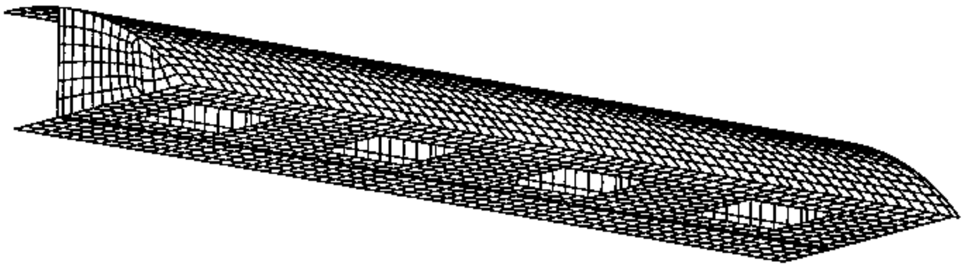

Figure 4: Typical finite element mesh used for analyses

Three analyses were undertaken:

(i) pressure load on the shell spar cap and shell outboard skin, accounting for progressive damage in the unidirectional high modulus carbon and including geometric non-linearity.
(ii) as (i) but with line loads along the length of the beam over the spar webs.
(iii) as (i) but disregarding geometric non-linearity.

Progressive damage was modelled by reducing the appropriate Elastic or Shear modulus of the damaged layer of the composite [2,3]. The Tsai-Hill criterion was used to determine when damage occurred.

Analyses (i) and (ii) were used to examine the effects of the likely loading patterns that might occur under test conditions. (iii) provided an indication of the ultimate capacity of the beam assuming that the arrangement for loading the beam in the test would be effective in preventing buckling of the curved outer shell after initial failure of the unidirectional reinforcement.

Figure 5 shows a load-central displacement plot for the beam as progressive damage occurs, obtained with quoted rather than measured material properties. Damage is generally confined to the unidirectional high modulus carbon in the shell spar cap. Table 2 shows the predicted failure loads from the analyses. The analyses will be used to optimise the lay-up of reinforcement in the beam. Since damage is confined to the compression zone it will be possible to reduce the tension region to give better material utilisation.

Table 2: Predicted failure loads from finite element analysis

| **Beam** | **Load to first ply failure (tonnes)** | **Maximum load (tonnes)** |
|---|---|---|
| Geometric non-linearity | 73 | 90 |
| Geometric linearity | 73 | 159 |

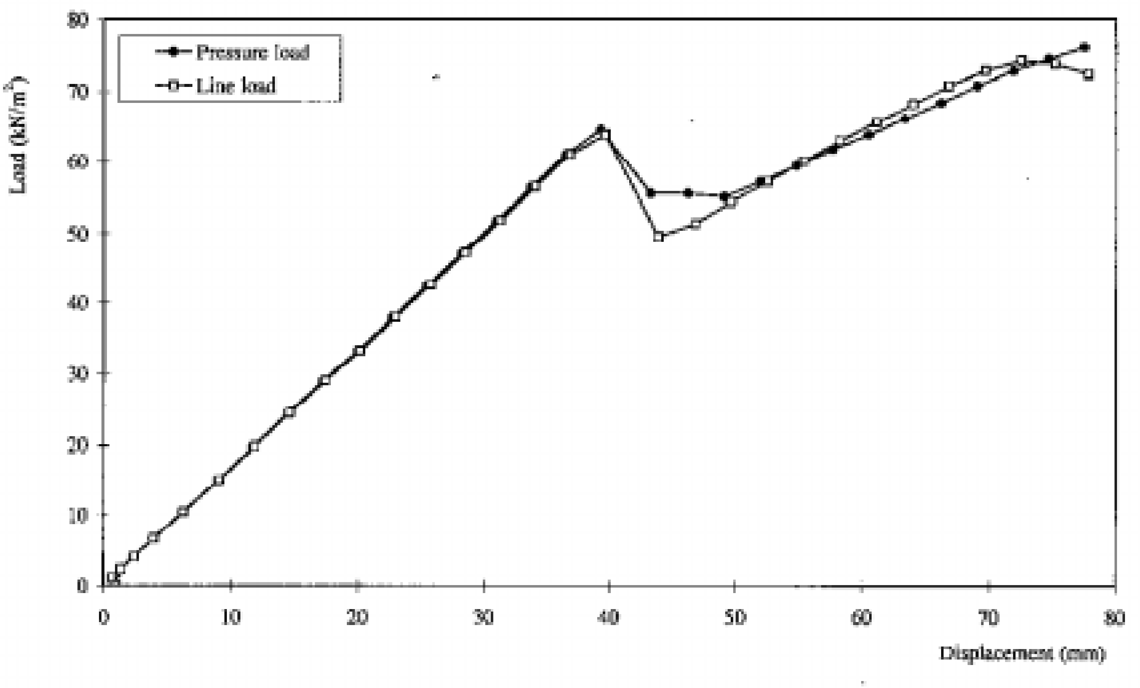


Figure 5: Load-central displacement plots of beam with progressive damage

## COUPON TESTING

Figure 6 (see end of paper) indicates the parameters of the extensive coupon testing programme which is being carried out at DERA Farnborough. This programme will give information on the degradation of the carbon fibre composites in very aggressive environments. Figures 7 and 8 show initial results of this programme.This information will be used to predict the effects of degradation on the static and fatigue strength of the main beams.

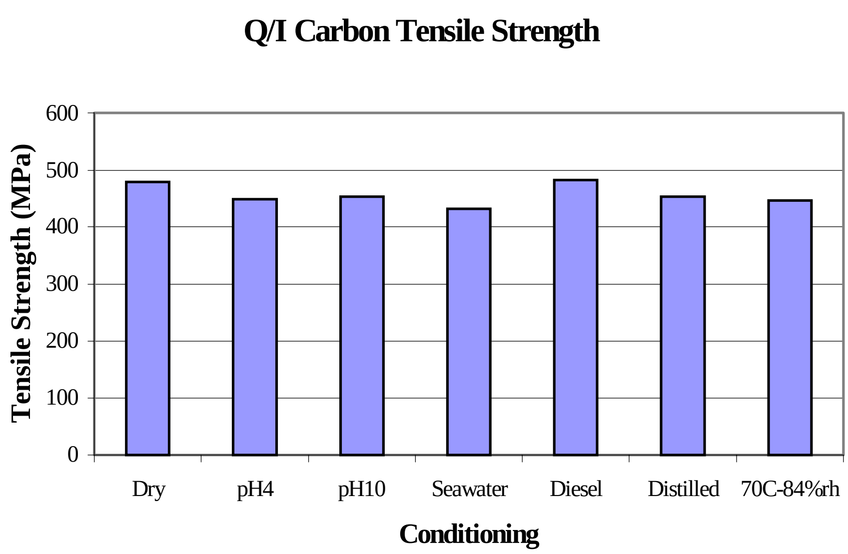


Figure 7: Exposure effects on tensile strength

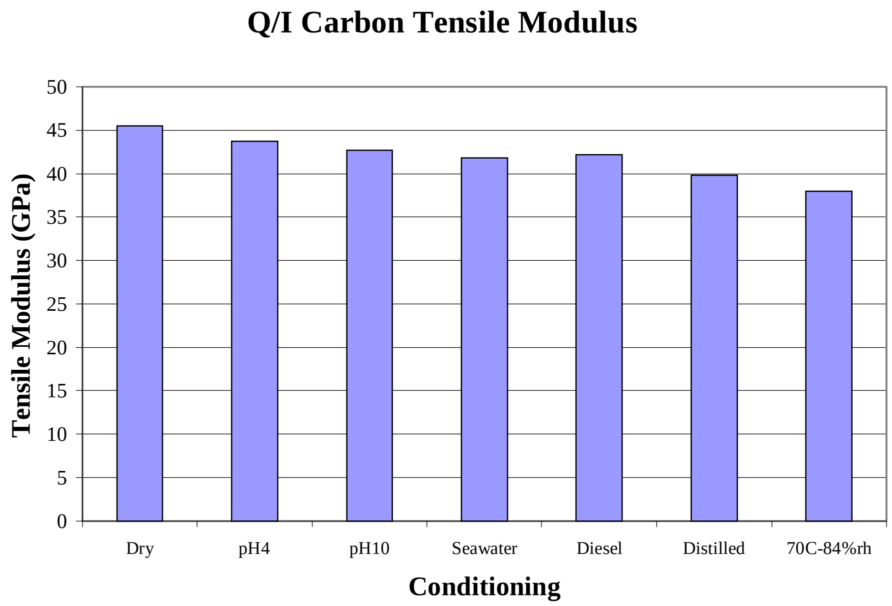


Figure 8: Exposure effects on tensile modulus

## BEAM TESTING

The research programme includes tests on two beams. The first, which has just been completed, was a static test to collapse. The second will be a fatigue test to a minimum of $10^6$ load cycles. The load is applied to the beam using a mixture of dead load and water pressure. The dead load is mainly from a series of concrete blocks that conform to the shape of the top of the beam and that are spaced along the beam so that they can articulate as the beam deflects under load. The blocks mimic the restraining effect of the jack arch on the in-situ beam. Water is confined in a bag above the concrete blocks and can be pressurised to provide a uniform pressure on the concrete blocks. In the fatigue test the dead load will provide the mean load and varying the water pressure will furnish the cyclic load. The test rig, which was custom made for the research, is a major structure in its own right capable of providing a uniformly distributed load of 500kN/$m^2$.

The static test specimen was heavily instrumented, using strain gauges at key points and displacement transducers to measure vertical and transverse deflections. Optical fibres were cast into the beam to trace damage formation during the test. The static test was carried out in the last few days and was a great success. At failure the beam was carrying a total load of about 115 tonnes. Unfortunately results are not available for inclusion in the paper but some will be presented at the conference.

## CONCLUSIONS

- The research reported involves the analysis and testing of very large carbon fibre composite beams.

- These beams, at full scale, are intended for the strengthening and life extension of tunnel supports in the London underground railway system.

- The research has two main objectives:

    1. To prove that carbon fibre technology has the strength and durability, not only for its immediate application in the London underground, but also for other infrastructure systems.
    2. To develop and disseminate a Design Guide which will allow engineers to choose suitable materials, structural forms and fabrication methods for the successful implementation of carbon fibre technology in construction.

- This paper is the first stage in that dissemination process.

- Since the project is still at a relatively early stage it has not been possible to present detailed results. These will be released as they become available.

## ACKNOWLEDGEMENTS

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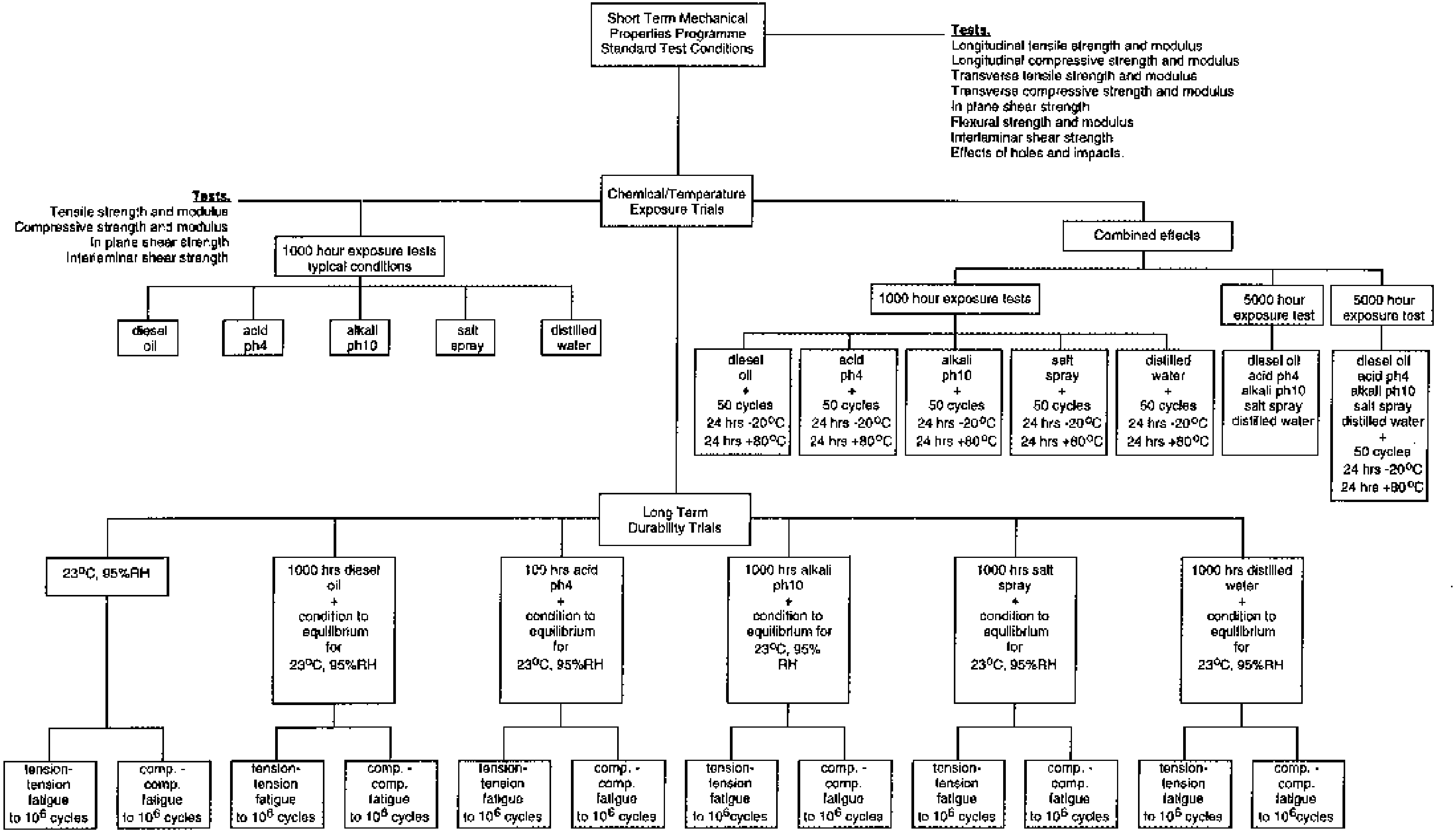


Figure 6: Coupon testing parameters