BUILDING CONFIDENCE IN THE USE OF FIBRE REINFORCED POLYMERS IN CONSTRUCTION

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ABSTRACT

The past decade has seen considerable growth in the use of fibre reinforced polymer (FRP) composites for structural applications in the construction sector, coupled with an increasing level of market confidence in their use. The challenges associated with safeguarding this level of confidence and with building upon it are explored. To do this, a simple business model, called the Innovation Analysis Tool, is used that differentiates between established and new applications and also between current and new technology. The tool provide a rational framework for considering the degree and type of innovation associated with a project and facilitates the systematic consideration of the role of research in maintaining and expanding market opportunities. The importance of differentiating between established, proven, applications and new applications is highlighted, with examples used to demonstrate the need to consider the underlying structural mechanics in making such a determination. Observations are also made on the benefits of aligning research into new technologies with the principal commercial drivers for the use of FRP composites.

KEYWORDS

Fibre Reinforced Polymer, FRP, construction, strengthening, innovation, business analysis

INTRODUCTION

The use of fibre reinforced polymer (FRP) composites in the construction sector has now gained wide international acceptance. The past decade has seen considerable market growth in the use of FRP composites for structural applications, coupled with an increasing level of market confidence. A broad range of practical applications has been established. FRP has been used in all-FRP elements or structures (e.g. CIRIA 2002; Holloway and Head 2001; Clarke 1996; and see Figure 1), as reinforcement and prestressing for new concrete structures (e.g. Burgoyne 2001; Lees 2001), and for strengthening existing structures (see e.g. ACI 2002; CIRIA 2004; Concrete Society 2004; Fib 2001). The field remains a very active area for research.

The main advantages of using FRP composites in construction stem from their high strength-to-weight ratio. Furthermore, reduced maintenance requirements are anticipated because of their corrosion resistance. In structural rehabilitation the low density of FRP materials can lead to easier site handling, reduced labour costs and more rapid installation compared with conventional strengthening techniques. The reduced disruption associated with their use can be particularly attractive. The potential to realise similar benefits is now stimulating heightened interest in the use of all-FRP structures and structural elements, as are exciting aesthetic possibilities (e.g. Kendall 2007)

This paper is concerned with the challenges to safeguarding and building confidence in the use of FRP composites in construction. To explore these issues, a simple business model is used. This model was first introduced by Denton (2007). Here the model, termed the Innovation Analysis Tool, is refined and extended.
INNOVATION ANALYSIS TOOL

The purpose of the Innovation Analysis Tool is to provide a rational framework for considering the degree and type of innovation associated with a project and, more broadly, to examine the potential for research to maintain and expand opportunities to meet a particular market need. The application of the tool seems particularly useful in fields, such as civil and structural engineering, in which, because of the typical scale of projects, prototyping is not feasible. As a result, any failures can be very costly and public events, and their consequences extremely far-reaching.

The inadvertent and unsuccessful use of a promising technology in an unproven area can result in a substantial loss of confidence in the technology itself, affecting its subsequent use in previously proven applications. For this reason it is crucial that designers are able to understand the degree of innovation in their projects, particularly if they are utilising emergent technologies. However, as illustrated later, doing so is not always straightforward.

It is important that the terms used here are clearly defined, although it is not necessary, nor intended, that the definitions should be universally applicable outside the present context. The term innovation is used here to refer to, ‘the successful exploitation of new ideas’ (DTI 2003). It is noteworthy that this definition therefore combines creativity with successful practical implementation.

The Innovation Analysis Tool is illustrated in Figure 2. It establishes four quadrants that differentiate between established and new applications and between the use of current and new technology. Quadrant 1 represents those projects that can be undertaken using current technology in established applications. As such, it defines those projects that are not, in the present context, considered innovative. Quadrant 1 can also be understood to represent the currently available market in which a particular technology can be used without the need for the additional controls appropriate for an innovative project.

The remaining three Quadrants represent opportunities for innovation: Quadrant 2 represents the use of new technology in established applications; Quadrant 3 is concerned with using current technology in new applications; and Quadrant 4 represents the use of new technology in new applications. Successful research outcomes enable innovation opportunities to be realised and transition into Quadrant 1. This is the basis of the definition of research used here, i.e.: Research is the process that enables Quadrant 2, 3 and 4 opportunities to be realised and transition into Quadrant 1.

The tool serves to differentiate between research and innovation leading to increased competitiveness (Quadrants 3 and 4) and that which extends the potential range of applications (Quadrants 3 and 4). In this context, competitiveness may be purely commercial, or may also be associated with other client or society needs, such as sustainability, risk management, durability, or aesthetics.
Some further terms in the model require definition: *An established application is an application that has been proven experimentally, analytically and through practical implementation; a new application is one that does not satisfy the requirements of an established application.*

The term technology is used here in its wide sense encompassing all aspects of the products of engineering design and invention. *Current technology comprises the materials, components, systems and processes that have been used in proving the effectiveness of established applications; New technology comprises those materials, components, systems and processes that do not fall within the definition of current technology.*

It will be clear that the definitions used for applications and technologies are coupled, and for this reason, it is legitimate to query whether Quadrant 2, in which new technology is applied in an established application, is a valid domain. In fact, as illustrated later, it does seem that this quadrant holds some valuable innovation opportunities. Key to recognising its valid existence is the acknowledgement that it is possible for new technology to be introduced, possibly based on the evolution of a current technology, that do not invalidate the basis upon which the relevant ‘established application’ was proven.

It will also have been noticed that the definition of an established application demands that it has been proven experimentally, analytically and through practical implementation. The need for such an onerous definition is best illustrated by an example. Here the strengthening of concrete elements using externally bonded FRP is used for that purpose.

FRP strengthening is typically undertaken to address an analytically-determined shortfall in strength by increasing a structure’s (ultimate limit state) capacity. It is quite common for structures that are not expected to experience significant changes in loading to be identified as requiring strengthening even when they show no signs of distress. That such structures show no signs of distress is not surprising since they may well not have experienced a particularly extreme loading condition or because some reserves of strength may exist that have not been taken into account in the analysis. Strengthening may nonetheless be entirely necessary to give assurance of an appropriate level of structural safety. For this reason, it is important to recognise that if, following a strengthening scheme, a structure shows no sign of distress, it cannot be concluded that the required enhancement in capacity has necessarily been achieved. It could be that the structure would have continued to show no signs of distress even if the strengthening had not been undertaken. Thus, successful practical applications are a necessary but not a sufficient condition to demonstrate that an application satisfies the categorisation of a proven ‘established application’ in the context of the Innovation Analysis Tool.

The requirement to have both experimental evidence and an analytical model stems from the need to be able to predict the sensitivity of behaviour to variations in parameters without having to undertake further
experimentation, and here caution must be taken in accepting unduly empirical models (see for example Denton 2004). As observed by Einstein (1934), the challenge in devising a theory is one of reducing the problem to as simple and as few basic elements as possible without surrendering its ability to model observed behaviour. It follows that a worthwhile theory, or analytical model, must be successful when its ability to predict behaviour is tested. Overly simplified or empirical models that do not capture the underlying mechanics will typically fail in this respect.

In commenting on the desirable attributes of analytical models, it is perhaps also worthwhile observing that in an engineering context, it can be extremely advantageous to accept models that give approximate results provided any loss in accuracy is compensated for through greater clarity and simplicity, and provided the underlying structural mechanics are not lost and any implicit assumptions are understood. The informed application of plasticity theory to quasi-ductile structures is such an example. Whilst complex numerical methods might initially seem attractive, their lack of transparency often leads to legitimate concerns about their predictive capabilities.

Application of the Innovation Analysis Tool

In its basic application the tool can be used as a prompt to designers to consider whether or not their project is innovative. In this respect, the onus must lie with the designer to satisfy him or herself which quadrant the project lies in. This judgement should be evidence-based and appropriately precautionary, consistent with the associated level of risk.

Accurately determining the correct quadrant requires knowledge and understanding. Inevitably, therefore, different designers may independently place the same project in different quadrants, and unfortunately for reasons examined later, it is not necessarily the less competent engineers that will be the more cautious. In fact the reverse may often be the case. There are particular dangers in emergent fields, such as structural application of FRP composites, where the depth of knowledge and understanding amongst designers is variable and the bounds on the safe application of design models given in guides and standards are yet to be fully established and broadly communicated. It is therefore important to acknowledge that the ability of designers to select the correct quadrant is dependent upon their competency and the quality of available guidance. The provision of expert advice may well therefore be appropriate in the early stages of projects.

If a designer judges a project to lie outside Quadrant 1, there is a need to establish additional controls to manage prudently the risks inherent in such innovation. The selection of these additional controls is beyond the scope of this paper, other than to note that they should be commensurate with the consequences of any failure.

As noted earlier, the tool can also provide useful insight into how research can be most effectively targeted to maintain and expand market opportunities and increase competition. If the boundaries of Quadrant 1 are understood then it is possible to identify families of projects that lie outside this domain, and devise research programmes that enable them to transition into Quadrant 1.

Quadrants 2, 3 and 4 all represent opportunities for research investment. Interestingly, it seems that Quadrant 4 research is often considered to have the highest status, and seems to be favoured by funding bodies. Yet in practice, Quadrant 2 and 3 research is crucial. It can yield a significant return on investment and also, as illustrated later, Quadrant 3 research is particularly important in safeguarding confidence in Quadrant 1 projects.

BUILDING CONFIDENCE IN THE STRUCTURAL USE OF FRP

The decision to use FRP for a structural application will typically represents the selection of one amongst several different options. Confidence in the use of FRP will be central to such a decision, as will market awareness of the available technologies and their competitiveness. The present focus is confidence, and this will be examined here by considering three contributory factors, in the context of the Innovation Analysis Tool. These are: maintaining market confidence in established applications; prudently extending current technology to new applications; and, the introduction of new technology. Market confidence cannot, however, be viewed wholly in isolation, and some reference is also made to issues of market awareness and competitiveness.

The subject is a broad one and it is necessary therefore to limit its coverage here. In the discussion of the challenge of maintaining market confidence in proven applications, emphasis is placed on the opportunities to reinforce confidence by drawing more fully on the expanding track record of practical experience. The
discussion of new applications focuses on the importance and challenges of differentiating between established, Quadrant 1, and new, Quadrant 3, applications. This is done using illustrations from the field of FRP strengthening of concrete structures. Observations on the introduction of new technology are limited to some suggestions on possible areas for future research effort.

**Maintaining market confidence in established applications**

Quadrant 1 in Figure 2 represents the available market for a particular technology (without requiring the additional controls necessary for an innovative project). As noted previously, because the use of FRP will typically represent one amongst several options, market share can increase or decrease within this quadrant and will be significantly influenced by confidence in the use of the material; such confidence will be driven by an expanding track record of successful applications, an ongoing sense of progression through further innovation, and perhaps most importantly, the avoidance of unsuccessful projects or structural failures.

One of the early barriers to the adoption of FRP in structural applications was the lack of an established track record in the sector. As a result of many successful projects this barrier is now less problematic. However, it would be a missed opportunity if the expanding population of projects were not drawn upon more fully to reinforce confidence and enhance practice.

Structures are almost invariably long-life assets. Structure owners are therefore seeking confidence in the long term performance of FRP structures or structural elements, particularly because the expected durability and reduced maintenance requirements of FRP have been key drivers for the adoption of the materials. Now that a considerable number of applications have been undertaken, there is the opportunity for a detailed independent review of the in-service performance of schemes. It is acknowledged that some work in this area has been done, but there is value in doing more.

Much work continues on the development of design guidance for structural applications of FRP. It seems, however, that less emphasis has been placed on the development of material and installation specifications. As the market expands it will be crucial for this to be addressed. The widespread adoption of robust and comprehensive material and construction specifications is fundamental to ensuring that quality standards are not compromised and suppliers and contractors implementing the best practices are not commercially disadvantaged.

In relation to FRP strengthening systems, the quality of installation is crucial to the effectiveness of a scheme. For this sector, a particularly important risk to the maintenance of market confidence is inadequate installation quality. Further efforts in developing industry-standard installation and quality control specifications and programmes for the accreditation of installers would seem very prudent steps forward.

Notwithstanding these important quality risks, perhaps the most significant risk to the maintenance of confidence lies in the inappropriate use of FRP in unproven applications, leading to unsuccessful projects or failures. This risk manifests itself when designers inadvertently stray from Quadrant 1 into Quadrant 3 applications; it is discussed in some detail in the next section.

**Extending current technology to new applications**

The successful extension of current technology to new applications is important in expanding the available market, driving economies, increasing market awareness and fostering greater market confidence. However, as noted previously, its unsuccessful extension can be highly damaging. It is therefore crucial that the extension of current technology to new applications is done consciously, prudently embracing the additional controls necessary for such innovation. A key challenge to maintaining confidence therefore lies in recognising the distinction between Quadrant 1 and Quadrant 3 applications. This distinction is important, but not always immediately apparent in practice. Recognising the distinction between Quadrant 1 and Quadrant 3 projects is the fundamental step in successfully extending current technology to new applications.

This issue will be explored here using four examples concerned with the strengthening of concrete structures using FRP. The purpose of using examples is that they best illustrate the challenges involved and because it clearly demonstrates the need for a thorough understanding of the underlying structural mechanics in order to explore the boundary between Quadrant 1 and Quadrant 3. It should be emphasised that the intention here is not to establish the conditions that define whether these four ‘applications’ fall into Quadrant 1 or 3. Since research is ongoing to explore some of these issues (see e.g. Darby et al. 2007), the situation is not a static one. The fundamental motivations here are firstly to highlight the need for care and rigour in design to safeguard
confidence in Quadrant 1 applications, and secondly to illustrate the importance and need for Quadrant 3 research.

Before progressing to these examples, it is helpful to note that the behaviour of FRP-strengthened structures can differ significantly from conventional reinforced concrete structures. Many of the assumption inherent in design procedures generally used by structural engineers are not therefore applicable to the design of FRP strengthening schemes.

**Flexural strengthening of curved elements**

The first example considered relates to the flexural strengthening of curved elements. Physically, it is possible for FRP systems, particularly those based on fabrics, to be bonded to irregular surfaces, and there have been practical cases where this has been done with the intention of increasing the flexural strength of curved structural elements. The influence of curvature on the effectiveness of FRP strengthening seems, however, to have received quite limited research attention (Porter et al. 2003), with the huge majority of the experimental and analytical research into FRP-strengthen concrete elements being on elements with little surface irregularity.

Beams or slabs strengthened in flexure using externally bonded FRP are subject to two families of failure modes. These are modes in which composite action is maintained between the concrete and FRP and modes where this composite action is lost because the FRP separates from the concrete.

The first family of modes includes concrete crushing and FRP fracture. In practice, however, it is the second family of failure modes that tend to be critical. These FRP separation failure modes are generally characterised by the unstable propagation of a longitudinal "crack" or failure surface beneath the FRP. Typically the longitudinal failure surface runs through the concrete, either near the concrete surface or at the level of the tension reinforcement, rather than the adhesive or FRP itself. This is largely because the tensile strength of the concrete is usually less than the adhesive or resin used to bond the FRP to the concrete.

The presence of curvature will lead to the development of normal stresses in the adhesive layer between the FRP and surface concrete. If the surface to which the FRP is bonded is convex, these normal stresses will be compressive and would not therefore be expected to result in the early initiation of FRP separation failure. Clearly, for the case of elements with concave curvature, where these normal stresses will be tensile, the same conclusion cannot be drawn. In fact, experimental evidence (Porter et al. 2003) indicates that the presence of curvature has a detrimental effect on FRP strengthening.

The relevance of this example is the simple illustration that by considering the stress regime at the interface between the FRP and concrete in curved FRP-strengthened elements, it is clear that the results of experimental and analytical investigations of reinforced concrete elements without surface irregularity cannot be simply extended to curved elements, particularly those with concave curvature. In the absence of specific work to demonstrate its effectiveness, the strengthening of elements with concave curvature would seem to fall into Quadrant 3.

**Flexural strengthening of statically-indeterminate structures**

The effectiveness of FRP strengthening has been demonstrated in both hogging and sagging regions in isolation. However, can the simple application of established FRP strengthening design rules to both sagging and hogging regions on the same structure be safely be considered a proven, Quadrant 1 application, or there are some specific issues that potentially place such applications in Quadrant 3?

As noted previously, the failure of concrete elements strengthened in flexure using FRP is generally found to be brittle. As a result, the lower bound theorem of plasticity cannot be applied to FRP-strengthened structures. This powerful theorem states that if a distribution of stresses throughout a structure can be found that is in equilibrium with the applied load and that nowhere exceeds its strength, then that load can safely be carried. The lower bound theorem unpins, often implicitly, much of the structural analysis undertaken in the design of conventional reinforced concrete structures. It explains why elastic analysis can safely be used for ultimate limit state design even though the distribution of stresses throughout at structure as collapse approaches is likely to vary significantly from the distribution found in an elastic analysis. It also explains why actions that lead to the development of self-equilibrating stress systems within a structure, such as thermal effects or differential settlement, generally need not be taken into account in ultimate limit state design.
The distribution of stress resultants in statically indeterminate structures cannot be established from equilibrium considerations alone. Thus for the simple structure shown in Figure 3, it is not possible to know the actual distribution of bending moments throughout the beam solely by analysing the effects of the applied loading. It is quite possible, for example, that one of the supports might have settled more than the others, or that it will do so in the future; the differential settlement of an end support would give rise to an increased hogging moment at the central support and a reduced sagging moment in the span. Consider then the implications that such a settlement might have on the behaviour of the structure in Figure 3 if it is strengthened in both the hogging and sagging regions, with the degree of strengthening determined using a simple elastic analysis, neglecting settlement.

If some settlement of an end support has occurred, the hogging moment over the support will be greater than that determined from the analysis. As a result, the moment at the support will reach its strengthened capacity before the full design loading has been applied. For a ductile structure this would not be a concern. A flexural hinge would form and increasing load could be carried until a further hinge forms in the span. However, if the FRP strengthening fails in a brittle fashion, the strengthened structure will not be able to attain its full design loading.

In reality, the non-linear moment-curvature behaviour of FRP-strengthened concrete elements will tend to diminish the significance of such effects. However, it is clear that, in the absence of specific work to demonstrate its effectiveness, the strengthening of multiple regions of statically indeterminate structures may well need to be viewed as falling in Quadrant 3. Research work in this field is ongoing (see e.g. Vasseur et al 2007).

Interestingly, designing a strengthening scheme for the structure shown in Figure 3 with the FRP located only in the spans and allowing a plastic hinge to form at the support can overcome many of these difficulties, probably placing it in Quadrant 1 even though on first consideration it might appear more adventurous than a scheme where FRP is installed both in the spans and over the support.

**Strengthening of non-prismatic structural elements**

One aspect of the behaviour of externally bonded FRP strengthening that differs markedly from conventional flexural reinforcement is that of anchorage. In the case of conventional embedded steel reinforcement beyond an ‘anchorage length’ the full strength of the reinforcement can be expected to be developed. Typically, this is not the case for externally bonded FRP.

In tests on the anchorage of FRP externally bonded to concrete, of the type illustrated in Figure 4, it has been found that beyond a limiting bonded length, of the order of 50-300mm, there is no further increase in the ultimate anchorage load-capacity with increased bonded length (see Neubauer and Rostasy 1997; Blaschko et al...
1998). Furthermore, it has been found that the maximum anchorage capacity is generally significantly less than the tensile strength of the FRP.

Figure 5 illustrates the variation in the maximum proportion of the FRP strength that can be anchored with increasing FRP thickness, according to proposals by Neubauer and Rostasy (1997). In this figure, $\varepsilon_{frp}$ is the strain in the FRP, $\varepsilon_{frpu}$ is the ultimate FRP strain capacity, $\varepsilon_{frpdb}$ is the predicted strain in the FRP when debonding occurs, $t_{frp}$ is the thickness of the FRP and $F_{ctm}$ is the concrete tensile strength. Other parameters are explained by Denton et al (2004). The figure shows that, for the parameters considered, only about 20% of the strength of a 0.5mm thick FRP plate can be anchored by bonding it to concrete in this fashion.

Interestingly, the anchorage force that can be developed in the tests on specimens of the type illustrated in Figure 4 is typically significantly less than the maximum force in the FRP measured (at midspan) in tests to failure of simply-supported FRP-strengthened reinforced concrete beams. It appears from these results that the development of distributed flexural cracking along the span of a beam or slab is important in enabling the gradual build up of stress in the FRP to a level in excess of the anchorage capacity.

![Figure 5. Variation in maximum anchorage force with FRP thickness (after [11])](image)

What then are the implications of this behaviour on the use of FRP to increase the flexural capacity of non-prismatic sections, and in particular, sections with a significant change in strength, such as that shown in Figure 6? Such a situation can arise in the strengthening of bridge cantilevers for the transverse moments induced by accidental vehicle loading.

![Figure 6. Strengthening of non-prismatic sections - cantilever example](image)

A potential concern arises about the behaviour of the FRP bonded to the deeper section, on the left hand side of Figure 6. It would seem that the behaviour of this FRP may be similar to that exhibited in the tests illustrated in Figure 4. As a result it is conceivable that the maximum force that can be sustained by the FRP at the point where the section depth changes may be limited to the anchorage capacity of the FRP bonded to the left hand side of the test, rather than the higher figure typically found at the equivalent position in tests on prismatic beams.

A conservative design approach would be to limit the FRP force at the change in section depth to the anchorage force and recent research supports such an approach (Darby et al 2008). But would this be unduly conservative? Many published design guides would not identify this potential issue at all, and even those that do tend not to do so in a particularly explicit fashion. In the absence of specific work to demonstrate the actual behaviour, perhaps
the flexural strengthening of non-prismatic elements with significant step-changes in strength should also be viewed as falling in Quadrant 3?

_Strengthening of large structures_

The fourth ‘example’ considered in exploring the boundary between Quadrant 1 and Quadrant 3 applications is a general one. It is well established that structures composed of brittle materials can exhibit a size effect, which may be statistical or mechanical in origin, whereby the strength of geometrically similar specimens does not increase in proportion to scale (see e.g. Bazant 1993). Since it is known that FRP strengthened structures can behave in a brittle fashion, it is reasonable to question whether the results of small scale experiments can safely be extended larger structures (see for example the discussion in Denton et al 2004).

Investigating the scale at which size effects become significant is problematic for researchers. Large scale testing is expensive, and can be impractical, so verifying large scale applications is rarely straightforward. Notwithstanding this difficulty, it does seem that the possible presence of a size effect should be considered in determining whether an application can prudently be considered to fall into Quadrant 1.

_Development of new technologies_

Quadrants 2 and 4 of the Innovation Analysis Tool are concerned with the development of new technologies for use in existing and new applications respectively. These are important areas for research to maintain competitiveness and expand market opportunities. Because of the diversity of activity in this broad area, specific new technologies are not discussed here. It is interesting, however, to consider the commercial drivers for the use of FRP composites and the opportunities for alignment between these drivers and research to develop new technologies.

Although costs have been reducing, FRP composites remain relatively expensive materials. It is therefore very rational to explore new technologies that enable greater design efficiency, for example by utilising a higher proportion of the strength of these materials (see e.g. Burgoyne 2001).

In the strengthening sector, it is not, however, necessarily material volume that governs the decision to use FRP. Speed of installation is often the primary commercial driver. The major commercial risk in this sector is whether the FRP is serving its intended purpose, i.e. whether it has been installed to appropriate quality levels and is behaving as expected. New technologies associated with more rapid installation and with providing assurance of FRP installation and behaviour would be valuable entrants to the market. Both of these could be Quadrant 2 innovations, and are example of promising areas for Quadrant 2 research investment.

The introduction of new technology will more generally constitute Quadrant 4 innovation, and therefore need to proven experimentally, analytically and through practical implementation. For such innovative projects it is important to recognise that traditional design assumption may not remain valid. For example, for St Austell Footbridge, the first FRP bridge on the UK rail network, which was recently designed by Parsons Brinckerhoff (see Figure 1), one of the governing design criteria was pedestrian comfort in response to dynamic train buffeting loading. Significant effort was expended in addressing this issue in the design and in undertaking dynamic testing following installation.

**CONCLUSIONS**

The challenges to safeguarding and building confidence in the use of FRP composites in construction have been considered with reference to a simple business model which differentiates between established and new applications, and current and new technology. This model, the Innovation Analysis Tool, was first presented by Denton (2007), and here it has been extended and refined.

Risks to maintaining confidence levels in established applications have been discussed. It is suggested that the in-service performance of a sample of FRP applications should be reviewed and that further effort should be employed towards the development of industry-standard material and installation specifications.

The importance of differentiating between Quadrant 1 and Quadrant 3 (i.e. differentiating between established and new) applications has been highlighted, particularly in safeguarding confidence in Quadrant 1 applications. Examples have been presented that illustrate some of the challenges in differentiating between these two quadrants, and in particular the need to approach such differentiation with a thorough understanding of the underlying structural mechanics. The importance of research in Quadrant 3 has also been highlighted.
In the context of research into new technologies, observations have been made concerning the merits of aligning such work with the key commercial drivers and risks that motivate the use of FRP composites in construction.

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