## Assessing the potential value of a SHM deployment on a proposed footbridge

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**ABSTRACT:** A fibre-reinforced polymer (FRP) cycle footbridge has been proposed for construction in Bristol, United Kingdom for South Gloucestershire Council. The superstructure will span 54m, comprising a bowstring carbon fibre-reinforced polymer (CFRP) arch with a 5m wide glass fibre-reinforced polymer (GFRP) deck supported by stainless steel hangers. Recently, a methodology has been proposed that provides a structured process to assess the value of a structural health monitoring (SHM) system for a bridge prior to deployment. This methodology outputs a simple metric that quantifies the likeliness of an SHM system to yield value to an asset owner. This FRP bridge is used as a case-study to 'road test' this process. Two possible systems were considered: a system of accelerometers and a system of strain gauges. From the resulting discussions, a deployment of accelerometers received a value-rating (VR) of 4.2. A strain gauge deployment received 3.7. The scores will contribute to a monitoring specification for the FRP bridge which is currently in the design phase. Expansions to the methodology have also been proposed to better capture the potential value of an SHM system which would be of interest to structural engineers and researchers, in particular to inform model validation and research activities.

## INTRODUCTION

### Structural Health Monitoring

SHM systems can be classified into five categories: 'anomaly detection'; 'sensor deployment studies'; 'model validation'; 'threshold check' and 'damage detection' (Webb *et al*., 2015). When specifying an SHM system engineers should consider how the data obtained from the monitoring can be used to make decisions. Once the aims of the SHM system have been initially established, a structured process is needed to decide whether monitoring will yield actual value. Vardanega *et al.* (2016) have proposed a methodology that (prior to any deployment) brings together (arguably) the three key stakeholders: the 'SHM engineer', 'structural engineer' and 'asset manager' to participate in a facilitated discussion. Table 1 shows the nine questions that are proposed for the structured discussion, divided into three sections each to be answered by the 'SHM engineer', 'structural engineer' and 'asset manager' respectively. Each question is rated 1 to 5 by the relevant stakeholder (see Table 2) and these scores are averaged to provide a simple metric that relates to a project value statement. The framework provides structure to the discussion and is centered on the likeliness of the project 'to yield value to the asset owner/manager' (Vardanega *et al.*, 2016). In this paper, this methodology is applied to the proposed FRP footbridge.

**Project Background**

A proposed FRP cycle footbridge is to be constructed in Bristol, United Kingdom for South Gloucestershire Council (SGC). The appointed designers are WSP. At the time of writing, the following description of the proposed design can be given:

- The superstructure will span 54m, comprising a bowstring arch made of CFRP, with a 5m wide GFRP deck supported by stainless steel hangers.
- The arch will have a triangular profile, inclined to the vertical.
- The arch material design will consist of unidirectional carbon fibres and biaxial glass fibres, bonded with an epoxy resin.
- The deck will be a modular construction, split into nine 6m long modules.
- The internal diaphragms will provide strength and stiffness to the deck and also provide space for Tuned Mass Dampers (TMDs) and service ducts.

Preliminary drawings taken from the public planning application are shown in Figures 1 and 2, with a visualization of the bridge shown in Figure 3.

This project presents the opportunity to design and deploy an SHM system during the construction stage: allowing the collection of monitoring data both during construction and service, and offering insights into how monitoring systems can be embedded into a structure from the early design stages. Data of potential interest include: (a) long-term behaviour of FRP in service (i.e. observed durability); (b) dynamic response of FRP in service; (c) applicability of existing deflection limits; (d) performance of constructed joints and (e) to inform bridge management practice.

**Pedestrian Bridges**

With the growing rate of urbanization and the accompanying increase in population, more pedestrian bridges (or 'footbridges') are being constructed. They are often used as statement symbols resulting in architecturally novel designs (Dallard *et al.*, 2001; Caetano *et al.*; 2010; Barbosa *et al.*, 2013). Long and slender in profile, they typically use much less construction material than bridges that need to carry vehicles and are therefore much lighter. This low weight relative to the applied loading can make them susceptible to pedestrian-induced vibrations. Such vibrations can reach 'uncomfortable' levels. In recent times, this issue was brought into the public sphere during the closure of the London Millennium Bridge in 2000 (Dallard *et al.*, 2001) just after its inauguration. Considerable retrofit costs were incurred to repair the situation, sparking many research efforts in the area of dynamic response of footbridges (Živanović *et al.,* 2005). Numerous SHM systems have been deployed on footbridges and this is well documented in the literature (Parsekian *et al.*, 2009; Caetano *et al.*, 2010; Hu *et al.*, 2012; Barbosa *et al.*, 2013; Russell *et al.*, 2017; Sá *et al.*, 2017; Primi *et al.*; 2017). Ingólfsson *et al* (2012) reported an extensive review of the state-of-the-art which focuses on cases of lateral bridge vibrations induced by pedestrians.

**Fibre-Reinforced Polymers (FRP)**

The deteriorating condition of infrastructure assets has been identified as a growing concern (cf. Thurlby, 2013). Cost-effective and innovative solutions are needed to maintain these assets which are typically made of concrete and steel. Research into the use of FRP in construction has been on-going for many years (Bakis *et al.*, 2002) leading to FRP being used as an alternative to these traditional materials. For instance, FRP has been reported to exhibit superior corrosion and fatigue resistance, high strength and stiffness-to-weight ratios, and can offer more rapid installation due to their pre-formed, modular construction and light weight (e.g. Bakis *et al.*, 2002; Hollaway, 2010). Altogether, these attributes contribute to lower maintenance costs over an asset's lifecycle (Kendall, 2008; Mara *et al.*, 2014).

Bridge decking is one of the more auspicious applications for FRP in infrastructure due to the benefits described above (Bakis *et al.*, 2002; Hota & Hota, 2002; Kumar *et al.*, 2004; Sonnenschein *et al.*, 2016). In the UK, the first major composite footbridge was the Aberfeldy Footbridge in Scotland, which was installed in 1992 (Skinner, 2009). Canning & Luke (2010) carry out a comprehensive review of the many FRP bridges constructed in the UK. This includes the Mount Pleasant bridge in Lancashire, UK, which was the first FRP bridge installed on the UK motorway network by the Highways Agency in April 2006 (Canning, 2008). Another 'pioneering' project is the St Austell FRP footbridge, which was designed by Parsons Brinckerhoff (Shave *et al*., 2010). Constructed in October 2007, it was the first structure built from FRP materials integrated into the UK rail network (Shave *et al*., 2009). Subsequently, many more successful installations have occurred across the UK transport network (Composites UK, n.d.) as design guidance such as BD 90/05 has been developed (DMRB, 2005; Shave & Bennetts, 2012).

Several SHM deployments on FRP bridges have been carried out to investigate structural behaviour, such as dynamic response and creep deformation (Kumar *et al*., 2004; Sebastian *et al.*, 2015; Votsis *et al.*, 2017; Siwowski *et al.*, 2018). Particular interest is held in the material's long-term behaviour (Sebastian, 2016), as well as how it is affected by environmental factors (e.g. moisture ingress, UV exposure). More performance data on FRP bridges is needed for them to become more ubiquitous in future bridge construction efforts.

## INSTRUMENTATION OVERVIEW

The sensor types which emerged as being most appropriate for this proposed deployment were *accelerometers* and *strain gauges*.

### Accelerometers

Accelerometers are widely used for measuring dynamic responses of structures, including bridges (e.g. Russell *et al.*, 2017). There are three main sensor types: piezoelectric, micro-electromechanical systems (MEMS) and piezoresistive (Middleton *et al.*, 2016; Hanly, 2016). Piezoelectric accelerometers are the most widely used for measurement applications (Hanly, 2016) and typically contain a piezoelectric element supporting a mass, which induces a charge that is proportional to the force caused by any acceleration the sensor encounters.

Two key characteristics to consider are sensitivity and frequency response range (MMF, 2001). The sensitivity of an accelerometer defines the magnitude of the electrical signal it generates in relation to the magnitude of acceleration. Higher sensitivity is more suitable when measuring small accelerations, as a cleaner signal (high signal to noise ratio) is obtained. The frequency response range gives the bandwidth of frequencies that a sensor can measure, usually specified as a tolerance band, relative to a reference frequency (range). Some typical performance characteristics for accelerometers are given in Table 3. For deployment on this bridge, accelerometers that can provide high accuracy readings in the 0.1 to 10Hz range with high sensitivity (e.g. 10V/g) would be ideal.

### Strain Gauges

Webb (2014) describes a wide variety of sensors that can be used for both dynamic and static measurements, such as Electrical Resistance Strain Gauges (ERSs), Vibrating Wire Strain Gauges (VWSGs) and Demountable Mechanical Strain Gauges (DEMECs). Detailed descriptions of ERSs and VWSGs and some of their considerations can also be found in Middleton *et al.* (2016). ERSs are frequently used in SHM deployments (Sebastian *et al.*, 2015; Hoult, 2016; Siwowski *et al*., 2018). They consist of a thin metal wire that is bonded to the surface of the structure being monitored. As this surface experiences a strain, it changes the length of the wire which causes a proportional change in resistance. This resistance can then be measured with a suitable data-logger. The 'unit strain' output is dimensionless and can be used to infer changes in stress and quantify different stress states in the monitored parts of the bridge.

Several considerations should be made when deploying strain gauges. Temperature can affect the resistance of a strain gauge – which is a well-known issue (Webb, 2014). To that end, most strain gauge manufacturers include temperature compensation capabilities in their sensors (National Instruments, 2016). Another key thing to consider is the adhesive which is used to bond the strain gauge to the surface of interest. Adhesives experience creep and can therefore lead to inaccurate readings in the long-term. Also, ERSs only provide discrete measurements with relatively small gauge lengths, ranging from 0.5mm to 100mm. Therefore, one sensor is needed for each point of interest. For bridges, this number can get very large, which can raise the cost significantly and diminish aesthetics. With this in mind, one must be discerning when selecting points of interest.

## APPLICATION OF VALUE ASSESSMENT METHODOLOGY

### Set-up and Agenda

As mentioned, this methodology involves facilitating a formal discussion between three key stakeholders: the 'SHM engineer', 'structural engineer' and 'asset owner'. For this case-study, these roles were filled by the persons shown in Table 4. Each participant has had at least four years' experience working in their respective field and was well-placed to have a meaningful discussion on this topic. The 2-letter references are used to signify spoken comments recorded from the meeting. The first author took the role of facilitator for the meeting. The third, fourth and fifth authors took on the key stakeholder roles.

These three key stakeholders were to meet and discuss the questions/criteria shown in Table 1. Each criterion was value rated 1 to 5 by the relevant stakeholder based on its likeliness to be met (see Table 2). Participants were invited to write down comments to justify their score. These scores are averaged to give a simple metric that can be used to '*decide whether a particular SHM configuration may be worthwhile for a particular project*' (Vardanega *et al.*, 2016). A more detailed description of the methodology development can be found in Vardanega *et al.* (2016).

Two SHM configurations were used for this case-study, one for accelerometers and the other for strain gauges, resulting in two pre-assessment matrices being filled out. Whilst these two configurations were the primary focus, other sensors were also discussed. The meeting took place in the South Gloucestershire Council headquarters on 27th March 2018. The results are summarised in the following sections.

### Results

*Accelerometer Scores*

Table 5 shows the assessment matrix filled out for the accelerometers scenario. Some entries in the comments column have been summarized for brevity. The resulting score of 4.2 indicates that deploying accelerometers on the bridge 'is very likely to yield value to the asset owner/manager'. This favourable score results from the relatively high ratings given in all the criteria, bar C3. The SHM engineer pointed out that "*it would be quite easy to make* [the system] *robust enough*" (SH) as accelerometers can be easily replaced. The structural engineer indicated maximum ratings for their criteria as "*expected levels of actual acceleration from the design phase and wind tunnel testing*" (SE) had been obtained which could be used to compare with the monitoring data for model validation. Given the light-weight nature of the FRP footbridge, the asset owner expressed concern over adverse public relations if the bridge were to exceed the serviceability limits for acceleration: “*we would respond to those* [acceleration] *trigger levels, definitely*” (AO). The asset owner identified that the use of accelerometers would work in tandem with the maintenance of the TMDs included in the bridge design. On the subject of potential user complaints about uncomfortable bridge vibrations they mentioned that “*we could do a ‘before and after’ and show that we’ve actually improved the situation by changing the* [frequency of] *the dampers*” (AO). Whilst funding for the project was secure for the next five years, the asset manager stated that from SGC’s point of view long-term funding would not be likely as the next incumbent of their position might “*not put the same importance*” (AO) to the monitoring system. Therefore, a score of 2 was given for question C3.

*Strain Gauge Deployment Scores*
The assessment matrix for a strain gauge deployment is found in Table 6. The average score of 3.7 indicates that deploying strain gauges on the bridge ‘is likely to yield value to the asset owner/manager’, making it potentially less valuable than the accelerometer deployment. From the SHM engineer’s point of view, the robustness of strain gauges in the long-term was a concern: “*Strain gauges are delicate… experience shows that when you stick them* [on a structure] *for 20 years, they’re not going to last*” (SH). It is also pointed out that if you replace a strain gauge “*it’s very hard to re-baseline… and you start getting more and more uncertainties in your absolute stress and strain*” (SH). To mitigate this, embedding the sensors into the structure during manufacture was suggested. This takes away most of the potential environmental deterioration and is much less intrusive aesthetically. However, the practicalities of embedding sensors are “*not as straightforward as attaching accelerometers*” (SH). Despite strain measurement being relatively easy from a sensor point of view, there is difficulty in interpreting the data because “*the magnitude of strain measurements is so much smaller than other things you try to correlate it with*” (SH). In other words, as strain changes are often small, it is challenging to distinguish meaningful data points from background noise. Furthermore, strain changes can be induced by various factors such as temperature, pedestrian loading and wind speeds, and it hard to separate the effects of each of these. This resulted in a lower score for ascertaining the required accuracy (A1).

The structural engineer was confident that “*given the level of modelling that’s been or will be undertaken, at certain locations you’d be able to put a threshold* [strain] *value*” (SE). Critical monitoring locations could be determined from the design models, with connections most likely to be targeted. However, developing specific load cases and condition factors to obtain threshold values and critical locations would be a more difficult process, resulting in slightly lower scores compared to the accelerometer deployment.

The asset manager expressed they would “*take a decision if a* [strain] *trigger value is exceeded*” (AO), such as deciding whether to “*close the bridge or not*” (AO). However, they expressed that it would be less likely to inform a maintenance regime because FRP design is currently so conservative that any excessive deflections were unlikely. This is also based on observations made on a previously built FRP bridge within South Gloucestershire Council's stock in Frampton Cotterell (Sebastian *et al.*, 2015): "*we were surprised that we got about half the deflection we anticipated so it performed really well, meaning it was a lot stiffer*" (AO). Similar to the accelerometer deployment, the same concerns over the lack of a secure budget from the asset manager's organization were stated, resulting in a lower score.

## FURTHER CONSIDERATIONS

Given the assessment results, the following implications and considerations emerge. A deployment of accelerometers would be expected to provide value to the asset owner. A system of these sensors would: (1) be simple to make robust, (2) be able to collect data that can inform the validation of design models, and (3) have the potential to inform the bridge's maintenance regime. The value obtained from a deployment of strain gauges would likely be lower, because they are harder to make robust and are perceived to have less value to the asset owner. However, the strain data can be used for model validation by structural engineers and inform research activities. To ensure long-term robustness, it is highly recommended they be embedded into the structure. This would involve liaising with the eventual manufacturers to co-ordinate installation.

The asset owner stated the desire for a layman's interpretation of the data: "*we wouldn't want to have to do any processing of the data, we'd want a system to go 'we've got an issue at hanger 12', we need to go out and do something.*" (AO). An appropriate user-interface may have to be developed to ensure insights are given to the asset owner. This leads to other considerations pertinent to an SHM system such as cabling, power supply, data transmission and data storage. These aspects require appropriate planning ahead of deployment and perhaps should be captured in the SHM criteria of this value assessment methodology.

Other potential instrumentation was also discussed in the meeting. It was noted that sensors that could be used for other projects were perceived to be more valuable to this asset owner. A weather station was brought up as an example: "*they would be very useful for multiple disciplines and then* [that means] *being able to fund those easier because I could share the funding with other teams*" (AO). It was also in the asset owner's intentions to install *"automatic pedestrian counters on the approaches to the bridge*" (AO). The structural engineer also described pedestrian counters as a "*useful*" (SE) sensor to investigate user-induced vibrations. This could be integrated into the monitoring system to provide context to accelerometer data.

## REFLECTIONS ON THE METHODOLOGY

Overall, the participants found this methodology a worthwhile exercise in assessing the potential value of the monitoring for this project: "*I think challenging all the proposals* *would be useful for the project*" (SE), to which the other participants agreed. Indeed, having this structured process to critique sensor proposals allowed for constructive discussions leading to a meaningful quantification of value. However, it became widely accepted as the discussion drew on that the framework was not entirely suitable to this project, as it was asset owner focused. As pointed out by the asset manager, the wider aim of the project was not for "*South Gloucestershire Council to have an all-singing, all-dancing bridge that could be monitored every minute of the day*" (AO), but it "*was for industry and for academics to learn from… and to help other asset owners get more efficient, cost-effective structures*" (AO). The SHM engineer expounded on this point: "*it's not just South Gloucestershire doing all this monitoring for their own purposes, but it's wider – using that information for other purposes which may or may not lead to value to the asset owner*" (SH).

From this, it can be said that any monitoring on this bridge would be predominantly for the purposes of 'model validation' and 'sensor deployment study' (cf. Webb *et al.*, 2015); rather than obtaining data that would directly drive decision-making by the asset owner. This shifts most of the potential value away from the asset owner, and towards the structural engineers and researchers involved in the project. Therefore, the framework (Vardanega *et al.,* 2016) has been modified for this scenario (cf. Table 7 and Figure 4). A fourth stakeholder – the research engineer – who may or may not be relevant for future projects, has been added to the framework. Additional questions have been included for the SHM engineer, structural engineer and research engineer (see Table 7). It is hoped these modifications better capture the likeliness of value for a monitoring system perceived to have a primary purpose of a 'model validation' deployment, where these four stakeholders are involved.

## SUMMARY AND CONCLUSIONS

The value assessment methodology proposed by Vardanega *et al.* (2016) was tested for a proposed SHM deployment. The methodology proved effective at facilitating discussion between the key stakeholders at an early stage in the project. A fourth (optional) key stakeholder has been included in the methodology (research engineer) and extra questions have been added (see Table 7).

The following recommendations for the footbridge are made:

(a) The system of accelerometers would probably be valuable for the asset owner as it has potential to inform a maintenance regime;

(b) A robust long-term monitoring system can be deployed;

(c) The collected data can be used to investigate the bridge dynamic response;

(d) The system of strain gauges would be of less value to the asset owner but are potentially useful for structural engineers and research engineers informing future designs and understanding FRP behaviour/performance.

## DATA AVAILABILITY STATEMENTS

The work reported in this study has not generated new experimental data.

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## TABLES

**Table 1. Framework Questions (adapted from Vardanega *et al.*, 2016)**

| Stakeholder | Question | Ref. |
|---|---|---|
| SHM Engineer | How likely is it that the required accuracy of the proposed measurements can be ascertained? | A1 |
| | How likely is it that the specified system can be designed to be sufficiently robust such that it can be maintained over the life of the monitoring project? | A2 |
| | How likely is it that the appropriate auditing will be conducted by a third party to certify that the gathered data are reliable? (e.g. monthly reports that give details of calibrations undertaken and 'sanity checking' of collected data.) | A3 |
| Structural Engineer | How likely is that relevant values of approximate threshold values will be assigned in consultation with the asset owner so as to ensure that the owner will act if these values are realized in the field? | B1 |
| | How likely is it that the critical monitoring locations on the structure can be determined? | B2 |
| | How likely is it that the data be used for validation (or falsification) of structural models which may assist with the design of more efficient future structures for the asset owner? | B3 |
| Owner/Asset Manager | How likely is it that the necessary actions (or decisions) will be taken if threshold (trigger) values are exceeded/reached? | C1 |
| | How likely is it that the data to be collected will be able to inform a maintenance regime? | C2 |
| | How likely is it that there will be a secure budget necessary for the intended period of operation of the monitoring project? | C3 |

**Table 2. Value Ratings (adapted from Vardanega *et al.*, 2016)**

| | |
|---|---|
| **1** | Very unlikely or not at all |
| **2** | Not likely |
| **3** | Neutral, i.e. may or may not occur |
| **4** | Likely |
| **5** | Very likely / certain |

**Table 3. Typical Accelerometer Performance (adapted from Midé, 2017)**

| | **Piezoelectric** | **DC MEMS** | **Piezoresistive** |
|---|---|---|---|
| **Frequency Response (5% Accuracy)** | 5Hz – 2000Hz | 0Hz – 1000Hz | 0Hz – 2000Hz |
| **Measurement Range** | ±0.5g to ±2000 g | ±16 g to ±200 g | ±100 g to ±500 g |
| **Sensitivity** (± 5%) | 10.0 V/g | - | - |
| **Resonant Frequency** | 370 Hz – 1220 Hz | - | - |
| **Resolution** | 0.0008 g – 0.06 g | 0.004 g – 0.05 g | 0.003g – 0.015 g |
| $g = 9.81 m/s^2$ and $V$ = volts | | | |

**Table 4. Roles Occupied in Discussion**

| **Role** | **Job Description** | **Experience** | **Ref.** |
|---|---|---|---|
| SHM Engineer | SHM Expert, WSP | >4 years | SH |
| Structural Engineer | Senior Engineer, WSP | 5 years | SE |
| Owner/Asset Manager | Structures Team Lead, SGC | 22 years | AO |

**Table 5. Filled in value assessment matrix for the accelerometer deployment**

| | 1 | 2 | 3 | 4 | 5 | Comments |
|---|---|---|---|---|---|---|
| **A1** | | | | | x | Accuracy easy to ascertain. |
| **A2** | | | | x | | Could set-up a portable system; sensors easy to replace without losing information. |
| **A3** | | | x | | | Depends on who is operating the monitoring. Sensors can be taken away for calibration. |
| **B1** | | | | | x | Threshold would be up to the asset owner but could be based from code defined accelerations, varying comfort criteria, or the Wind Tunnel/dynamic analysis output. |
| **B2** | | | | | x | Locations for peak expected accelerations are known from analysis therefore critical locations can be identified. |
| **B3** | | | | | x | Testing in-situ, with the Tuned Mass Dampers (TMDs) locked and unlocked would allow the design output to be validated. |
| **C1** | | | | | x | Could respond to concerns over vibration – aiding public relations. Could be used to change TMDs. |
| **C2** | | | | x | | Would aid maintenance of TMDs. Would start with manufacturer maintenance regime then inform through monitoring. |
| **C3** | | x | | | | Currently funded by Bristol University – v. likely. In 5 years' time, probably unlikely. Would need to be in Operation & Maintenance manual. Finding funding for short time period activities easier. Short-term cost a stronger driver than long- term. |
| **AVG** | | | **4.2** | | | |

**Table 6. Filled in value assessment matrix for the strain gauge deployment**

| | 1 | 2 | 3 | 4 | 5 | Comments |
|---|---|---|---|---|---|---|
| **A1** | | | | x | | Measuring strain is relatively easy from a sensor point of view. Required accuracy would depend on the structural engineer, so is closely interlinked to B1. |
| **A2** | | | | x | | Sensor replacement may increase data uncertainty as it's difficult to re-baseline data. Can mitigate by embedding the sensors into the structure, reducing risk of a damage. |
| **A3** | | | x | | | Depends on who is operating the monitoring. Strain gauges are much harder to calibrate. |
| **B1** | | | | | x | Consideration should be given to long-term and short-term monitoring. The threshold values could be established from the design models; however, we wouldn't expect these to be reached in practice in the short term given the various loading and material factors that are considered in FRP design. They could still be considered useful threshold for **long-term** monitoring and management of the structure.<br><br>For **short-term** monitoring, a specific load case could be developed, run in the design model and replicated in practice on the structure. Threshold values could be established for this and strain measurements reviewed at regular intervals. |
| **B2** | | | | x | | The anticipated strain can be identified at any location in the structure from the design models. Expected locations of peak strains/stresses can be determined and areas of high utilisation could be targeted.<br><br>The behaviour around bolt groups would be of interest. |
| **B3** | | | | x | | In order to influence future design, the data and lessons learned would need to be fed into the development of future design guidance and standards. It is envisaged that data from other structures and wider considerations would be needed for this to happen.<br><br>The matrix answer has been based on the assumption that a particular load case is developed and run in the mode and on the structure for validation. We would consider the answer to be not likely/neutral if this was not undertaken |
| **C1** | | | | x | | Damage detection at specific places would be valuable – e.g. vandalism/fire – give alert to prompt inspection, should target non-visual issues.<br>Don't want to do lots of data analysis – needs a user interface. |
| **C2** | | | x | | | Less likely to inform maintenance regime than accelerometer. |
| **C3** | | x | | | | Currently funded by Bristol University – v. likely. In 5 years' time, probably unlikely. Would need to be in O&M manual. Finding funding for short time period activities easier. Short-term cost a stronger driver than long- term. |
| **AVG** | | | **3.7** | | | |

**Table 7. Revised methodology questions (adapted from Vardanega *et al.*, 2016)**

| Stakeholder | Question |
|---|---|
| SHM Engineer | How likely is it that the required accuracy of the proposed measurements can be ascertained? |
| | How likely is it that the specified system can be designed to be sufficiently robust such that it can be maintained over the life of the monitoring project? |
| | How likely is it that the appropriate auditing will be conducted by a third party to certify that the gathered data are reliable? (e.g. monthly reports that give details of calibrations undertaken and 'sanity checking' of collected data.) |
| | *How likely is it that the system can be designed as (part of) a network (considering power supply, cabling, data storage etc.) to enable effective data transmission to key stakeholders? |
| Structural Engineer | How likely is that relevant values of approximate threshold values will be assigned in consultation with the asset owner so as to ensure that the owner will act if these values are realized in the field? |
| | How likely is it that the critical monitoring locations on the structure can be determined? |
| | How likely is it that the data be used for validation (or falsification) of structural models which may assist with the design of more efficient future structures for the asset owner? |
| | *How likely is it that the findings from the monitoring will be disseminated to relevant authorities to develop standard guidance? |
| | *How likely is it that the findings from the monitoring will inform standard practice 'in-house'? |
| Owner/Asset Manager | How likely is it that the necessary actions (or decisions) will be taken if threshold (trigger) values are exceeded/reached? |
| | How likely is it that the data to be collected will be able to inform a maintenance regime? |
| | How likely is it that there will be a secure budget necessary for the intended period of operation of the monitoring project? |
| *Research Engineer (if applicable) | *How likely is it that data collected from the monitoring system will be useful for current research activities? |
| | *How likely is it that the monitoring of this bridge will be shared to other research organisations to contribute to related topics? |
| | *How likely is it that there will be sufficient resources (e.g. labour, funding) available to operate and maintain the monitoring system? |
| | *How likely is it that support will be received from the asset manager to monitor the bridge in the long-term? |
| * Denotes newly added questions to the original framework cf. Table 1 | |

## FIGURES

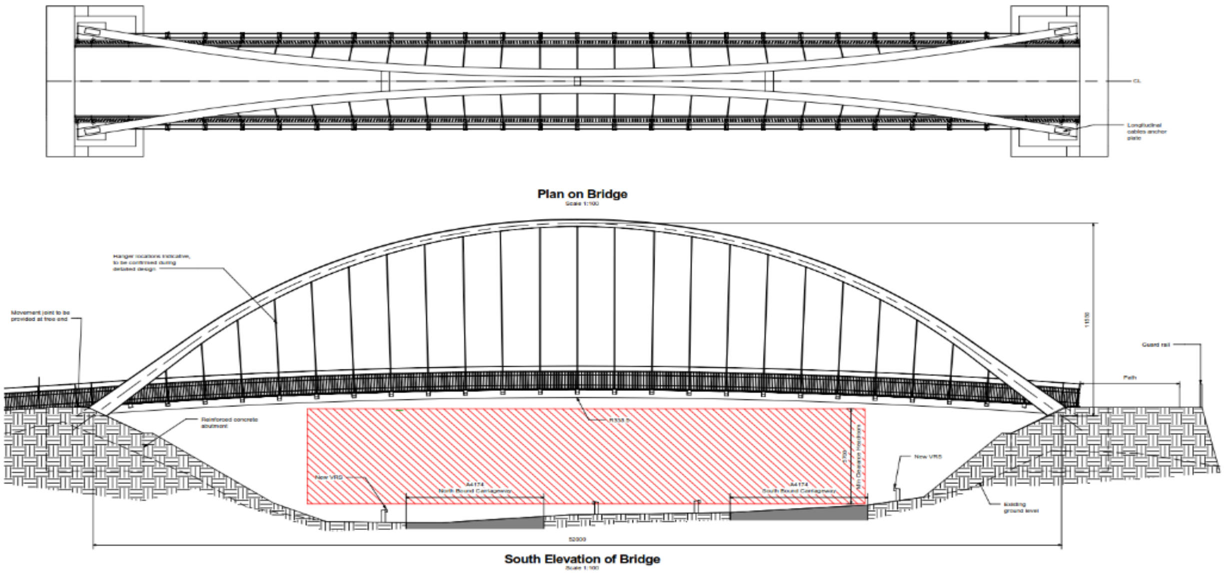


**FIG. 1. Bridge Plan and South Elevation (adapted from WSP, 2017), used with permission**

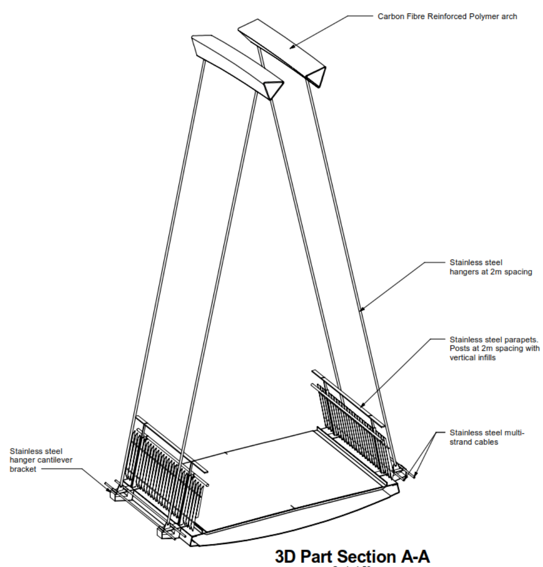


**FIG. 2. 3D Part Section (adapted from WSP, 2017), used with permission**

**FIG. 3. Bridge Visualisation (adapted from WSP, 2016), used with permission**

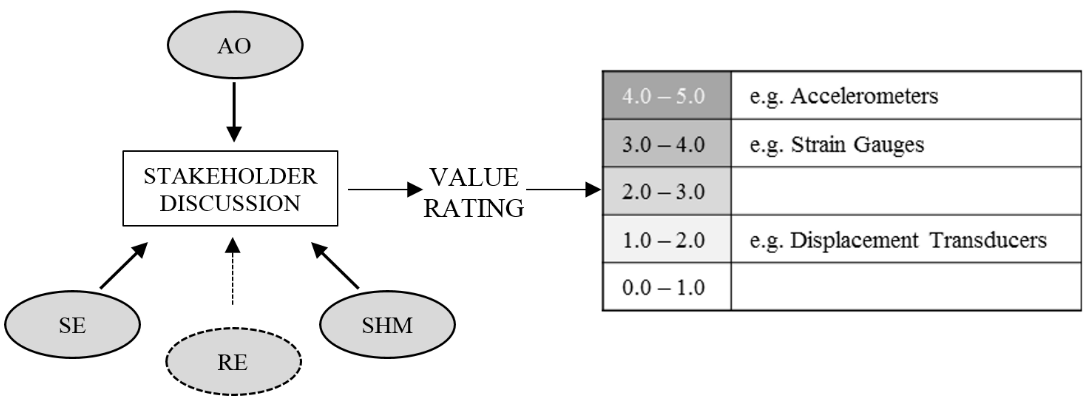


**FIG. 4. Methodology Visualisation**