Perceptions of long-term monitoring for civil and structural engineering

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Perceptions of long-term monitoring for civil and structural engineering

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ABSTRACT

Long-term in-service monitoring has been heralded as having the potential to radically reshape the design and operation of civil structures and infrastructure. However, in order for civil and structural engineers to extract the greatest value from in situ structural monitoring there are a range of practical, cultural and social barriers which must be overcome. To explore current perceptions of long-term monitoring in civil and structural engineering, a multi-national survey of 146 participants was conducted to understand perceived uncertainties within the existing civil/structural engineering design process, perceptions of long-term monitoring, and the potential for the future integration and use of long-term monitoring in the civil/structural engineering design process. This study highlights that while views of long-term monitoring as a tool within the engineering design process are broadly positive, there is a wide disparity on its current implementation in practice, little agreement on how it may offer the greatest benefit to civil and structural engineering design, and a current lack of direct financial incentive to prompt its use within industry.

1. Introduction

In-service or *in situ* monitoring, measuring the behaviour of structures under in-service loads and environmental conditions, has undergone rapid development over the last 20 years due to decreasing hardware costs, increases in the durability and sensitivity of the monitoring technology, and increased computation and data storage capabilities. These developments have largely been focused on the potential benefits *in situ* monitoring may offer for condition assessment, damage-detection and structural health monitoring [1–3], however recent research has started to explore the potential for long-term monitoring to inform the design of civil structures. Model updating, updating finite-element models based on in-service measured performance, offers a direct way in which the predicted behaviour of a structure may be compared to its in-service behaviour [4]. Building-information modelling (BIM) has allowed engineers to integrate design calculations, assumptions, and material and construction information within a virtual model of an asset [5]. More recently, digital twins, virtual models of assets updated and integrated with real-world measurements and data [6], have allowed long-term monitoring to be used to inform the operation and maintenance of both large infrastructure assets [7] and individual structures [8], forming a crucial part of Construction or Industry 4.0, the automation and digitization of the construction industry [9,10]. However, little work has explored industry perceptions of how long-term in-service monitoring may be used to influence and improve the civil and structural engineering design process.

A key aspect which must be addressed if long-term monitoring is to inform future designs is characterizing perceived uncertainties within the design process, so as to identify areas where long-term monitoring may offer the greatest benefits. Alongside this, the perceptions and current use of long-term monitoring within industry must be understood to identify areas of successful implementation and barriers to future use. Extensive research into perceptions of BIM (e.g. [11–13]) have highlighted how BIM's successful implementation and dissemination within civil and structural engineering are due in large part to understanding the demands and functionalities required within industry. Building on this work, the study presented in this paper aims to identify areas where long-term monitoring may offer the greatest benefit to engineers through exploring current perceptions of unknowns and uncertainties in the engineering design process. It also seeks to understand some of the cultural and social issues which may help or hinder the integration of long-term monitoring within civil and structural design.

Based on the survey of industry perceptions of long-term monitoring, technological solutions are identified which may allow perceived uncertainties and unknowns within the design process to be addressed. Also discussed are technologies and design methodologies which may

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address the barriers identified in the study as preventing wider uptake of in situ monitoring to inform the design of civil structures.

2. Methods

2.1. Questionnaire development and dissemination

The questionnaire was designed to gather quantitative and qualitative information from those involved in civil/structural engineering across three areas:

- Perceptions of unknowns and uncertainties in the existing civil/structural engineering design process.
- Perceptions and current uses of long-term monitoring within industry.
- Future potential and barriers to adoption of long-term monitoring within civil and structural engineering.

To ensure that the respondents constituted a representative sample of the engineering design community information about the respondents engineering experience and current/most recent engineering employment was also collected as part of the questionnaire.

To gather information across the areas listed above an online questionnaire, delivered via Google Forms [14], was developed. The questionnaire, developed in line with guidance provided in Brace [15] and Saris and Gallhofer [16], contained a mixture of open- and closed-ended questions. Open-ended questions, also referred to as open-requests for answers [16], were used to ensure that the respondents was given ample opportunity to convey their beliefs, free from the confines which may be introduced by categorical selections or scales. A key aspect of the questionnaire was that it was designed to gather information on both perceptions and beliefs. This was reinforced throughout the question wording, making explicit reference to the individuals own views and experiences. The qualifier “why?” was introduced to many of the open-ended questions so as to encourage the respondents to expand upon their answers [15]. The closed-ended questions were predominantly categorical and sought to gather quantitative information on the respondents beliefs which could be unambiguously compared across the sample set. Careful consideration was given to the choice of categorical questions over numerical scales, which have been shown to be highly subjective and more open to misinterpretation [16]. The questionnaire was divided up into clearly defined sections to both indicate to respondents their progression through the process, and remove ambiguity as to the focus of each question, for example by clearly demarcating which questions referred to current use of long-term monitoring as opposed to the potential future uses. Each section was introduced with a short (one or two line) preamble to provide context for the questions within the section and further reduced ambiguity [16].

Hyperlinks to the questionnaire were disseminated between June 2020 and August 2021, primarily via correspondence with regional, national and international professional institutions who shared the questionnaire with their members through direct correspondence, newsletters and via their websites. Additional dissemination was carried out via posts on online forums and professional networks, such as LinkedIn and GeoWorld. It is should be noted that no incentive was given for completion of the questionnaire, and that the questionnaire was only available in English.

2.2. Ethical considerations and data privacy

In line with European General Data Protection Regulation [17], explicit consent was obtained at the start of the questionnaire for collection, processing and storage of the data. All data was anonymised prior to processing through assignment of a unique numerical identifier. The purpose of the study, and how data would be used and stored, was communicated to the participants through a data collection consent form at the start of the questionnaire, adapted from that provided by the University of Edinburgh [18]. Demographic information about the participants was limited to that strictly applicable to the research, with all potentially sensitive or non-relevant information, such as the gender and race of the participants, not included as part of the data collection.

2.3. Respondent characteristics

In total, 146 responses to the questionnaire were collected from participants spread across 31 countries, with all continents represented in the data apart from Antarctica. The geographical distribution of the respondents are provided in Fig. 1, highlighting that while respondents were geographically diverse, respondents current/most recent employment were predominantly in English-speaking countries. Participants were also disproportionately likely to be from countries with high gross-domestic product (GDP) per capita. This should be considered when interpreting the results as the current use of long-term monitoring in lower-income countries, alongside the challenges they face for integration and implementation of long-term monitoring within design, are likely to be different. The respondents represented a cross-section of levels of engineering experience, as illustrated within Fig. 2, with a skew towards more senior positions, with 59.6% of respondents coming from senior or leadership positions, compared to 30% of respondents indicating lower levels of experience. This may indicate a greater interest in technology such as long-term monitoring from senior members within the field, but may also indicate differences in the engagement with professional institution literature and communications (the primary method for disseminating the questionnaire) or differing time-constraints. 47.6% of respondent most recent/current employer were large companies (more than 200 employees), 28.3% were medium sized companies (100 to 200 employees), 14.5% were companies with fewer than 100 employees, and 9.6% identified as self-employed. Within these companies the respondents represented an extensive range of self-identified areas of expertise, as shown in Fig. 3. As may be expected, more general classifiers, such as “design” and “structural”, were self-identified as classifiers by a wider range of respondents than more technically specific areas such as “environmental” or “digital”. However, when respondents were asked to describe in their own words areas in which they have specialized a much broader range of, in some cases highly specific, areas were elicited, illustrating both the intersectionality of civil and structural engineering and the inter-disciplinary nature of engineering design, findings further reflected in a similar question which asked respondents for a one sentence description of their employer.

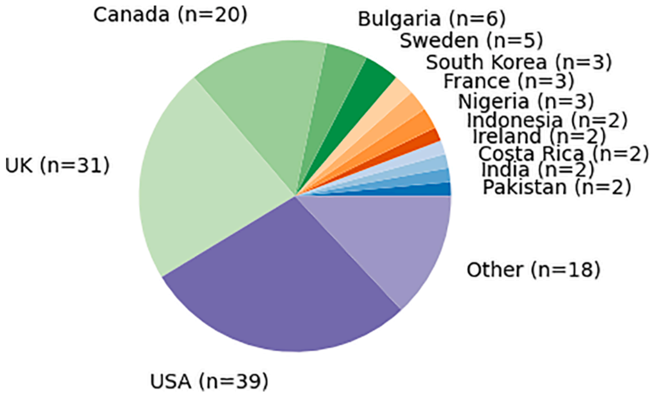

Fig. 1. Predominant country of current/most recent employment of respondents.

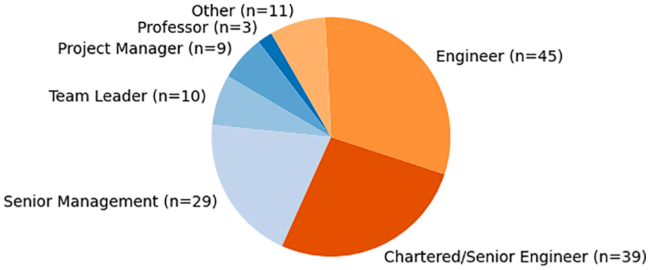

Fig. 2. Respondents self-reported engineering experience.

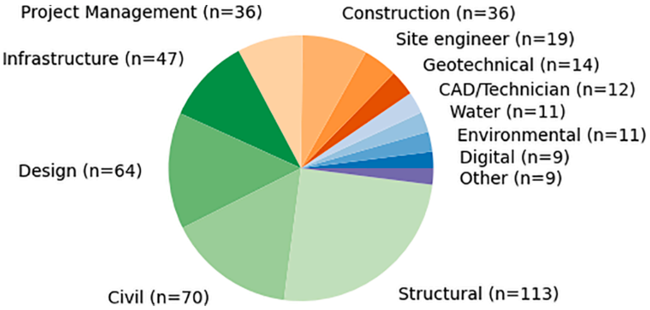

Fig. 3. Respondents self-reported areas of engineering expertise.

3. Results

3.1. *Perceptions of uncertainty within design*

The compiled results from a series of categorical questions exploring respondents' confidence in characteristic design loads, dynamic loads, material parameters and performance limits are presented in Figs. 4–7. Note that in these questions respondents were given the option to select "not applicable" for parameters which they felt they were not sufficiently familiar with the relevant design codes, standards or guidelines as to comment. The common theme through all responses is that, for the most part, participants view the majority of codified guidance on the engineering parameters as either being close to the true value (41.0% of total applicable responses) or an appropriately conservative value (36.8% of total applicable responses).

Within the responses relating to the characteristic design loads (Fig. 4), the responses which should be of most immediate concern are those which suggest that respondents perceive current guidance as underestimating or substantially underestimating design loads. For all categories except the mass of structural elements, greater than 10% of the respondents view current guidance as underestimating design loads.

The key limitation of the data presented here is that it is a broad generalization of multi-faceted and complex categories. However, future work in long-term monitoring should prioritize addressing these concerns due to the devastating consequences which may accompany the underestimation of structural loads. Of the overestimation of design loads, the most notable result is that after removal of the "not applicable" responses, 20.5% of respondents viewed current guidance on floor occupancy as an excessive overestimate of the true value. This is something which is a topic of long-standing debate within the engineering literature (for example [19–21]). Significant proportions of respondents perceived excessive overestimates for non-structural elements (8.6%), vehicle loading (5.7%), wind loading (8.1%) and snow loading (8.2%), after the removal of non-applicable responses. As these are all parameters which are difficult to estimate through conventional surveys and short-term measurement methods, data related to these areas may be effectively supplemented by long-term in situ monitoring to inform design codes and guidance. However, it is crucial that the basis for the design values are understood within the engineering community so as to address any misconceptions regarding the origin of the values specified in design codes and standards.

For the perceptions of dynamic loading (Fig. 5) there is a decrease in the percentage of respondents who feel they have the experience necessary to respond to the question. This decrease in participation may partially explain the increased percentage of responses, after exclusion of the non-applicable responses, who perceive substantial underestimates in the existing design guidance. Those who are more technically familiar with specific areas of structural or civil engineering may be concerned with the higher consequences which would accompany underestimation of design loads, an illustration of rational cognitive biases due to over-representation of extreme events [22]. Conversely it could be that familiarity with the design standards and guidance causes an implicit bias towards over-estimating its flaws, a possible example of expert overconfidence such as described in detail within the work of Lin and Bier [23].

Within the responses for the material design parameters (Fig. 6) it is notable that many participants who had not previously stated any specific geotechnical expertise felt confident that existing guidelines on geotechnical/foundation strength/stiffness were either an excessive underestimate or a substantial overestimate of the true value, with both geotechnical categories representing the most polarizing topic explored within the questionnaire. This may be explained in several ways. At the most basic level, all civil structures must interact with geotechnical engineering and foundations in some manner, a nexus point of design not found in any other major subdivision of civil and structural engineering, and most civil engineers will have experienced project delays and contractual conflicts due to unforeseen ground conditions [24]. Geotechnical engineering may also offer the greatest range of uncertainties within the engineering design, due to both the lack of

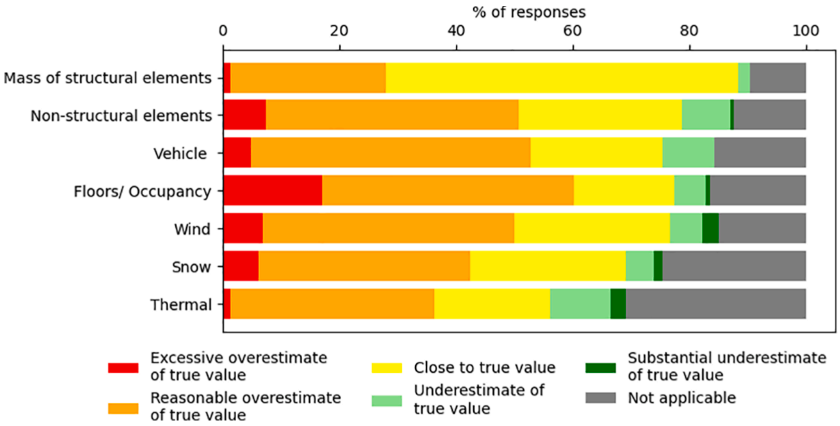

Fig. 4. Respondents reported confidence that the characteristic design loads (given or calculated) available in codes and standards reflect reality.

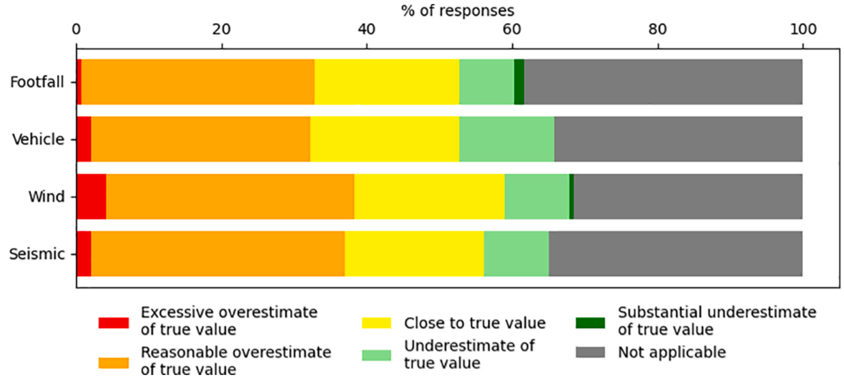

Fig. 5. Respondents reported confidence that the characteristic dynamic design loads (given or calculated) available in codes and standards reflect reality.

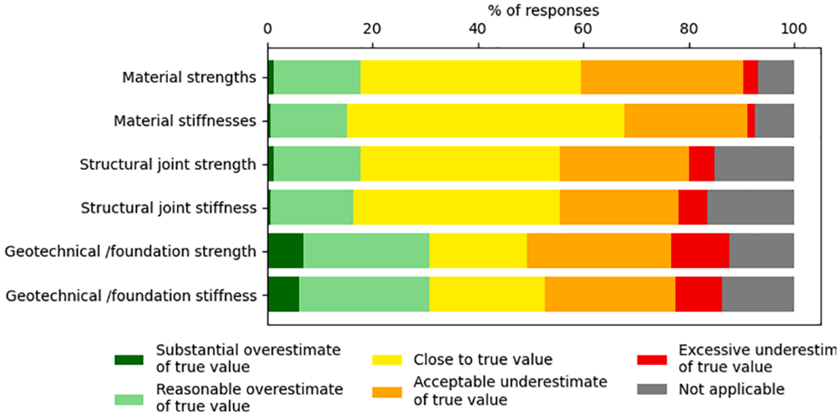

Fig. 6. Respondents reported confidence that the design parameters (given or calculated) available in codes and standards reflect reality.

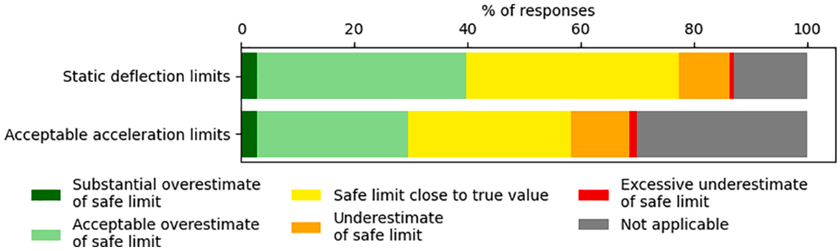

Fig. 7. Respondents reported confidence that the performance limits available in codes, standards or other guidance are appropriate.

information available at the design stage and the complexities of soil-structure interactions [25]. Greater uncertainties translates to greater numbers of assumptions and assumptions which are broader in scope. Therefore, given the polarization of the area, geotechnical and foundation behaviour may be an area in which long-term monitoring may help narrow the scope of design assumptions through access to data about the in situ behaviour of existing structures.

While smaller in scale, the polarization in perception of current guidance on static deflection and acceptable acceleration limits (Fig. 7) may stem from similar reasons. However, unlike geotechnical/foundation stiffness and strength, these values are largely subjective and context specific as reflected in standards and design guidance around the world. The benefit which long-term monitoring may offer with regard to this polarization of opinion is a move away from codefied limits and towards performance-based design [26,27] in which specific design objectives and performance criteria, such as limiting occupant complaints or acceleration and deflection induced serviceability issues such as cracking, are met.

When asked *If you had access to a single set of perfect information about a structure you designed in the past to inform your future designs, what would be of most use to you?* a common theme in the responses was the need for greater information on the load history applied to structures, particularly with regard to the interactions and co-occurrence of loading types. Highlighted within these responses were the impact of climate change on both the severity and frequency of extreme loading events, fitting with previous observations on the cognitive biases towards extreme events [22] within the responses. Also noted were the importance of material degradation and fatigue, both with respect to how this will impact the long-term behaviour of structures in-service, and how they might be better mitigated against. However the responses to the subsequent question, *In which area of civil/structural design do you think there is the greatest uncertainty about design assumptions?*, highlighted a very different selection of factors, with greater emphasis placed on the impact of factors which are difficult to recreate in controlled experiments, such as environmental loading, changes in environmental conditions or the human-structure and human-infrastructure interactions. This difference in the responses to the two questions can be interpreted in several ways. It could be due to the reluctance of participants to repeat previously given answers. Alternatively there may be a disconnect between the engineering parameters with the greatest uncertainty and those which would have the greatest impact on the load. Conversely, it may be due to limitations in the existing design process and the challenges of incorporating factors such as the degradation of structural materials, climate change or changing patterns of usage. However, careful consideration should be given as to whether long-term monitoring offers the greatest benefit solely by reducing the largest causes of uncertainty, or whether improved accuracy of better understood behaviour may result in greater gains in design efficiency and resilience.

3.2. *Current use of long-term monitoring*

Of the 146 responses, only 39.7% of respondents reported that they had worked on projects which had been evaluated by the designers following construction, 45.9% of respondents had not, and 14.4% responded that the question was either not applicable or did not fill in a response. This highlights one of the largest hurdles to be overcome if long-term monitoring is to be used to guide the design of future structures: whether the format of the existing design process allow for reflection on the successes or failures of past designs. The reported extent of assessment post-construction is largely informal, such as lessons-learnt and site walkthroughs. Where more extensive evaluations do take place these were identified by respondents as being primarily driven by two factors, paraphrased as: i) where there is a problem with the finished structure, ii) where it is mandated by the client as part of the contractual obligations. However the extent of evaluations is one of the few areas of the survey where there is meaningful difference in responses depending on fields of expertise, with respondents working on sensitive and critical infrastructure, such as bridges and power generation, reporting that evaluations are more detailed and longer-term than is reported for respondents working primarily on other types of civil structures. As with the implementation of BIM, this may suggest that intervention and leadership from governments and large clients may significantly increase the use and effectiveness of post-construction evaluation [28].

When asked how long-term monitoring data from previous projects could be used within the design process the predominant interest was in creating more efficient designs, for example "[long-term monitoring data] could be used for future projects with similar occupation and similar structural schemes to avoid common failures and utilise more of the capacity of the materials/structure", and reducing long-term risk to the structures, for example "[confirming] when major upgrades are required and the reasons behind them" and "[i]n the prediction of fatigue development; particularly in areas which cannot be easily inspected". These aspects are in line with the previous observations made on current perceptions of uncertainty within the design process. Numerous respondents also highlighted that for rapidly developing technologies such as ultra-slender buildings, timber engineering, and reclamation of industrial brownfield land, the long-term efficacy of the design guidance is unknown, and in situ monitoring may bring immediate and specific benefits to their continued development, summarized by one respondent as: "[long-term monitoring] data could help code and standards writers to modify and improve design requirements".

The final questions on the current integration of long-term monitoring into the engineering design process examined the knowledge and literacy of the respondents with respect to digital twins, virtual models of assets updated with real-world data. Digital twins by definition will require the use of long-term monitoring data and are considered to form a key next-step in "Construction 4.0" or the digitization of the construction industry [29,30]. Of the 146 respondents, 38.4% reported that they were familiar with the concept of a digital twin. This result in particular may be affected by some sampling bias, as it is likely that those who choose to take part in the survey have a prior interest in the application of new technologies within civil and structural engineering. Of those who reported familiarity with digital twins, 37.5% reported that their current or most recent employer was actively using digital twins. However, when the respondents who were familiar with digital twins were asked to define it in their own words, many respondents failed to make the distinction between BIM, "a digital representation of physical and functional characteristics of a facility" as defined by the National Institute of Building Sciences [31], and digital twins, "which is characterized by the cyber–physical integration" [6] or the updating of virtual models using real-world monitoring data [7]. Examples of responses where participants conflated BIM and digital twins, either explicitly or implicitly, included:

- "A digital representation of a structure storing data about each component"
- "Computer (BIM) model of actual structure"
- "It is a methodology for design; material specs; construction procedures; time delivery; cost and collect information of the projects stages along the life cycle of the projects and collaborate the stakeholders for share the same information In real time"
- "A geometrically accurate 3D computer model linked to a database of information containing details of the structures components"

Selected examples of responses which fully or partially captured key aspects of digital twins included:

- "A digital analytical model that can simulate/reproduce all the responses of interest given the parameters representing the real environment"
- "Using a digital (simulated) version of a system or piece of infrastructure to evaluate changes in performance with changing inputs."
- "A digital (BIM or otherwise) model of the as-built structure to which; in theory; perturbations associated with the real structure can be applied in an attempt to either estimate and effect from a cause or 'reverse engineer' a cause from an observed effect"
- "A multiphysics models allowing simulation of an as-built structure; component; infrastructure; etc. fed with data measured in a real component; infrastructure; etc.; to mirror the life of the real structure"

3.3. *Future potential of long term monitoring*

The final section of the questionnaire explored the possible benefits and challenges of integrating long-term monitoring into the future civil/structural design process. The respondents were predominantly in favor of this integration, with 78.3% reporting that they though that long-term monitoring data could be of use to them in future projects, with large proportions of respondents identifying that better understanding in situ behaviour could reduce the risk in future projects. 10.9% of respondents left the question blank or had a non-committal response. Of the 9.5% who responded that long-term monitoring would not be of use in future designs a wider range of reasons were given, these are summarized as:

- lack of direct financial benefit to the engineer
- the difficulty and risks involved with interpreting in-service monitoring data
- the difficulty of extrapolating from past projects to future projects
- the applicability of current behaviour under a changing climate
- the reliance on highly standardized designs and codefied standards not allowing for design flexibility
- the lack of financial incentive to create more efficient designs when working on small domestic projects

These responses were more generally reflected when respondents were asked about the barriers for the use of long-term monitoring data within the design process. The largest barriers to adoption identified within the results were the economic costs associated with long-term monitoring (46.9% of responses), the challenges presented by curating and maintaining long-term monitoring data or data privacy issues (23.8% of responses) and the challenges of using monitoring data to inform future designs (23.1% of responses). When asked whether the respondents current/most recent employer *should* engage in long-term monitoring of a structure if an opportunity arose, 65.0% of respondents responded positively, whilst 14.6% of respondents felt that they should not, and 20.3% respondents believed that it should only be undertaken if there was a financial incentive to do so. Those who felt that their employer should not become involved in long-term monitoring highlighted the "potential [legal] liabilities that is could expose", the time commitment necessary, and the "lack of knowledge regarding what data to collect and why" and "what is [a] normal response and what is a response that may indicate problems".

There was a slight difference in the responses when respondents were asked *would* their employer engage in such an opportunity, with the number of positive responses dropping to 45.5%, the number of negative responses increasing to 22.8% and the number of respondents highlighting the need for a financial incentive increasing to 31.7%. This highlights that the lack of current financial incentive, the perceived risks, lack of expertise, and time costs of long-term monitoring are likely to be major barriers to its widespread adoption within industry. However, it does indicate that if there is a client demand for such monitoring the industry is likely to adapt to meet it. This is reflected when respondents were asked whether their company *should* use long-term monitoring data from a project designed by another company, with 78.2% of respondents believing that this data should be used, 13.4% reporting that its use was dependant on the completeness of the data and the availability of other information about the project, and only 8.4% of respondents feeling that this data should not form a part of the design of other structures. This strongly suggests that when the costs and complexities associated with implementing long-term monitoring are removed as factors, there is majority support for using in-service monitoring to inform future designs. However, as highlighted in the responses, any legal liabilities associated with the use of such data much be understood and addressed if it is to anyway inform the design of future structures.

The challenges of implementing long-term monitoring as part of the civil/ structural design process identified through the survey are broadly similar to those of BIM [32–34]. However, integrating long-term monitoring, as well as the move to Construction 4.0 more broadly, has it own set of unique challenges as highlighted within the questionnaire responses. The include the difficulty of interpreting in situ monitoring data, the risks associated with its use within design, the lack of clear legislative guidance, and the lack of appropriate experience and data analysis skills within civil and structural engineering. These additional challenges may limit the uptake of long-term monitoring. However, a growing interest from clients for in situ monitoring to inform the maintenance and operation of civil structures may create the financial incentives needed to prompt rapid uptake of long-term monitoring within the industry, without the need for the government intervention required to encourage the uptake of BIM [35].

4. Facilitating long-term monitoring

The previous section has identified a demand within civil and structural engineering for long-term monitoring data to supplement the current engineering design process alongside areas in which engineers report the greatest need for data to support decision making.

This section presents an overview of areas of development which are necessary to facilitate the integration of long-term monitoring into the civil engineering design process as identified through the survey of industry perceptions. These areas are: i) emerging monitoring technologies which might aid the collection of data to meet demand, ii) industry-specific software for the analysis and communication of insights gained through long-term monitoring, and iii) design procedures which are conducive to incorporating long-term monitoring to address specific shortcomings in the civil engineering design process.

4.1. Emerging monitoring technologies

Beyond the range of conventional structural monitoring technologies, such as strain gauges, displacement potentiometers, or load cells, there have been rapid advances in novel technologies which might address areas of uncertainty within civil engineering design highlighted by the survey responses. One of the areas of greatest disagreement identified within the survey was whether the characteristic static and dynamic design loads provided in codes and standards reflect reality. Video image recognition may provide a robust method for assessing in situ loading through estimating the mass of non-structural elements [36], vehicle loading [37] or floor loading/occupancy [38]. These established techniques could be rapidly applied at a relatively low-cost, and allow for the creation of statistical distributions of likely loading which are more representative of the loads applied to structures in-service than those presented in current design guidance.

For some loading types, such as snow loads, the data on likely loadings is readily available from the historical records, with the key issue being ensuring timely updating of design guidance and accurate interpolation of extreme events [39]. Other environmental loadings, such as wind or thermal loads, remain challenging to measure in-service due to their distributed nature. However, recent advances have shown there may be methods to indirectly estimate these loads. For example, the thermal loads on structures might be estimated based on the strain response of structures in-service as discussed by Borah et al. [40]. More accurate determination of the wind loading applied to structures may be inferred from computational models updated based on in-service measurements of a structure's dynamic response [41,42].

Quantifying the in-service strength or stiffness of materials and joints in civil structures remains challenging as direct measurement of these parameters is often not possible. Therefore, it is necessary to interpolate strengths or stiffnesses from other parameters through techniques such as updating of numerical models to match measured behaviour [43], or multi-factorial analysis with known loadings [44].

As previously discussed, whether the design parameters for geotechnical/foundation strength or stiffness reflected reality were the most polarizing topics explored within the survey. However, estimating geotechnical parameters in-service has also seen rapid development in recent years including instrumented foundation piles [45,46], satellite monitoring of ground types and settlement [47,48], and high-resolution ground-penetrating radar [49]. Utilizing these technologies or data from nearby sites with similar geotechnical characteristics may allow for long-term geotechnical monitoring data to be implemented in the design of future structures without the need for bespoke data collection to be specified.

4.2. Industry-specific analysis software

Despite the advances of in-service monitoring technology, the survey of industry perceptions has highlighted that the cost and complexity of collecting and analysing long-term monitoring data remains a key barrier to entry. With the exception of some specialized domains, there is a lack of commercially available software designed for the collection and analysis of structural monitoring data. Where this software does exist, the specialized knowledge required for its use presents a high barrier for entry. Alongside this, the software may fail to reflect current best practice or advances in the analysis of in-service monitoring data. These issues are further complicated by the lack of established standards for data storage and processing for long-term structural monitoring.

Technologies such as digital twins, which have been widely adopted in the manufacturing industry [50], may provide an intuitive basis for integrating structural monitoring with the design of civil structures. The survey has highlighted a strong demand within industry for technologies to facilitate the integration of long-term monitoring into civil engineering design. However, the development of such systems should balance two competing requirements. The first of these are that of accessibility, so that the concerns about the time-demands of analysing structural monitoring data reported in the survey may be addressed. The requirements for accessibility must be balanced with the concerns surrounding the interpretability and extrapolation of results to future engineering designs. In practice, this might be achieved through ensuring that parameters measured in situ are reported in the same units or formats as currently used within design standards or codes, and that the uncertainty in any extrapolated parameters is clearly and succinctly communicated.

4.3. Performance based design methodologies

A barrier to the adoption of long-term monitoring identified within the survey was the perceived inflexibility of current design codes and standards. Such standards often provide prescriptive guidance on the strength and stiffness of structural elements and connections to meet an, often unspecified, implicit design performance criterion. There are numerous drawbacks to this approach, as highlighted within the survey responses, including the lack of design standards for novel materials and structural forms, the reliance on an implicit relationship between the structural behaviour as described by design standards and the performance criteria to be met, which may not be true in all the diverse conditions for which structures are designed, and the complex interplay of different structural behaviours which may impact in-service structural performance.

An alternative design approach that has gained traction in the last thirty years is limit state or *performance-based design* (PBD), in which structures are designed to meet a specific set of performance criteria with minimal prescriptive requirements for the properties of individual materials, structural elements and connections [51]. PBD is primarily based on the concept of performance targets [26]. These are often specified displacement, acceleration, stress or strain limits. These may be expanded to consider different use cases or scenarios such that the performance targets for day-to-day use of a structure are different from those used for extreme events such as earthquakes. The key challenges faced in PBD are selecting appropriate performance targets, selecting appropriate design scenarios, and balancing the multi-faceted behaviour of structures in-service [26].

Key areas which have seen the development of PBD methodologies include seismic design of civil structures [26], economically driven lifecycle structural design [52], design of bridges for vehicle impact [53,54], and blast loading [55]. PBD methodologies have also been developed for serviceability events such as the design of structures under wind loading [56,57,27], minimizing maintenance requirements of offshore wind turbines [58], user-comfort of footbridges under footfall vibration [59,60] and the development of more energy-efficient mixed-use buildings [61].

The key challenge facing the continued use and development of PBD, as highlighted by Poland and Horn [62], is the proactive real-world verification, calibration and validation of the design techniques developed, something which is dependant on the analysis and interpretation of data from structures collected in-service. Wider industry adoption of long-term monitoring of civil structures in-service may allow a virtuous circle to be established, with greater monitoring data allowing for the development of more robust and efficient PBD methodologies which in turn drives greater adoption of long-term monitoring of civil structures to validate that PBD requirements are being met.

5. Conclusion

Through a multi-national survey of civil and structural engineering professionals, this study investigated perceptions of the use and potential of long-term monitoring of structures. Some key findings were that:

- 78.3% of respondents highlighted demand within civil and structural engineering for long-term monitoring data to validate design assumptions and create more efficient designs;
- there is disagreement on where this data may be of greatest use within the design process, with 51.6% of respondents identifying an interest in the use of long-term monitoring for reducing the risk of adverse outcomes, while 48.4% of respondents identified the key use as being to support the uptake of more efficient materials and designs; and
- barriers to the adoption of long-term monitoring identified within the survey include the cost of implementation, identified by 46.9% of respondents, and a lack of client demand, identified by 31.7% of respondents.

The broad-range of respondents' areas of expertise, experience, geographical location, and employment lends weight to the conclusions drawn in this paper. Key emerging technologies which may aid the adoption of long-term monitoring have been identified from the literature and potential barriers to implementation discussed. Performance-based design methodologies have been highlighted as an alternative design approach for civil structures which may reduce the the perceived inflexibility of current design codes and standards, allowing for long-term monitoring to inform future engineering designs. Future work should prioritize how the uptake of long-term monitoring may be incentivized within the industry, the wider legal issues surrounding the use of monitoring data to inform future designs, and specific areas within existing design guidance which are sources of either the greatest uncertainty, or which most influence design efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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