Chapter 3
Towards PEAR: a Benchmark Dataset for Population-based SHM

Connor O'Higgins, David Hester, Keith Worden, and Daniel S. Brennan

Abstract Population-based Structural Health Monitoring (PBSHM) is a developing approach in Structural Health Monitoring (SHM) that leverages data from multiple structure's to enhance the understanding of an individual structures health. Where traditional SHM utilises only a single structure's data, PBSHM utilises the collective knowledge from a population of structures. A pivotal component for facilitating the aforementioned collective knowledge is transfer learning: the ability to infer knowledge from a source structure to a target structure within the population. To ensure the transferred knowledge enhances rather than hinders the target structure, a degree of structural similarity is first established.

Both sub procedures of PBSHM require robust data modelling, which in turn requires substantial amounts of high-quality data; something that with PBSHM in its infancy is not openly available for researchers to benchmark algorithms against. In this study, the aim is to address this data shortfall of PBSHM by developing a comprehensive dataset of semi-realistic bridge models. This dataset is intended to serve as a test bed for developing, benchmarking, and validating PBSHM algorithms, particularly focussing in on the necessitated data for similarity metrics and transfer-learning techniques. Subsequently, it is explored how the proposed dataset can be expanded to include additional structures and discuss the potential applications of the dataset in advancing PBSHM research.

Keywords Population-based structural health monitoring · Benchmark dataset · Irreducible element model · Bridges · Machine learning

Introduction

In structural health monitoring (SHM), the availability of benchmark datasets, like the S101 [1] and Z24 [2] bridge datasets, have been instrumental in advancing the field. These datasets provide researchers with a common platform to test, validate, and compare the performance of new SHM methods and algorithms. However, in the emerging field of PBSHM, no such benchmark datasets currently exist. This is partly because of the relatively recent development of PBSHM, but also in part because any PBSHM benchmark dataset would inherently require data from multiple structures to form a population, thus gathering such a dataset is inevitably more complex.

As a potential solution to this problem, this paper proposes the curation of PBSHM dataset consisting of synthetic structures based on real-world engineering principles: Population-based SHM Engineered Asset Resource (PEAR). The aforementioned PEAR dataset will serve as the benchmark for future research to be evaluated against within the PBSHM community. The breadth of knowledge required to generate synthetic structures across the range of PBSHM structure is vast; therefore, the goal of this paper is not to create an immutable dataset, rather establish the fundamentals required to facilitate an evolutionary approach to including new structures and associated data within the dataset. To provide an initial set of structures, this paper uses beam-and-slab bridges.

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Thomas Matarazzo et al. (eds.), *Data Science in Engineering, Vol. 11*, Conference Proceedings
of the Society for Experimental Mechanics Series, https://doi.org/10.13052/97887-438-0156-6_3

This paper follows the following flow: firstly an overview of PBSHM is given with details on existing databases, schemas, and benchmark datasets, thus motivating this work. The next section outlines the design process for both the overall dataset and the individual sub-datasets contained within, detailing the key requirements for ensuring that the dataset can become an effective benchmarking tool for the community. After the description of the dataset, a detailed example of the first stage in developing a sub-dataset is presented, including the procedures used to design realistic structures for the sub-dataset and the outputs required for inclusion in a PBSHM database. Finally, the conclusions are presented to explore considerations regarding the current dataset, its future expansion, and the potential paths for further development to enhance its utility in PBSHM research.

Background

Population-Based Structural Health Monitoring (PBSHM) focusses on the analysis of data from multiple structures within a related population, providing valuable insights into both the population as a whole and individual structures within it [3]. Unlike traditional Structural Health Monitoring (SHM) methods that concentrate on a single structure, PBSHM allows for the application of methods such as transfer learning. Transfer learning involves applying knowledge gained from one task to improve performance on a different but related task. Instead of starting from scratch with each new task, models trained on one structure can be adapted for use on others, leveraging shared knowledge to enhance the accuracy of a given model. However, for transfer learning to be effective in the context of PBSHM, it is crucial to ensure that structural similarities are well understood to avoid negative transfer. To address this, Irreducible Element (IE) models, combined with graph-based approaches, play a key role in identifying structural similarities and variations.

This framework of finding similarities between the structures to inform where transfer learning is appropriate mitigates the risks of negative transfer. Further foundational details on PBSHM can be found in works such as [4, 5, 6, 7]. One of the main challenges in the emerging field of PBSHM is the scarcity of data for similar populations of structures. This has been addressed in several studies where [8] collected data from four beam-and-slab bridges and two pedestrian footbridges. [9] and [10] simulated a population of 10 degrees of freedom and toy structures to validate a PBSHM transfer-learning method and a graph-matching algorithm, respectively. It is believed that PBSHM benchmark datasets would aid in the development of PBSHM research. These datasets will play a part in developing and validating PBSHM methods.

PEAR Foundations

The premise behind the Population-based SHM Engineered Asset Resource (PEAR) dataset, is to provide a set of known reference data to enable PBSHM algorithms to be developed, evaluated, and validated against. As alluded to in the previous sections of this paper, building a dataset to cover the full remit of potential PBSHM algorithms and applications is no trivial task; therefore, this goal will need to be achieved over time via multiple expansions and iterations to PEAR. As such it would be naive to believe that all of these expansions and iterations to PEAR will be done by the authors of this paper; consequently, the first portion of this paper will be focussed on setting a list of requirements, structures, and stages necessitated to enable growth of PEAR by the PBSHM community.

PEAR foundations: requirements

The purpose of the requirement's section of the PEAR Foundations is to provide a guide for the type of data that should be included within PEAR.

Requirement 1: A key requirement for the dataset is that it should be suitable as a testbed for both current and emerging PBSHM methods and techniques. This includes facilitating the development and evaluation of approaches such as transfer learning, which allows for the application of knowledge from one structure to another within a population. The dataset should support the comparison of structures via similarity metrics such as IE models and graph-matching algorithms, as this is a vital step in the transfer of knowledge between structures. The dataset should also be well-suited for the application of various machine learning methods, providing a source of data for training and validating machine-learning models.

Requirement 2: The dataset should be searchable, allowing users to find and extract subsets of the data easily. This functionality is aimed at making the database more user-friendly, enabling researchers to focus on specific types of structures or specific structure configurations relevant to their studies. To meet this requirement, the dataset must be properly indexed, ensuring that all relevant variables, such as structure type or number of spans (for bridge structures), can be queried and filtered from the database.

Requirement 3: The methods used to design the structures in the dataset should be clear, transparent, and, where possible, rooted in real-world structural design practices; this ensures that the generated structures are representative of real-world structures. Additionally, the variations in the structures, such as span lengths for brides, beam sizes, and deck thicknesses, should reflect the diversity found in actual structures, or in the case of the dataset described in this paper, in real-world bridge stocks.

Requirement 4: Since the inception of PBSHM, it has been understood that providing a shared-data domain for which PBSHM data resides, is crucial in seeing wide-scale adoption of the technology. The recently-published work by Brennan et al. [7] introduce the PBSHM schema as the domain in which the PBSHM data gets regulated into the same standardised data form. As such, the dataset will store its data in the PBSHM schema format and any additions to the dataset will have to adhere to this. If there is not an area within the PBSHM schema to store the relevant data, a new extension to the PBSHM Schema must be proposed and included within the next update.

PEAR foundations: structure

Designing the dataset's structure is important to ensure effective data retrieval and utilisation. A well-structured dataset will facilitate users to quickly access the specific data they need, making it easier to perform tasks with the datasets and subsets of the data. The purpose of the structure section within the PEAR Foundations, is to not only organise the dataset's data into a logical order for easy retrieval of data, but to also facilitate the required expansion of new data within the dataset, without invalidating any existing dataset data. Figure 1 depicts the four hierarchical categorisations of data within PEAR: root category, subtype, parameter set, and scenario. To best explain how these categories interact with each other, the example of a file system will be used.

Root Category
↓
Subtype
↓
Parameter Set
↓
Scenario

Fig. 1 The hierarchical structure of the PEAR dataset.

At the root of the filesystem, there will be a 'PEAR' folder. Within the 'PEAR' folder there will be a folder for every 'root category'. Inside each 'root category' folder there will be a folder for every 'subtype'. Inside the 'subtype' folders will be a folder for every 'parameter set'. Inside a 'parameter set' folder their will be the first occurance of PBSHM data within the filesystem. The 'parameter set' folder will include a description file which outlines the allowable variations within the hyperparameters for that 'parameter set'. Additionally, Stage 0 and Stage 1 data files — see the following sections for details — will also be stored within this folder. Within the 'parameter set' folder there will also be folders for each 'scenario'. Inside the 'scenario' folder will be Stage 2+ data files — again see the following section for details.

A 'root category' would be any category of structure which would normally not be categorised with another, for instance two root categories could be aeroplane and bridge. A 'subtype' would be a categorisation within a 'root category' to differentiate purpose or style, for instance within the aeroplane 'root category' one could have two 'subtypes' of narrow-body and wide-body. Conversely, within the bridge 'root category' one could have 'subtypes' of truss and suspension. The 'parameter set' is a named group of hyperparameters within the subtype to generate the Stage 0 and Stage 1 data files. These hyperparameters are specific to the 'subtype' and enable different values of the 'subtype' hyperparameters to generate unique Stage 0 and Stage 1 data. The 'scenario' is a named group of action(s) performed on the Stage 1 data of the 'parameter set' to generate Stage 2+ PBSHM data.

During the initial planning for PEAR, three initial 'root categories' of structures were identified for inclusion within the dataset: bridges, masts, and wind turbines. Figure 2 shows the initial dataset hierarchy using the PEAR Foundations structure.

PEAR
- 1. Bridges
  - 1.1 Beam and slab
  - 1.2 Ladder deck
  - 1.3 Truss
- 2. Wind turbines
  - 2.1 Monopole
- 3. Masts
  - 3.1 Lattice tower
  - 3.2 High guided
  - 3.3 Monopole

Fig. 2 The initial 'root categories' and 'subtypes' for PEAR

PEAR foundations: stages

As discussed, PEAR has been designed from the ground up to mutate over time via iterations and expansion of the data included within. The purpose of the stage's section within the PEAR Foundations is to provide known 'save points' within the dataset to facilitate collaboration across the multidisciplinary areas of knowledge within PBSHM. The PEAR dataset by necessity, must contain data for both the 'similarities' portion of PBSHM, but also the knowledge transfer portion of PBSHM; therefore, it must be a supported workflow to have one team design and build the IE models (Stage 1 data) within the dataset, and another team to then build the simulations to generate Stage 2+ data. To support this distributed workflow, each stage must therefore only rely upon data being available from the previous stage, for instance a Stage 2 data process, must only rely upon the data being present for Stages 0 and Stage 1.

For a sub-dataset to be included in PEAR, the minimum requirement is the 'parameter set' description file, and a completion of Stage 0 & 1. Once a dataset is produced, it is given a reference within PEAR. Once this reference has been produced, the individual structures within that sub-dataset will remain unchanged to ensure consistency and reproducibility of results. The specific subcategories for Stage 2+ are not rigidly defined, providing researchers the freedom to choose the most appropriate structural responses for their research.

The stages described below are designed to be generic and applicable to all sub-datasets regardless of the 'root category' and 'subtype'.

Stage 0: Structure Design. In this initial stage, realistic structures are designed with pseudo-random properties from the range of hyperparameters set within the 'parameter set'. A Structural Information (SI) model and structural report are produced for each generated structure. The report provides a detailed description of the structure in a human-interpretable way, and the SI model provides a computer-interpretable way for indexing and querying each structure included within the dataset. A 'parameter set' with only Stage 0 models is not a valid 'save point'; a Stage 0 model must always be accompanied by an associated Stage 1 model to be a valid 'save point'.

Stage 1: IE Models. In this stage, IE models are generated for each SI model present within the 'parameter set'. Depending upon the hyperparameters set within the 'parameter set', this may include generating detailed IE models, Canonical Form IE models, or any future IE model type yet to be declared. This is the first stage where a process may stop, and multiple independent processes continue to generate Stage 2+ data.

Stage 2+ Scenario Data. Using the data from Stage 0 and Stage 1, a simulated scenario can then be run on the generated IE models. How this scenario is simulated is outside the purview of the PEAR Foundations; however, the response from the simulation must be saved back into the PEAR dataset as a valid PBSHM Schema document. Possible, but not limited to scenarios are: static load displacements, natural frequencies, mode shapes, and frequency response functions. A scenario is not limited to treating the structure from the associated IE model as a 'healthy' structure, a scenario may introduce 'damage' into the model before performing its simulation and saving the response back into a PBSHM Schema document.

Populating PEAR

In this section of the paper, we look at how to populate PEAR with its first initial sub-dataset to the minimum stages defined above: a beam and slab bridge sub-dataset to Stage 1. For this example, the ‘root category’ is stated to be ‘bridges’ with a ‘subtype’ within that ‘root category’ of ‘beam-and-slab’. This will first start by providing a definition and description of their general form. The procedures used to design a semi-realistic beam and slab bridge model for our sub-dataset will then be presented, ensuring these models are representative of real-world structures. Where appropriate, the decisions made during the design process will be explained with reference to established principles from bridge engineering. This will help clarify how the models are rooted in practical engineering knowledge and the balance one has taken between realism and the constraints imposed by the simulation of thousands of structures.

Beam-and-slab bridges were selected for the initial sub-dataset test structure because of their prevalence, particularly within the UK. Beam-and-slab bridges are one of the most common forms of concrete highway bridge construction as they offer a straightforward and economic bridge solution, with readily-available standard sections and a relatively high speed of construction. Their simplicity in design and construction makes them ideal candidates for this study, especially since their widespread use means there are well-established design rules to guide the design of these structures. These design rules allow one to create realistic structures that are grounded in practical engineering while ensuring consistency and reliability across the dataset.

Populating PEAR: general from

The general form of a beam-and-slab bridge consists of precast concrete beams that serve as the primary structural components of the bridge. These beams are typically lifted into place, where they are supported by piers or abutments that have been constructed in advance. Once the beams are positioned, an *in situ* concrete deck is poured over them to form the main deck of the bridge.

Below are the main components and a brief description of a typical beam and slab bridge:

1. Precast Prestressed Bridge Beams: These are the primary load-bearing components of the bridge. Precast off-site and prestressed to increase their load-carrying capacity, these beams are designed to resist the main traffic loads of the bridge.
2. Reinforced Concrete Deck: The reinforced concrete deck is poured in situ on top of the precast beams, forming the main surface of the bridge. Reinforcement bars are embedded within the concrete for strength.
3. Diaphragm: The diaphragm is a transverse structural element placed between the bridge beams. Its primary function is to distribute loads evenly across the bridge and provide lateral stability, and help transfer load to the supporting structure of the bridge.
4. Columns: Columns are vertical structural supports that transfer the load from the bridge deck and beams down to the foundation.

Populating PEAR: variables

This section will outline the structural variations that will be modelled within the beam and slab bridge sub-dataset, and will describe the key variables that will be adjusted from one bridge model to another, such as beam dimensions, span lengths, and deck thickness. The procedure employed to ensure that these variations result in semi-realistic bridge models will also be outlined. By randomly varying these parameters, the aim is to reflect a range of real-world scenarios while maintaining a level of consistency and realism that supports the effective evaluation of PBSHM methodologies. This approach will help ensure that the dataset provides a robust testbed for examining the performance of transfer learning techniques and other PBSHM methods across diverse bridge configurations. The variables are categorised into two main groups:

- General Bridge Variables: These include aspects that affect the overall bridge configuration and performance, such as number of spans, width of bridge and material properties. The procedures for selecting these variables ensure that each bridge model reflects realistic scenarios that may be found in the real world.
- Element Geometry Variables: This category covers the specific dimensions and geometrical features of individual bridge elements, such as beam dimensions and diaphragm heights. The procedures for these variables involve selecting specific element geometries that would be suitable so that the bridge can support the typical traffic loads that would be encountered.

Some variables are selected randomly from a predefined list, such as the number of spans and deck thickness. Other variables are dependent on prior selections, for instance, the diaphragm height, which is set to match the height of the primary beam. Additionally, certain variables, such as the geometric properties of the bridge beams, are selected from appropriate manufacturer technical documents. For this work, the Shay Murtagh Technical Manual [11] was used, although any equivalent design guide could be substituted. A detailed description of each variable and the procedure used to select them can be found in Table 1, located in Appendix A.

Populating PEAR: outputs

For each bridge, a short report will detail all the key properties, including both General Bridge Variables and Element Geometry Variables. This report will also include drawings of the bridge structure. The individual structure reports are designed to provide users of the dataset with a quick overview of each beam and slab bridge structure. These reports contain the bridge details for each structure in a standard table. An example of the table included in each of the reports is given below. Each report also includes a set of standardised bridge drawings that show the general arrangement of the main structural elements for each bridge. The drawings include:

- Cross-Section Through the Deck: shows the arrangement of the main bridge beams and deck slab
- Cross-Section Through the Support: shows the arrangement of the bridge beams, diaphragms, and columns if included in the structure.
- Elevation of the Bridge: The elevation provides a side view of the bridge, showing the overall span arrangement.
- Plan of the Bridge Showing the Superstructure: This top-down view showing the arrangement of the bridge beams and diaphragms.

Individual Structure Reports
The individual structure reports are designed to provide users of the dataset with a quick overview of each beam-and-slab bridge structure. These reports contain the bridge details for each structure in a standard table. An example of the table included in each of the reports is included within the appendices.

Each report also includes a set of standardised bridge drawings that show the general arrangement of the main structural elements for each bridge. Figure 3 shows an example of the bridge drawings included in the reports.

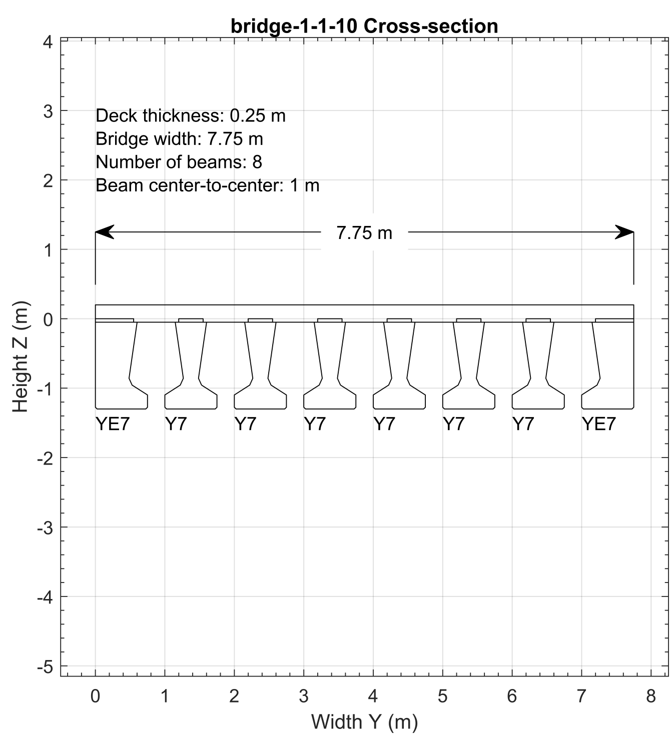

Fig. 3 Example of bridge drawings, cross-section through deck

Structural Information Models

Each bridge will be accompanied by a Structural Information (SI) model that contains all the bridge's properties in a format compatible with the dataset's database (JSON format), allowing for efficient data retrieval about the individual structures. The SI models contain all the necessary data to describe each beam-and-slab bridge structure fully. These models are stored in JSON format, to allow easy integration into the broader PBSHM Framework. The use of JSON ensures that the information models can be efficiently stored and queried by the framework. Each Structural Information model contains a comprehensive set of data points, covering both general bridge variables and element geometry variables; this includes details such as span lengths, beam dimensions, deck thickness, and material properties. The structured nature of these models allows users to obtain all relevant information about a bridge in a single, easily interpretable file. Beyond serving as a detailed record for each structure, the SI models will be used for database integration. Users can leverage the information models to filter and identify specific subsets of bridges based on defined criteria, such as finding all bridges with a certain number of spans or selecting bridges with specific material properties. This capability ensures that the dataset is flexible and can be adapted for various PBSHM research tasks.

Dataset Statistics

The dataset statistics are designed to provide an overview of the beam and slab bridge structures included in the dataset. These statistics offer insights into the distribution of key variables across the dataset, allowing users to better understand the variability of the generated structures. The primary focus of the statistics is on the distributions of the bridge variables, such as the number of spans, beam dimensions, deck thickness, and material properties. For instance, one important statistic is the distribution of the number of spans in the dataset, which provides information on the range of bridge configurations included in the dataset. In addition to providing an overview, the dataset statistics also aid in validating the design process. For variables that are randomly selected from a defined set of values, the statistics can help confirm that the variable has the expected distribution. For example, if a variable such as span length is randomly chosen from a predefined set of values, the resulting distribution in the dataset should be roughly even; this ensures that no unintended biases have been introduced during the generation of the bridge models. Other variables that are dependent on other factors are expected to have different distributions. Figure 4 gives an example of the distribution of number of spans and number of primary beams from a dataset that contains one thousand structures.

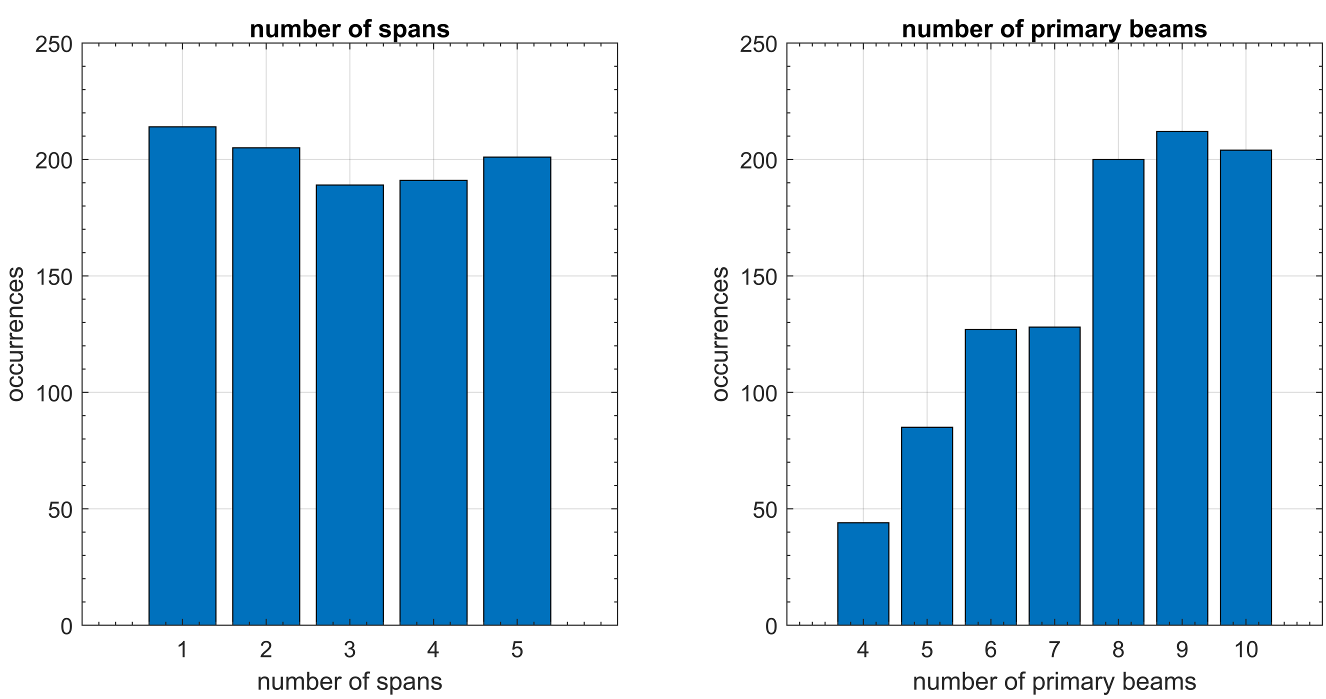

Fig. 4 Example of dataset statistics, number of spans and number of primary beams

Conclusion

In this work, the foundations have been laid for the PEAR benchmark PBSHM dataset by defining its core requirements, structure, and stages. By establishing a structured approach to creating sub-datasets, starting with beam-and-slab bridges presented in this work, the aim is to ensure consistency in the structures and structures that are grounded in sound engineering design practice.

For the future development of this work, the next step involves extending the process outlined in this paper to other types of bridges, such as ladder-deck and truss bridges, as well as to masts and wind turbine structures. Once the initial PEAR dataset is populated, researchers will have the opportunity to suggest or develop additional types of structures or perform new structural simulations on existing datasets, with the aim of enhancing the datasets for their particular research needs.

The potential use of PEAR in the development of PBSHM methods is widespread. It can be used to train and validate machine-learning algorithms, develop transfer-learning methods, and evaluate their performance across different structure types. Although developed with PBSHM as a focus, PEAR should be equally suited for the development and validation of traditional SHM methods; this potential may be investigated in a future piece of work.

Via continued expansion and refinement of the work presented here, it is hoped that PEAR will serve as a valuable tool for advancing PBSHM research.

Acknowledgments The authors of this paper gratefully acknowledge the support of the UK Engineering and Physical Sciences Research Council (EPSRC) via grant reference EP/W005816/1. For the purpose of open access, the authors have applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

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Appendices

Table 1 The available hyperparameters within the proposed 1.1 dataset.

Parameter	Description	Selection process
Number of spans	Total number of bridge spans	Spans for beam and slab bridges are typically between 1 and 5 spans, so the number of spans is randomly selected from this range.

Length of spans	Individual length of each span of the bridge	The maximum length of the span is dictated by the bridge beams and what they are rated for. The other consideration is that the length of span for a given bridge is typical of a similar length. E.g. you don't typically have a 5 m span and a 50 m span in the same bridge. The maximum variation of spans is set to be 70%
Number of primary beams	The number of primary bridge beams across the width of the bridge	This is dictated by the width of the deck and the recommended spacing of the bridge beams
Width of deck	The width of the bridge deck	The overall approximate size of the deck is randomly chosen between 6 m and 20 m. This range accommodated typical roads ranging from a single carriage to a 4-lane motorway with a hard shoulder lane. The final specific width of the road may be adjusted to fit into the recommended spacing of the bridge beams.
Thickness of deck	The thickness of the reinforced concrete deck	The thickness of the deck is randomly chosen from 0.15 m to 0.3 m as this would be the typical thickness of a deck in a beam and slab bridge.
Beam centre to centre	The centre to centre distance between the primary bridge beams	This is taken from the bridge beam technical manual.
Column ends	Binary variable: are there columns located at each end of the bridge	Randomly chosen to have or not have columns at the two ends of the bridge.
Column middle	Binary variable: are there columns located at the intermediary supports of the Bridge	Columns were randomly chosen to have or not have at the intermediate supports of the bridge. However, if the structure has columns at the ends and is greater than one span, then 'Column middle' is set to 1.
Column number	The number of columns (if present) per support of the bridge	The number of columns is chosen randomly (if present) from 2 (the minimum needed to provide support) to the number of primary beams. The columns are typically used to support the primary beams of the structure.
Column height	The height of the columns (if present)	The height of the columns is randomly chosen from 5 m to 8 m (0.5 increments). This height is the minimum required, as stated by UK government standards, and the maximum is chosen to be a sensible upper limit that a typical bridge would have.
Column diameter	The Diameter of the columns (if present)	Randomly chosen to be between 0.5 m and 1.0 m in 0.1 m increments.
Diaphragm height	The height of the diaphragm	This is the depth of the primary beam so that the diaphragm lies between the deck and the top of the columns.
Primary beam geometry	The bridge beam reference that defined the cross-sectional geometry of the primary Beams	The primary beam geometry is decided by starting with a list of all the most common bridge beam types, eliminating any that would not be suitable for the larger span length and bridge width and then randomly choosing from the remaining allowable bridge beams.
Edge beam geometry	The bridge beam reference that defined the cross-sectional geometry of the edge beams (if different from the primary beams)	Some of the bridge beams require different geometry for the two outer edge beams. If this is the case, each primary beam that needs a different edge beam will have a complementary edge beam, which is selected as required.
Diaphragm width	The width of the diaphragm	Random between 0.8 m and 1.6 m because this is the typical width of diaphragms.