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RESEARCH ARTICLE

The Built Environment Data platform for experimental test data in earthquake engineering

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Abstract
Experimental testing of full structural systems and their components is crucial for understanding their response to earthquakes. Since the 1960s, global interest in such testing has grown, supported by numerous national and international funding initiatives. This has resulted in valuable data that has improved understanding of structural behaviour, spurred the development of new mitigation solutions and helped validate numerical models critical for simulation studies. These advancements have enabled engineers to improve building codes and guidelines, and have allowed risk modellers to more accurately assess risk. With advanced computational resources, integrating experimental findings into broader initiatives becomes crucial. This article discusses a recent European initiative, *Built Environment Data* (BED) (https://builtenvdata.eu/), which currently offers a platform to store and manage data from experimental research, embodied carbon and simulated design services. BED aims to serve the European Plate Observing System (EPOS) distributed research infrastructure as one of its Thematic Core Services (TCSs). This paper focuses on the *Experiments* service for managing experimental data, compares it to similar global efforts and outlines the specific requirements and system architecture, including the web services and datasets currently offered. The *Experiments* service is expected to significantly support engineers worldwide by making experimental research and data more findable, accessible, inter-operable and re-usable.

KEYWORDS
built environment, database, experimental testing, FAIR, web services

1 | INTRODUCTION

In recent years, there has been a growing need for solutions to mitigate the devastating impacts of natural hazards like earthquakes on the built environment, infrastructure and the environment. For example, following the 2009 L'Aquila earthquake, the estimated cost of damage was €16 billion, with nearly 100,000 buildings damaged and around 67,500 people left homeless.[1] Elsewhere in the world, the Haitian government reported that following the 2010 earthquake, more

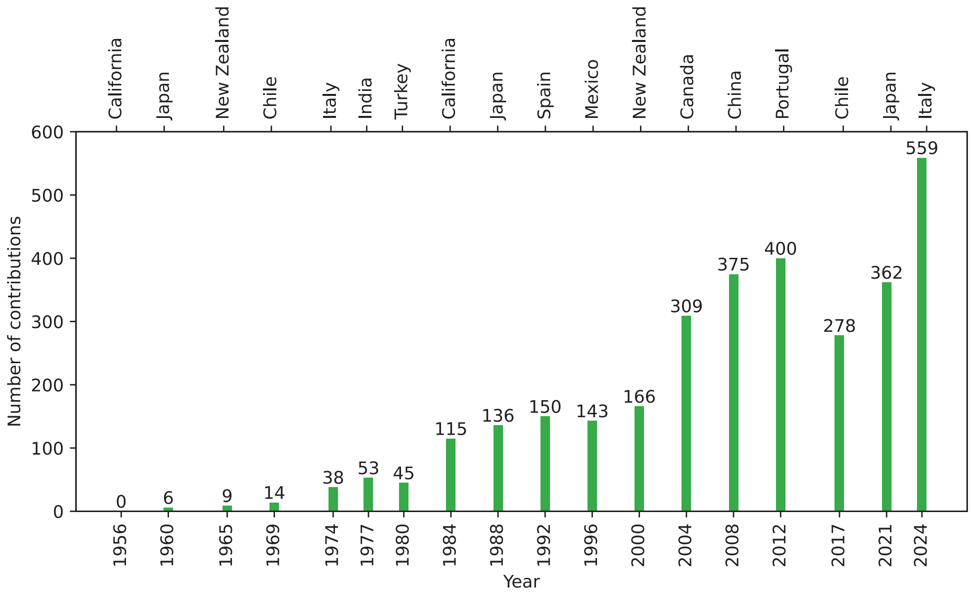

FIGURE 1 Trend in number of contributions related to experimental testing at the world conferences in earthquake engineering from 1956 to 2024.[9]

than 230,000 people died, 300,000 people were injured and 1.3 million were left homeless[2] and the total economic loss was estimated to be between 7.8 and 8.5 billion US dollars. Recently following the 2023 Turkey earthquakes, the World Bank estimates the direct damage from the earthquakes at $34.2 billion, with re-construction costs accounting for emergency response and a surge in the costs of construction amounting to twice as much.[3] These examples, along with many others from various global events, highlight the increasing need for strategies to alleviate the severe effects of natural hazards such as earthquakes on society.

While the knowledge of engineering statics goes back several centuries, the understanding of how lateral dynamic forces such as earthquake shaking affect structures is a relatively recent development, with Housner[4] terming it a 20th-century development. Following the 1908 Messina earthquake in Italy, the idea that dynamic forces of earthquakes could be tackled via equivalent static forces was born and practical recommendations were subsequently established.[5] The development of equivalent static methods whereby a certain percentage of the building's weight is applied laterally was initially derived from a simple deduction. With some estimate of the ground acceleration and the lateral strength of the structure subjected to it, one could derive an equivalent lateral capacity.[6] Hence, with an estimate of the lateral force demand, engineers focused on how to provide such lateral capacity via different structural solutions.

With an increased understanding in the earthquake engineering community in the subsequent decades (e.g. ductility and energy dissipation in the 1950s,[5] capacity design in the 1960s[7]) on how to practically address the problem of earthquakes, the need to experimentally test structures grew in interest. This is evident from the world conferences on earthquake engineering held every 4 years since 1956, where Figure 1 shows the number of contributions to these conferences with mentions of 'experiment' or 'test' in the title of the contribution to give an indication of the general interest over time. Also, Penzien et al.[8] produced a report examining the feasibility of an earthquake simulator in the United States – generally referred to as a shake-table nowadays - and several other laboratories were subsequently developed worldwide, such as the E-Defence shaking table in Japan, the outdoor shaking table in San Diego and United States and the Eucentre Foundation's facilities in Italy, to name a few. Thus, the key role and importance of experimental testing in understanding and mitigating the effects of earthquakes became clear.

While the interest in experimental techniques and computational capabilities steadily grew, several notable initiatives funded by the European Union (EU) were commissioned (Table 1). Among these projects, several focused specifically on the experimental testing of structures and their components to better understand their seismic behaviour. In addition to this, computational advancements meant that utilising this data to calibrate and develop numerical models became paramount to research and development. Through several of these projects, the European Facilities for Earthquake Hazard and Risk (EFEHR) was established to foster continued cooperation and collaboration between the hazard and risk sectors of earthquake engineering research in Europe. Of the several developments of EFEHR, a notable development has been

TABLE 1 Notable EU-funded projects addressing earthquakes and their impacts on structures.

Period	Project	Title	Funding programme	Funding
1993–1996	PREC8	Pre-normative Research in Support of Eurocode 8	FP3-HCM	–
1993–1996	ECOEST	European Consortium of Earthquake Shaking Tables	FP4-HCMP	–
1996–1999	ECOEST2	European Consortium of Earthquake Shaking Tables	FP4-TMR	–
1997–1999	ICONS	Innovative Seismic Design Concepts for New and Existing Structures	FP4-TMR	–
2001–2005	SPEAR	Seismic Performance Assessment & Rehabilitation	FP5-GROWTH	€1.3M
2004–2007	LESSLOSS	Risk Mitigation for Earthquakes and Landslides	FP6-SUSTDEV	€9.8M
2009–2012	SAFER	Services and Applications for Emergency Response	FP7-SPACE	€26.9M
2009–2013	SERIES	Seismic Engineering Research Infrastructures for European Synergies	FP7-INFRA	€10.7M
2010–2014	NERA	Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation	FP7-INFRA	€12M
2017–2020	SERA	Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe	H2020-INFRA	€11.1M
2022–2026	ERIES	Engineering Research Infrastructures for European Synergies	HORIZON-INFRA	€10.6M
2022–2026	Geo-INQUIRE	Geosphere INfrastructures for QUestions into Integrated REsearch	HORIZON-INFRA	€13.9M

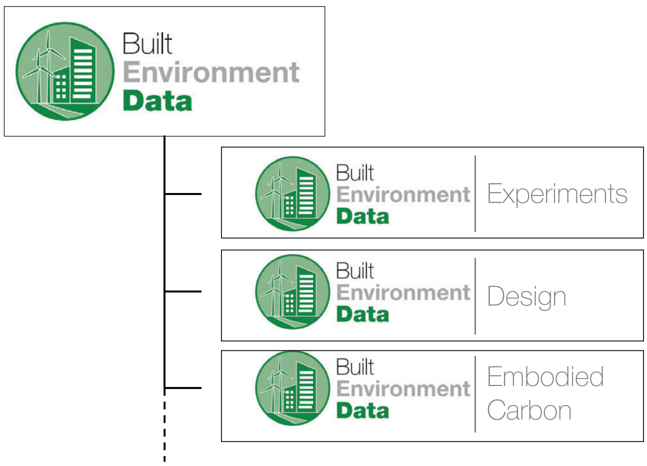

FIGURE 2 Current hierarchy of the Built Environment Data Built Environment Data (BED) initiative.

in the provision of web services whereby databases and information are readily available and searchable to users. To date, this primarily relates to seismic hazard products like hazard curves and seismic risk products like fragility functions and exposure databases. What is still lacking to date is a centralised and consolidated database comprising European experimental test data that is fundamental to the development and calibration of many of these seismic risk products. Some other initiatives with such an objective have been established around the world (e.g. DesignSafe in the United States), and will be discussed further below.

A recent initiative entitled *Built Environment Data* (BED) has been under development since 2022 with financial support from the Italian Ministry of Universities and Research (MUR) and the EU. The BED platform is currently planned to have three core services: *Experiments* for managing experimental data (the focus of the current paper), *Design* for the simulated design of buildings and *Embodied Carbon* for the provision of valuable data on embodied carbon of the built environment (Figure 2), where the dotted lines indicate the expected future services to be added.

The *Design* service offers a collaborative platform for simulating the design of buildings in Europe according to historical and current seismic design standards, using open-source tools and data. It enables European engineers to add to a database of existing design codes. The service produces a Building Class Information Model (BCIM) for various potential building realisations, capturing the differences between buildings. These realisations undergo an iterative design process, and the details of the final building designs, such as reinforcement and structural dimensions, are stored in the Building Design Information Model (BDIM). Using OpenSees[10] in.tcl and.py formats, these models facilitate non-linear analyses and the creation of probabilistic seismic demand models. These models help develop fragility functions and vulnerability models for residential buildings in Europe.

Embodied Carbon is a service maintained and developed by the Global Earthquake Model (GEM) Foundation that provides access to data and maps of the embodied carbon associated with the replacement of residential, commercial and industrial buildings around the world. This service can be used in various studies on the built environment, such as (i) to provide benchmark data on the embodied carbon of different building typologies, (ii) to assess the environmental impact of natural hazards on the built environment and (iii) to assess the impact on the global carbon budget of different forecasts of urbanisation.

The following sections of this paper focus on the *Experiments* service for managing experimental data, describing the motivation for developing this service, comparing it to similar global efforts and outlining the specific requirements and system architecture, including the web services and datasets currently offered.

2 | MOTIVATION

The notion of developing a centralised database to store data from experimental testing is not a novel concept. In many instances, individual laboratories will possess their own internal storage system, which may or may not be available to the public, with the level of curation and file organisation at the discretion of the technicians storing the data at the time of testing. This may be in the form of a restricted intranet, where files are accessed across a common network locally, or more traditionally, stored on portable hard disks that are accessed directly by the users.

This approach to data management leads to clear issues in terms of publicity and sharing as it generally relies on a laboratory report (e.g. Engelhardt and Popov[11] and Graziotti et al.[12] or scientific publication (e.g. Kallioras et al.[13] and Ricci et al.[14]) being produced, whereby the data are described and discussed. For a third party to obtain and utilise this data, they must be aware of the specific report or publication and contact the authors to request they share this data with them. In past years, this was through the mailing of a physical disk with the data, or in more recent years, the sharing of a ZIP file via email, or the insertion of a link directly within the publication. When the data were not available via this route, it was not uncommon for researchers to digitise the images of the data available in the publications in order to use them, which introduces obvious and notable errors. Advances in online cloud computing and storage, bibliographic indexing and online engine searching mean that more modernised means of making data *Findable* and *Accessible* are now available, which relate to the first two aspects of the Findable Accessible Interoperable Re-usable (FAIR) guiding principles for scientific data management and stewardship, described below.

Once the data are accessed, further issues may arise whereby the experimental data obtained (by whichever means) needs to be integrated and compared with other scientific findings. This depends on the quality of the documentation, level of curation and organisation implemented by the laboratories developing the data, which can vary. Should findings of notable interest be reached, it is reasonable to assume that the third party would wish to publish these in reports or scientific publications. Again, the ability to actually utilise the data made available is not always a given, nor is it always possible to publish such data due to ownership, privacy or commercial interest concerns. In many cases, the authors would need to contact the data providers and seek explicit permission for the re-use of such data in subsequent work. These issues relate to the *Interoperable* and *Reproducible* aspects of FAIR.

In the context of European research, the Findability, Accessibility, Interoperability and Re-usability (FAIR) principles[15] seek to address these concerns for what regards scientific data. Findability emphasises the importance of ensuring that data and associated metadata are easy to find by both humans and machines through the use of standardised identifiers and metadata vocabularies. Accessibility underscores the need for data to be readily accessible, ideally through open access mechanisms, while also addressing issues related to authentication and authorisation to ensure appropriate data access. Interoperability emphasises the use of standard data formats, vocabularies and protocols to enable seamless data integration and exchange across diverse systems and disciplines. Finally, Re-usability emphasises the importance of providing clear and comprehensive metadata, as well as ensuring that data are well-described, documented and licensed to facilitate their re-use and reproducibility by other researchers. Instead of focusing on the infrastructures and technical specifications databases should possess (e.g. file formats, backend technologies), the FAIR principles set out a series of requirements that the databases should strive to meet. The goal is to provide guidelines that help improve the reusability of data collections. Unlike other efforts that concentrate on the human scholar, the FAIR principles specifically aim to boost the capacity of machines to autonomously locate and utilise data, while also facilitating its re-use by other researchers.

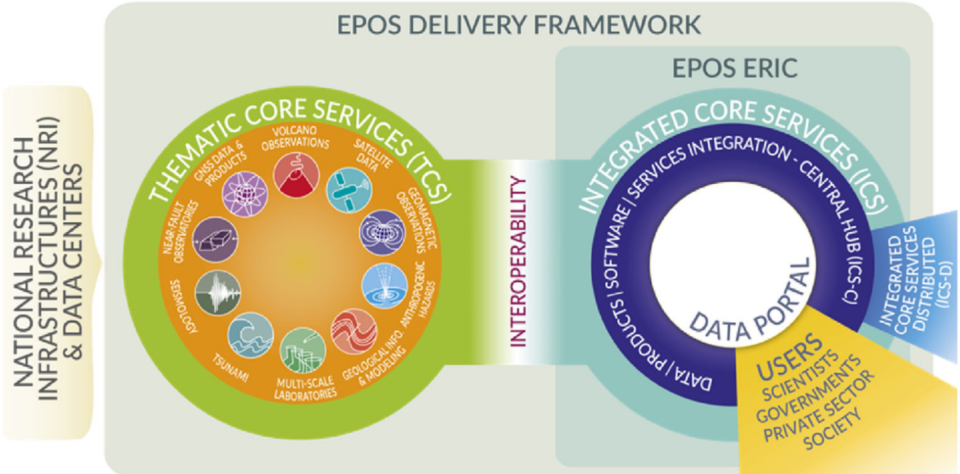

FIGURE 3 Overview of EPOS.[16]

These have become a mainstay in European Union (EU) projects, becoming widely endorsed and adopted by many of the projects receiving funding.

Similarly, while the development of a generalised experimental data storage archive that meets the FAIR principles and fosters more collaborative research is the primary motivation of the BED *Experiments* service, other aspects relating to the longevity of such an initiative need to be addressed. That is, the continued maintenance and development of the platform is required beyond the life of a single project's available funding, or a research group's willingness to support it free-of-charge. Initiatives like the European Open Science Cloud (EOSC) in Europe, or the Natural Hazards Engineering Research Infrastructure (NHERI) in the US strive in this direction, providing a more global support infrastructure to researchers that wish to host and store data. Another initiative is the European Plate Observatory System (EPOS) framework, which has emerged from many of the projects presented previously in Table 1, and which focuses specifically on earth sciences and brings many different disciplines together through its integrated core services, Thematic Core Service (TCS) and online platform (Figure 3). Unlike EOSC or NHERI, which are still funded through specific grants, the European Plate Observing System (EPOS) framework is supported through a number of EU projects, and also through the national membership fees and infrastructures of participating EU countries, to better ensure longevity; for this reason, the BED initiative aims to become a TCS of EPOS.

2.1 | Past and existing efforts

There have been some past efforts to create storage databases throughout the years. These refer to efforts to provide a generalised system that many can use, rather than laboratory-specific databases with a limited focus. Many of these have been specific tasks of some of the projects listed in Table 1, for example, but have tended to encounter some of the issues relating to FAIR or continued support and longevity described in Section 2. Issues typically encountered comprised the data handling and storage methods being outdated by newer approaches, meaning that efforts worked well upon completion but lacked proper support and maintenance to ensure longevity. Other issues were the reluctance of researchers to utilise such generalised databases instead of their own internal storage system, unless specifically required to do so.

Using the United States as an example, the Network for Earthquake Engineering Simulation hub (NEEShub) initiative, active from 2010 to 2014, provided resources and tools for the earthquake engineering community to share data and collaborate around a distinct set of facilities in the United States. NEEShub transitioned to *DesignSafe* in 2015 as part of a broader initiative by the National Science Foundation to modernise and expand the infrastructure by supporting natural hazards research. The goal of DesignSafe is to provide a collaborative environment with advanced tools for data analysis, visualisation and simulation, catering not just to earthquake engineering but to other natural hazards, including hurricanes, tornadoes and floods. DesignSafe describes a strict set of rules regarding file organisation and tagging that needs to be followed when uploading experimental data, which has led some researchers to instead share their data on other data repositories such as Zenodo, which can be viewed as simpler. This, however, offers less scope for the engineering community to find and make use of the data, compared to initiatives like DesignSafe.

For what concerns European research, a centralised Data Access Portal (DAP) was created as part of the SERIES 2009–2013 project described in Table 1, which allowed facilities participating in the project to establish and maintain individual nodes that would be linked through a centralised access portal. This portal was utilised again through subsequent projects like SERA 2017–2020 before being transitioned to a cloud-based metadata portal within the ERIES 2022–2026 project. As before, these portals are well-implemented and satisfy the requirements of FAIR, but lack clarity on their longevity once the specific projects conclude, especially in terms of ownership and funding for their long-term maintenance.

At the time of writing and to the authors' knowledge, no other national or international initiatives exist to host and store experimental data beyond individual laboratory facilities own local system that may be open to the public. However, as mentioned before, these tend to completely lack any form of quality assurance when it comes to FAIR-ness but they are much more resilient when it comes to longevity and maintenance, as there is a specific interest of the laboratory to maintain them.

2.2 | Current objectives

With the above motivations in mind, and considering the strengths and weaknesses of past and current initiatives, some objectives for the BED initiative (https://builtenvdata.eu/) and more specifically, the *Experiments* service offered within it are outlined. These may be summarised as follows:

- **Cloud-based** – this is basic requirement meaning that all tools and storage should be completely online and the service should rely upon infrastructures that are well-adopted and easy to update/maintain.
- **Minimalist and user friendly** – this relates to both the data uploading and the searching and downloading phases. For uploading, strict data structures and individual tags for each of the channels of data recorded are not required. This information is deemed to be of little use to users beyond the specific test programme; hence, it is not worth enforcing and the data are provided as a single ZIP file (with recommended contents) to facilitate a more expedite uploading process. These recommended contents refer to the experimental test data and metadata that ensure reproducibility and usability. Specific guidelines will be available to users uploading their own data in future on what information will be required and how to structure it in folders and sub-folders. For example, some information related to the specimen instrumentation, the laboratory test logbook describing the sequence of tests, technical drawings illustrating all dimensions, material characterisation results, data acquisition channel metadata, in addition to the actual experimental results and associated technical papers/reports. In cases where the single ZIP file's size become too large due to the amount of data contained within it, this has been found to cause difficulty in downloading when the internet connection is not very stable. To remedy this, it is also possible for the user to upload multiple ZIP files of smaller size, with the partitioning of the data into several ZIP files decided by the users.
- **Searchable and downloadable** – this availability of a single ZIP file makes the data available to the user with a single click. Furthermore, organising the data under a series of searchable taxonomy tags, such as those developed as part of the Building Taxonomy of the GEM Foundation,[17,18] further enhances the users' ability to find the data they are most interested in. Web services, such as those offered by EFEHR for their hazard and risk products, can also be implemented to allow automated access.
- **FAIR compliant** – this implies that the service should be constructed to comply with specific principles, which have become fundamental to how data are handled and stored in Europe in recent years. This ensures that many issues of the past regarding datasets not being findable or accessible are addressed. The data is also inter-operable and reproducible since the licensing and terms of service would be made clear from the outset, which is an issue that hampers some of the current efforts. Another aspect to ensure the data FAIR compliant is related to the formatting of files used, meaning that the file-types should be commonly used ones (e.g. .TXT, .CSV, .JSON and .XSLX for data and metadata, .DOCX and .PDF for documents, .JPG, .TIFF and .EPS for images) and not proprietary or legacy file-types that would hinder usability for others.
- **EPOS integrated** – means that the data repository should seek to align and integrate itself with nationally and internationally supported initiatives like EPOS shown in Figure 3. In the case of the BED initiative, this is through the creation of a Thematic Core Service (TCS), which receives continued support to facilitate further research as part of EPOS. This also has a two-fold benefit to ensure a certain degree of quality in how the service is implemented and also that the

issues of longevity are mediated. This was an objective described in a deliverable of the SERA 2017–2020 project where a road-map to integrate with EPOS was first discussed. It should also be noted that similar efforts to EPOS exist in the United States (EarthScope) and also in Australia (AuScope), meaning similar initiatives to BED could also be followed elsewhere for the sharing of data and services related to the built environment.
- **Interactive** – meaning that technologies like application programming interface (API) adopted so that communication to and from the *Experiments* service are possible. This means that users can query the service programmatically through the provision of web services, which will be described later. Additionally, this provision also allows for the possibility of interacting with other national or ad hoc services adopting similar technologies (e.g. DesignSafe in the United States), meaning that search results on the *Experiments* service may also refer to data queried and stored in other locations.

The layout, structure and features of the *Experiments* service are described in the following section in addition to the computational architecture utilised. The compliance with the FAIR principles are also outlined, followed by the datasets currently available at the time of writing. It is envisaged that this service will be developed to encompass datasets from all over the world in an easy and user-intuitive platform, facilitating the development of additional web services and research products that will be to the benefit of the entire earthquake engineering community.

3 | BUILT ENVIRONMENT DATA: EXPERIMENTS

The *Experiments* service provides open access to experimental test data on the performance of buildings and infrastructure. This data has been generated by many experimental tests in Europe and can be used for the validation and calibration of numerical models required to assess the vulnerability of buildings and infrastructure. The web service offers a taxonomy-based search engine for seamless and efficient exploration of datasets. Users can not only access data through a user-friendly interface but also programmatically via web-services, ensuring flexibility in integration. Emphasising community collaboration, the platform welcomes open experimental data contributions, assigning each dataset a Creative Commons Attribution CC-BY licence with a digital object identifier DOI, for persistence, proper attribution and recognition.

3.1 | Layout

In terms of its webpage structure, Figure 4 illustrates the page available at https://experiments.builtenvdata.eu/. It aims to be simple in its presentation, with a focus on helping users find the datasets relevant to their research. This is primarily through the taxonomy-based classification (Section 3.2) and also the provision of web services (Section 3.4) previously discussed as some of the core objectives for the service.

3.2 | Taxonomy-based classification

The taxonomy used to classify the types of experiments that are included in the BED *Experiments* service combines a new taxonomy for experimental specimens. There are four attributes in the proposed Experimental Test Taxonomy string:

```
Specimen Type / Specimen Sub-type / Material Type / Material Technology
```

The Material Type and Material Technology attributes are taken directly from the GEM Building Taxonomy[17,18] (available from https://github.com/gem/gem_taxonomy). Instead, the possible values and associated IDs (used in the taxonomy string) for the Specimen Type and Specimen Sub-Type are described in Tables 2 and 3. It is noted that this is an evolving taxonomy, and additional attributes may need to be added as more experimental test datasets are uploaded, with the latest version available from here: https://experiments.builtenvdata.eu/taxonomy.

Another advantage of the implementation of the BED Experiments service is that these taxonomy codes are directly integrated in the URL of the search results. For example, the screenshot illustrated in Figure 4 shows search results for 'Full structural assembly (FSA)' Specimen Type and 'Masonry, unreinforced (MUR)' Material Type. It is noted that the URL dynamically changes to https://experiments.builtenvdata.eu/explore?tax=FSA%2FMUR to incorporate the 'FSA+MUR+'

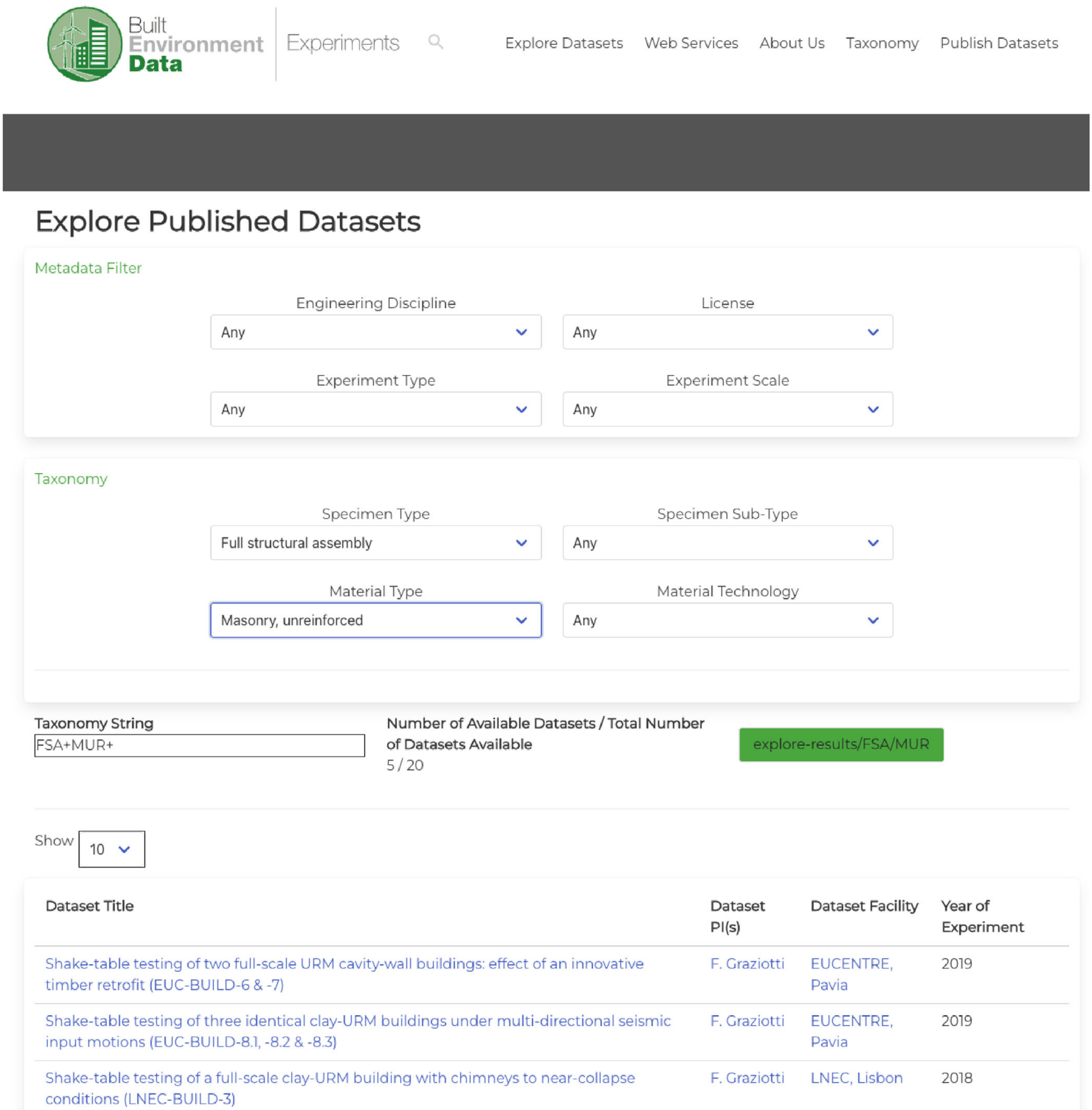

FIGURE 4 Layout of the Explore section of the *Experiments* service of BED.

TABLE 2 Specimen Type taxonomy attributes.

Specimen type	ID
Un-defined	–
Structural element	SE
Partial structural assembly	PSA
Full structural assembly	FSA
Non-structural element	NSE
Electrical/mechanical equipment	EMS

TABLE 3 Specimen sub-type taxonomy attributes.

Specimen sub-type	ID
Undefined	–
Beam	BEA
Column	COL
Slab	SLA
Wall	WAL
Beam–column joint	BCJ
Moment frame	LFM
Infilled frame	LFINF
Braced frame	LFBR
Post and beam	LPB
Dual frame-wall system	LDUAL
Flat slab/plate or waffle slab	LFLS
Infilled flat slab/plate or infilled waffle slab	LFLSINF
Hybrid lateral load-resisting system	LH
Other lateral load-resisting system	LO
Partition wall	PW
False ceiling	FC
Piping	PIP
Air conditioning units	ACU
Computer systems	CS
Medical equipment	MEQ
Transformers	VTR

elements of the taxonomy string created, and an additional explore button also appears. The page also illustrates how many experimental datasets for that taxonomy string exist as a fraction of the overall total.

3.3 | Architecture and implementation

This section outlines the principal components of the service and its implementation strategy. The system architecture is given in Figure 5 and its main components are

- Web application interface for admin dashboard accessible to authenticated users only. It allows them to perform administrative tasks such as registering new datasets into the system. Authenticated users can input metadata, descriptions and other relevant information about the datasets through the dashboard.
- Freely available web-based, user-friendly interface for browsing, searching and accessing datasets. Users may view dataset details and download data files without prior registration.
- The backend built using Django to provide a set of Representational State Transfer (REST) Application Programming Interface (API) to handle various functionalities such as user authentication, dataset submissions, search and retrieval of dataset information and download of data files among others.
- Although Django's ecosystem is primarily tailored for relational databases, MongoDB, a NoSQL database, was utilised to store key attributes and metadata related to each dataset. While NoSQL databases still adhere to a defined data model, they offer more flexibility compared to the strict schema of relational databases. MongoDB employs a document-oriented data model, storing data in JSON-like documents that may include nested data structures, arrays and various data types. Using MongoDB, data are securely stored in a scalable, efficient and flexible storage system. Retrieving data are simplified due to the straightforward structure of the storage system, enabling easy access to nested items without the complexity of intricate joins. This allows easy programmatic access and usage in various tasks by the users to facilitate data analysis and visualisation tasks.

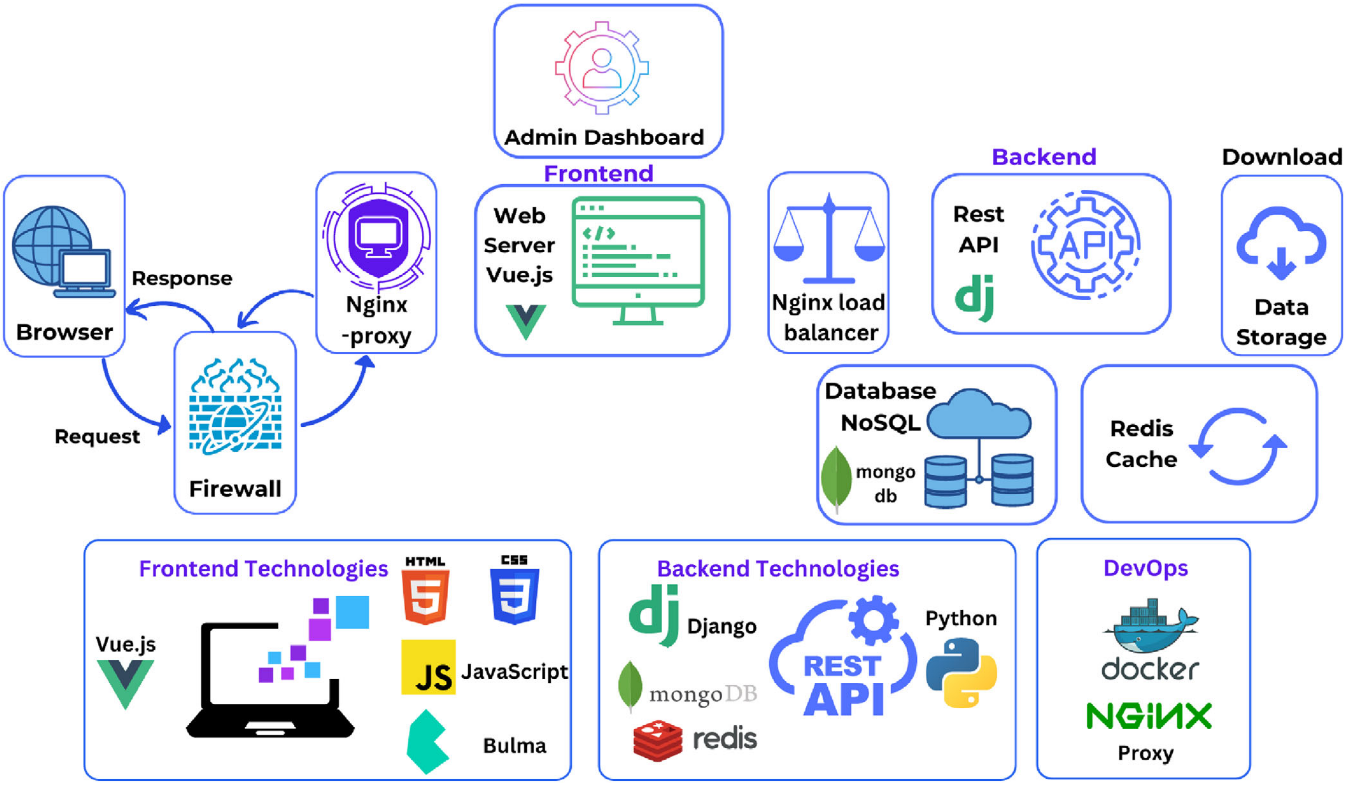

FIGURE 5 System architecture and technology stack.

- On-premise data storage for storing the data files associated with each dataset. Storing datasets on-premise allows for enhanced data control over computing resources, including servers, networking equipment, software applications and security. At the current stage, the on-premise system allows for faster and more reliable performance. This advantage stems from data processing taking place within the organisation's infrastructure, eliminating the need for external network connectivity.
- Redis for in-memory caching to improve the performance of the application. By caching frequently accessed data, Redis reduces the need to retrieve data from the database on every request, thus optimising query performance and reducing latency.

The backend is structured on Django and REST Framework, chosen for several advantages. This includes built-in support for serialisation and deserialisation of complex data types, the use of modular and re-usable code with class-based views and viewsets, seamless integration of REST Framework and Django object-relational mapping (ORM) for database operations and excellent testability with built-in testing tools. Django offers built-in support for authentication and authorisation, including token-based authentication, OAuth and various other methods. While the initial release of the web service restricts authentication to admins exclusively, subsequent iterations may introduce diverse authentication options for the users. Django facilitates rapid development by offering array of built-in functionalities like ORM which further enhances security by preventing common database-related issues, admin dashboard, authentication, uniform resource locator (URL) routing, middleware support, scalability and default security features aimed at mitigating common web vulnerabilities such as cross-site scripting (XSS) and structured query language (SQL) injection.

The admin dashboard APIs are restricted through a virtual private network (VPN)-based access. It provides a secure encrypted connection, offering an additional layer of security and control over who can access sensitive administrative functionalities, safeguarding data transmitted between the user and the admin dashboard from interception or eavesdropping. This approach protects critical data and system configuration from potential threats enhancing security posture, mitigating risks and helping maintain compliance with data protection regulations.

Even though infrequent access patterns are expected to offered API services, load balancing was implemented through Nginx. First, load balancing ensures improved performance and availability by distributing incoming traffic across multiple servers. This prevents any single server from becoming overwhelmed and ensures that the APIs remain responsive and available at all times, even during periods of peak demand. Additionally, load balancing enhances fault tolerance and redundancy. In the event of server failure, the load balancer automatically routes traffic to healthy servers, minimising downtime and ensuring uninterrupted access to the APIs. This proactive approach to server management contributes to a more reliable and resilient infrastructure. Furthermore, load balancing facilitates scalability, allowing for easy expansion of infrastructure as the web services grow and user traffic increases. Overall, while the APIs may not be accessed frequently, implementing load balancing offers significant benefits in terms of performance optimisation, fault tolerance, scalability and reliability, ensuring a seamless user experience even during periods of low demand.

3.4 | Web services

Experiments offers a suite of RESTful web services that users can interact with programmatically. This section details the collection of API requests currently supported by *Experiments* web services, organised for easy access and integration into users' projects. Data must be obtained using any programme supporting the HTTP-POST and HTTP-GET methods, for example, (client URL (cURL).[19] *Experiments* provides a comprehensive set of web services that enable users to interact with datasets, filter datasets based on taxonomy and metadata and retrieve datasets using search queries or unique identifiers.

REST[20] defines a client–server architecture, guiding the behaviour of client applications and web services. It embodies several design principles and restrictions, like stateless communication and the use of uniform interfaces and self-descriptive messages. API interfaces following the REST approach are generally termed as RESTful APIs and each API locates the resource by using the uniform resource identifier (URI) accessible via the web. RESTful web services provide standardised interfaces accessed exclusively through HTTP methods, promoting interoperability and simplifying development of client applications.

An example of an API call offered through the web services is to retrieve datasets based on provided taxonomy strings using the following parameters:

- -H "Content-Type: application/json": This header specifies the content type of the request payload as JSON.
- -d "{ "tax": "key1/key2" }": This option sends the taxonomy string with the *tax* keyword as a JSON object in the request body. Replace 'key1/key2' with the desired taxonomy string where each *tax* keyword is separated by a slash.

The following is the cURL usage (note that API versions may change in the future) that retrieves datasets associated with full structural assembly (FSA) and reinforced concrete (CR):

- curl -X POST "https://experiments.builtenvdata.eu/api/v1/datasets/explore-results/" -H "Content-Type: application/json" -d "{ \"tax\": \"FSA/CR\" }"

One key feature of the *Experiments* web service is the ability to filter datasets based on taxonomy strings using the *tax* keyword. By specifying taxonomy strings, users can narrow down datasets to those that match specific criteria, such as Specimen Type, Material Type and technology used. Additionally, BED offers APIs for filtering datasets based on metadata attributes such as engineering discipline, licence type, experiment type and experiment scale. These APIs allow for efficient data exploration and analysis, helping researchers and engineers find relevant datasets. Furthermore, currently available web services include APIs for retrieving most downloaded and recently uploaded datasets, as well as accessing detailed information about datasets, principal investigator (PI) and facilities. These services provide researchers and engineers with valuable insights into dataset popularity, contributor information and facility capabilities. Overall, the *Experiments* web services offer a robust platform for accessing and analysing scientific data, supporting research endeavours across various disciplines.

3.5 | Compliance with FAIR

To ensure high levels of FAIR compliance, each dataset was linked with a distinct DOI to ensure proper attribution and acknowledgement. A DOI is the primary source for achieving a high level of FAIR compliance by providing a persistent and unique identifier for datasets. The goal was to ensure that the datasets are easily findable (F) as researchers and any interested parties can locate them using the DOI, which remains consistent even if the dataset is moved or its metadata is updated. Additionally, the DOI facilitates accessibility (A) by serving as a stable link to the dataset, ensuring that it

TABLE 4 Number of available datasets according to Specimen Type taxonomy attributes (as of September 2024).

Specimen type	Number of datasets
Structural element	7
Partial structural assembly	5
Full structural assembly	8
Non-structural element	1
Electrical/mechanical equipment	1

remains accessible over time. Interoperability (I) is enhanced as DOIs are standardised identifiers recognised across different systems and platforms, allowing for seamless integration with other datasets and tools. Finally, the DOI supports re-usability (R) by providing proper attribution and recognition to the creators of the dataset, making it easier for users to cite and re-use the data in their own work while adhering to licensing and attribution requirements. Overall, the use of DOIs significantly contributes to achieving FAIR compliance.

Considering the aforementioned, each facet of the FAIR principles is elaborated upon, accompanied by explanations of how they are attained. To achieve findability, metadata includes descriptive core elements and keywords, along with associated data file details and URLs for downloadable data content. Each dataset is assigned a globally unique and persistent identifier, facilitating easy location, while metadata retrieval is enabled programmatically, ensuring discoverability across various platforms and systems. Each DOI includes necessary information regarding access restrictions and usage rights to achieve accessibility for users. Additionally, metadata incorporates a resolvable link to the data using the secure hyper text transfer protocol secure (https). To ensure interoperability, metadata is structured using a formal knowledge representation language, such as lightweight Linked Data format (JSON-LD). Active namespaces like the 'http://purl.org/ontology/bibo' ontology are employed to enhance semantic inter-operability and consistency. By adhering to established standards and vocabularies, such as BIBO,[21] metadata achieves greater inter-operability and compatibility with other systems, facilitating data integration and exchange. Moreover, the metadata clearly defines associated datasets, publications and prior versions of the dataset, enhancing the comprehensiveness and utility of the provided information. Finally, to achieve re-usability, each dataset is released with a clear and accessible data usage licence. Detailed provenance information is provided, documenting the origin and transformation processes of the data, enhancing transparency and trustworthiness. Additionally, the dataset adheres to domain-relevant community standards, ensuring compatibility and interoperability with other datasets in the same domain, thus promoting effective data re-use and integration.

3.6 | Available datasets

At the time of writing, a total of 22 large scale experimental test datasets have been uploaded, distributed as shown in Table 4 with respect to the Specimen Type taxonomy attribute.

It is hoped and expected that the number of experimental datasets available from this platform will increase significantly in the years to come. Any researcher interested in sharing their data through this platform can do so by contacting the authors or filling the contact form available here: https://experiments.builtenvdata.eu/publish. Further efforts will be made to publicise and establish the *Experiments* service through its integration with the EPOS research infrastructure and also dissemination via online social media channels and other public forums like conferences and workshops within the research community. A GitHub organisation with the source code and other data related to all BED services has been created and is available at https://github.com/builtenvdata. While most of the data uploaded and shared are expected to be from the researchers who themselves conducted the experiments, this does not preclude situations where experimental data from third parties can be uploaded. In this case, however, the appropriate recognition will need to be assigned, and issues related to permissions and licensing restrictions on the data verified also. Likewise, if users should find experimental data that they feel should not be publicly available, they are asked to submit a motivated request to remove the data via the Contact Us page.

4 | FINAL REMARKS

This paper has provided an overview of the recent BED initiative, with particular reference to its *Experiments* service, which aims to provide access to experimental test data to researchers around the world. The background and motivation for experimental testing were first discussed, where the idea that the seismic capacity of structures needs to be identified through experimental tests became clear several decades ago. This increased interest in experimental work led to notable advancements in the development of seismic mitigation solutions, the validation of numerical modelling techniques, and contributed to the overall increased understanding of seismic risk mitigation. With this, the need for specific infrastructures that archive, store and render experimental data available to the wider research community became of interest. This is in keeping with other fields' advancements in the provision of digital and cloud-based services that enhance the earthquake engineering community's ability to collaborate, share and exploit the experimental data available.

The specific motivations for this initiative were described with reference to past efforts and other similar efforts around the world, and the specific objectives for a European-based service were outlined. These related to *Experiments* service being cloud-based, minimalist and user friendly, and overall easy for researchers to interact with. Two important aspects were described, which related to the service's compliance with the FAIR principles for findable, accessible, interoperable and re-usable data, and its integration with long-term initiatives like EPOS to ensure the longevity of the *Experiments* service.

The *Experiments* service's architecture and implementation were described, with state-of-the-art cloud-based technologies used to handle its backend and frontend, along with the provision of an API and web services, similar to other initiatives related to hazard and risk products currently available. These features exploit the taxonomy-based structure adopted for the service, which was developed here by extending the existing GEM Building Taxonomy[17,18] (available from https://github.com/gem/gem_taxonomy).

Finally, a brief description of some of the available datasets at the time of writing was given to illustrate the service's full functionality. It is anticipated that the quantity of experimental datasets provided by this platform will grow substantially in the coming years. Researchers interested in contributing their data from all over the world can do so by reaching out to the authors or by completing the contact form at this link: https://experiments.builtenvdata.eu/publish.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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