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1 Physics-informed Knowledge Driven Decision-Making Framework for 2 Holistic Bridge Maintenance

3
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15 16 Abstract

17 Bridge maintenance is a highly intricate task that involves considering a wide range of factors
18 in order to achieve optimal decisions that align with multiple objectives, criteria, and the entire
19 lifecycle of the bridge. While physics-informed analysis, such as the finite element method
20 (FEM), can simulate complex and closely coupled scenarios, such as bridge structural analysis,
21 it cannot account for some loosely coupled discrete factors, which could be addressed by
22 ontological reasoning. Therefore, this paper presents a knowledge-driven decision-making
23 framework that combines static knowledge reasoning with dynamic FEM analysis results to
24 support holistic bridge maintenance decisions. One significant contribution of this research is
25 the development of a comprehensive bridge maintenance ontology that incorporates knowledge
26 derived from bridge maintenance standards. Another key contribution is the ability to employ
27 complex runtime rules-based reasoning to tackle intricate bridge maintenance scenarios. To
28 enable automatic knowledge-driven reasoning, an integrated workflow is developed to
29 orchestrate semantic modeling with numerical modeling through a Python-based Web
30 Ontology Language application programming interface (OWL API). This integration facilitates
31 the efficient orchestration of the framework. A case study is presented to demonstrate the
32 potential for the developed framework in assisting with the complex holistic decisions required
33 for bridge maintenance.

34 **Keywords:** Bridge maintenance; Knowledge engineering; Ontology; Finite element method;
35 Holistic decision-making; Web Ontology Language; Semantic reasoning; Semantic Web.

36 **Introduction**

37 Bridges are a major component of the architecture, engineering, and construction (AEC)
38 industry, and they are aging rapidly due to factors such as increasing traffic (Wu et al. 2021a).
39 By the end of 2017, the total number of bridges in China that posed serious safety risks to
40 human society was approximately 70,000 (Zhou and Zhang 2019). To restore the sub-standard
41 bridges to optimal condition, ¥69.7 billion was invested in renovating 34,000 of China's unsafe
42 bridges between 2016 and 2020 (Ministry of Transport of the People's Republic of China
43 2021). With the rapid increase in number of constructed bridges in China, optimized
44 maintenance strategies are needed to ensure stability and safety throughout their lifecycle
45 (Zhou and Zhang 2019; Wu et al. 2021a). Maintaining these assets is a complex process
46 involving the identification of deterioration and defects, structure maintenance costs, safety,
47 and environmental issues. Navigating this process requires smart, proactive, holistic methods
48 that consider structural conditions and the bridge's entire lifecycle (Jiang et al. 2023a).

49 Bridge maintenance standards encapsulate extensive knowledge of safety guidelines,
50 maintenance procedures, and environmental considerations. They are typically represented in
51 a manner recognized by humans, which then, in some cases, are converted to a machine-
52 readable format. Although that format is computer-readable, the domain-specific uniqueness
53 poses a challenge for machines to achieve a nuanced semantic understanding of complex
54 concepts (Liu and EL-Gohary 2017). Leveraging these documents in practical applications
55 frequently demands considerable human effort to capture the diverse patterns in textual
56 information, resulting in operational inefficiencies. To address this challenge, there is an

57 increasing focus on leveraging the Semantic Web (SW) technologies to effectively organize
58 and utilize domain-specific knowledge (Pauwels et al. 2017; Khudhair et al. 2021; Farghaly et
59 al. 2023).

60 The SW is a group of languages or technologies (e.g., Web Ontology Language (OWL),
61 Resource Description Framework (RDF)) that allow machines to understand the meaning or
62 semantics of information on the World Wide Web. This facilitates the representation and
63 integration of information from diverse knowledge domains (Pauwels et al. 2017). The
64 development of the SW has advanced knowledge management methods from interpretation
65 systems based on human actions to semantics-based approaches (Hou et al. 2015). As one of
66 the core SW technologies, OWL ontology is widely used in bridge engineering. Existing
67 ontology-based applications relating to bridge maintenance tasks can effectively integrate static
68 information from industry manuals and norms (Ren et al. 2019; Li et al. 2021). However, there
69 is still limited research on dynamically linking semantic reasoning to information on structural
70 safety analysis from third-party applications. Thus, traditional SW methods utilized for bridge
71 maintenance applications may be further enhanced.

72 The finite element method (FEM), which is an effective numerical method for structural
73 analysis, is widely used in the AEC domain. Its powerful mesh processing ability can simulate
74 complex boundary conditions and load cases to manage damage simulation, modal properties,
75 and deterioration processes (Fan et al. 2019; Mancini et al. 2021; Smioldo et al. 2021). Bridges
76 are assembled from a finite number of discrete elements that are defined by structural and
77 mechanical equations, but mathematical equations cannot express their mechanical behavior.

78 Thus, FEM can simulate complex behaviors of bridges. However, it is difficult to account for
79 some loosely coupled discrete factors, such as the cause of deficiencies (or defects) and
80 maintenance actions. Moreover, FEM has rarely been utilized for logic-based reasoning to
81 support holistic decision-making. Since bridge maintenance must consider the results of
82 structural physical performance, integrating FEM with knowledge-driven methods that can
83 handle complex mathematical operations should be explored.

84 Therefore, by leveraging both SW and FEM, this paper presents a knowledge-driven
85 decision-making framework that can support holistic bridge maintenance by dynamically
86 integrating bridge lifecycle data with embedded numerical-based analysis. The fusion of
87 different approaches can improve holistic decision-making and bridge maintenance
88 optimization. The paper is structured as follows. Following this introduction, a literature review
89 is provided, which outlines the most relevant findings relating to the research topic.
90 Subsequently, the methodology, which represents the overarching framework for this research,
91 is presented. The fourth section describes the proposed knowledge-driven decision-making
92 framework, including ontology modeling and the Python-based reasoning mechanism. Then, a
93 case study of an actual bridge project in China is presented to demonstrate the proposed
94 framework. Finally, the conclusion section summarizes the key highlights of the research, while
95 also discussing the limitations and providing recommendations for future work.

96 **Literature Review**

97 *Review of Bridge Maintenance Standards*

98 Bridge maintenance industry standards are widely present in various countries worldwide

99 and are typically formulated by their respective transportation or highway management
100 authorities. In the United States, the Federal Highway Administration (FHWA) plays a central
101 role in developing and updating national bridge maintenance guidelines, such as the “national
102 bridge inspection standards” (Federal Highway Administration 2022). With its extensive
103 network of bridges, China has developed a sophisticated system of standards to ensure the
104 structural integrity, functionality, and longevity of these critical assets. In this research,
105 information requirements for bridge maintenance are collected based on the industry standards
106 distributed by Ministry of Transport of the People’s Republic of China (2023), as shown in **Fig.**
107 **1.**

108 These standards guide the standardization of maintenance operations to ensure
109 maintenance quality; accordingly, they include various technical requirements. For example,
110 “the standard for technical condition evaluation of bridges (JTG/T H21-2011)” and “the
111 specification for bridge maintenance (JTG 5120-2021)” address the current visual condition of
112 bridges in service, maintenance operations, and technologies. Moreover, “the specification for
113 inspection and evaluation of the load-bearing capacity of bridges (JTG/T J21-2011)” and “the
114 specification for bridge design (JTG D60-2015)” cover the bridges’ material condition and
115 load-bearing capacity in diverse limit states. Additionally, “the specification for strengthening
116 design (JTG/T J22-2008)” was formulated for several types of highway bridges to restore their
117 functions, improve their load-bearing capacity, and enhance safety. These specifications reflect
118 the requirements of bridge maintenance. By examining their content, three key performance
119 indicators (KPIs) relating to maintenance, along with their respective data needs, are

120 summarized in **Table 1**. These KPIs include the current visual condition of the bridge, its
121 material condition, and its safety performance. This knowledge serves as a guide for the
122 subsequent development of an ontology.

123 *Review of Ontology Applications*

124 The term “ontology” comes from philosophy --it goes as far back as Aristotle’s attempt to
125 classify the things in the world--where it is used to deal with the nature of existence, reality,
126 and the relationships between entities (Gruber 1995; Uschold and Gruninger 1996). In the
127 context of Artificial Intelligence (AI), an ontology is a formal, explicit specification of a shared
128 conceptualization (Gruber 1993; Studer et al. 1998), taking the form of a set of classes,
129 relationships, and axiomatic constraints. “Formal” refers to the fact that it must be machine-
130 readable. “Explicit” means that the type of concepts used and the constraints on their use are
131 explicit. “Shared” describes consensual knowledge that is accepted by a group. In this way,
132 ontologies provide an approach to represent knowledge in a structured and organized manner,
133 which can be used by humans and machines, enabling efficient information retrieval, data
134 integration, interoperability, and knowledge discovery (Saba and Mohamed 2013; Zhang et al.
135 2018; Xu and Cai 2020).

136 In bridge engineering, numerous ontologies have been developed. From 2000 onwards,
137 some ontologies emerged with certain attributes relevant to bridge elements. For example, the
138 ontologies developed by El-Diraby and Kashif (2005), Osman and El-Diraby (2006), and El-
139 Diraby and Osman (2011) focus on modeling design and construction knowledge within the
140 infrastructure domain, with some coverage of bridge elements. The in-depth focus on

141 ontological research specifically designed for bridge engineering began in 2010 and has been
142 continually advancing. The most prominent ontologies relating to bridge maintenance tasks are
143 analyzed and listed in **Table 2**. The table provides information for each ontology, including
144 their names, key concepts, uniform resource identifiers (URIs), and the language in which their
145 latest versions are published.

146 These studies are divided into two groups: 1) ontology-based knowledge management and
147 information retrieval and 2) logical inference for holistic decision-making. The first group
148 focuses on the development of domain-specific ontologies to generate semantic relations
149 among information sources, such as books, standards, manuals, and guides. For example,
150 valuable data in bridge inspection reports show significant potential for improving the
151 understanding of bridge deterioration. An analysis of these documents led to the development
152 of BridgeOnto (Liu and El-Gohary 2016). In 2022, the BridgeOnto underwent maintenance
153 and evaluation through various means (Liu and El-Gohary 2022). Additionally, Hu and Liu
154 (2022) introduced a structural deterioration knowledge ontology (DT-KL-Onto) leveraging
155 knowledge embedded in existing mathematical physics models. Moreover, Li et al. (2021)
156 proposed the Bridge Structure and Health Monitoring (BSHM) ontology, employing an
157 analysis of domain-specific vocabularies to enhance sensory data analysis and information
158 sharing. By extracting terms from Chinese standards relating to bridge maintenance, Zhang et
159 al. (2023) developed the Bridge Maintenance Domain Ontology (BMDO). BMDO covers three
160 interconnected ontologies: the bridge structure ontology, the bridge defect ontology, and the
161 bridge maintenance ontology. The BMDO enables rule reasoning, allowing for the automatic

162 completion of missing relations or attribute values and the execution of consistency checks.

163 Studies in the second group focus on the advantage of semantics in evaluation and
164 decision-making processes. For example, there are some ontologies for common defects on
165 bridges. The Crack Type Ontology (CTO) and Crack Cause Ontology (CCO) introduced by
166 Jung et al. (2020) aim to facilitate the automatic inference of concrete crack causes, reducing
167 potential errors in human judgments. Chai and Wang (2022) developed a framework integrating
168 computer vision and ontology to automate and standardize the assessment of concrete surface
169 quality. Jiang et al. (2023b) presented a Bridge Corrosion Evaluation Ontology (BCEO)
170 designed to assess the extent and severity of corrosion on railway bridges. Hamdan et al. (2021)
171 proposed a semantic modeling approach for the automated detection and interpretation of
172 bridge damage, consisting of two main ontologies: Damage Topology Ontology (DOT)
173 (Hamdan et al. 2019) and Bridge Topology Ontology (BROT) (Hamdan et al. 2020). It is
174 noteworthy that BROT was developed through the integration of BIM-related bridge
175 information, allowing the definition of bridge constructions, including aggregated zones and
176 components, along with their topological relations. Furthermore, Ren et al. (2019) developed
177 the Bridge Maintenance ontology (BrMontology) to manage the heterogeneous and discrete
178 knowledge in the bridge maintenance domain and enable smarter decision-making. By using
179 semantic rules, relatively powerful reasoning capabilities are achieved, including automation
180 of the bridge evaluation process, sorting and providing information about bridge maintenance,
181 assisting in selecting material suppliers, and assisting in arranging big events. It facilitates a
182 smarter decision-making process for bridge management by informing engineers of choices

183 with different considerations rather than a single objective-targeted delivery. In another
184 contribution, Wu et al. (2021b) proposed a Concrete Bridge Rehabilitation Project
185 Management Ontology (CBRPMO) to address the need to enhance information integration and
186 automate information retrieval in bridge rehabilitation projects. A standout feature of the
187 CBRPMO is its effectiveness in managing information in ongoing projects. It supports various
188 management functions based on project information, encompassing the evaluation of project
189 progress, removal of constraints, and assessment of participants' performance.

190 In both groups, ontology modeling is achieved by adhering to a series of standards set by
191 the World Wide Web Consortium (W3C) (2024). The aim is to ensure interoperability between
192 ontologies in different systems, enhance maintainability, and provide consistency and
193 connectivity for applications. These include standards to identify resources (i.e., URI), bind a
194 meaning to every information atom (i.e., OWL), perform logic-based reasoning (i.e., semantic
195 web rule language (SWRL) and shapes and constraints language (SHACL)), and to query
196 information (i.e., SPARQL Protocol and RDF Query Language (SPARQL) and Semantic
197 Query-Enhanced Web Rule Language (SQWRL)).

198 Based on the review of the aforementioned studies, two critical issues are identified:

199 (1) **Ontologies for holistic bridge maintenance.** Most existing ontologies are designed to
200 achieve specific goals, e.g., bridge deterioration prediction, structural health monitoring,
201 and bridge damage evaluation. Bridge maintenance is a complex task that requires the
202 consideration of a wide range of factors, with the analysis of structural safety performance
203 being a crucial aspect. However, the content in current ontologies lacks coverage of

204 structural analysis. Therefore, there is a need for a comprehensive bridge maintenance
205 ontology that includes classes and properties not only relating to bridge elements and
206 damage types but also associated with structural physical performance.

207 (2) **Ontology reuse.** Although an increasing number of ontologies have been developed, many
208 are still difficult for researchers to find, access, and understand due to issues such as the
209 absence of valid URIs. Ren et al. (2019) and Farghaly et al. (2023) emphasized the
210 significance of researchers reviewing existing ontologies and integrating them into their
211 work. Therefore, a simple and effective method for creating accessible, understandable,
212 and reusable ontology on the web should be investigated.

213 **Methodology**

214 This section describes the general methodology of this research. The overarching
215 framework that we propose for broader adoption is shown in **Fig. 2**. The framework consists
216 of two steps: (1) lifecycle data integration for finite element model generation and (2) physics-
217 informed logical-based reasoning for holistic maintenance.

218 **(1) Lifecycle data integration for finite element model generation.** Using the ANSYS
219 parametric design language (APDL), a script was developed to generate and optimize a finite
220 element model that integrates data from different lifecycle stages. Based on the data collected
221 from the design and construction phases, the geometric model of bridge sections was built and
222 exported in a standard ACIS Text (SAT) format, which is used to store 3D model geometry.
223 The exported file was then imported into ANSYS to generate an initial finite element model
224 using APDL.

225 During the operation and maintenance phase, bridge owners regularly conduct bridge
 226 inspections. The collected data from these inspections is then stored in the bridge management
 227 system (BMS). The characteristics of the initial model are optimized using these stored data.
 228 The optimization of dynamic characteristics was conducted using the response surface method
 229 (RSM), with the natural frequency of the structure as the objective and material parameters as
 230 design variables. RSM primarily uncovers analytically complicated or unknown relationships
 231 between several inputs and the desired output through empirical models (Chakraborty and Sen
 232 2014; Kim et al. 2017). The established response surface equation and the objective function
 233 are shown in Equations 1 and 2.

234 The Monte Carlo Simulation (MCS), which is a probability analysis method involving
 235 random sampling to observe the results (Kartal et al. 2011), was performed to find the optimal
 236 solution. Thus, the value of the objective function (F'_{obj}) was calculated by randomly adjusting
 237 the values of the design variables within its range, with the value of the design variables
 238 corresponding to the smallest F'_{obj} being the optimal solution.

$$239 \quad y_k = b_0 + \sum_{i=1}^n b_i x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^n b_{ij} x_i x_j + \sum_{i=1}^n b_{ii} x_i^2 \quad (1)$$

$$240 \quad F'_{obj} = \sqrt{\sum_{k=1}^m c_k \cdot (Y_k - y_k)^2} \quad (2)$$

241 where, Y_k is the measured response; y_k is the target response; x is the design parameter;
 242 b_0 is the constant term coefficient; b_i is the linear term coefficient; b_{ij} is the cross-term
 243 coefficient; b_{ii} is the quadratic term coefficient; c_k is the coefficient for the importance of
 244 each term; n is the number of design parameters; and m is the number of the response.

245 For the optimization of the static characteristics, an iterative optimization approach was

246 employed to modify the initial model's necessary internal force responses, which were
247 considered as the design variables. The established objective function is shown in Equation 3.
248 The value of the objective function (F''_{obj}), was calculated after each adjustment of the design
249 variables. When its value converges, the optimization results can be obtained. Finally, the
250 optimized model was used to analyze the safety performance,

$$251 \quad F''_{obj} = \sqrt{\sum_{i=1}^n (T_i - T'_i)^2} \quad (3)$$

252 where n is the number of optimized internal force responses; T'_i is the response of the
253 initial model; and T_i is the response of the inspection data source.

254 **(2) Physics-informed logic-based reasoning for holistic bridge maintenance.** A
255 comprehensive ontology that integrates domain knowledge relating to bridge maintenance was
256 developed. Ontology Development 101 was selected to build the ontology since it provides
257 guidelines for implementing an ontology that is accessible to inexperienced developers (Noy
258 and McGuinness 2001). Protégé was employed as the ontology management system to model,
259 edit, and work with the ontology. It has several plugins, such as SWRL and pellet reasoner,
260 which were used in this research. Pellet reasoner was used to check the structure of the
261 proposed ontology during its development to ensure correctness and consistency between its
262 terms.

263 SWRL provides a mechanism for expressing complex relationships and logical constraints
264 that surpasses what can be expressed using OWL ontologies alone. The knowledge required to
265 evaluate the structural condition is expressed in the form of SWRL rules. Specifically, the
266 evaluation methods are as follows:

267 • **Visual condition evaluation.** The current visual condition can be assessed by indicators
268 such as technical condition level. In accordance with the standard JTG/T H21-2011, the
269 level of the bridge's visual condition (D_j) is determined based on the value of the bridge's
270 overall technical condition (D_r). D_r (Equation 4) is calculated using the combination of
271 stratified condition assessments and five levels of an independent control index,

$$D_r = BDCI \times W_D + SPCI \times W_{SP} + SBCI \times W_{SB} \quad (4)$$

272 where $BDCI$, $SPCI$, and $SBCI$ denote the technical conditions of the bridge deck system,
273 superstructure, and substructure, respectively. W_D , W_{SP} , and W_{SB} represent the coefficients
274 for the importance of the bridge deck system, superstructure, and substructure in a bridge.
275 These coefficients are assigned values of 0.4, 0.4, and 0.2, respectively.
276

277 • **Material condition evaluation.** In bridge maintenance operations, the concrete strength
278 of the structure is an important benchmark for evaluating the material condition. In
279 accordance with the standard JTG/T J21-2011, the level of the bridge's material condition
280 (S_j) is determined based on the value of the uniformity coefficient of the calculated
281 strength of concrete (K_{bt}). According to bridge inspection data, Equation 5 is used to
282 calculate K_{bt} ,

$$K_{bt} = R_{it}/R_d \quad (5)$$

283 where R_{it} is the calculated value of the actual strength of concrete and R_d is the grade of
284 concrete design strength.
285

286 • **Safety performance evaluation.** The safety performance of a bridge is calculated based
287 on indicators of the components' load-bearing capacity and the indicator of strengthening

288 design. In line with the standard JTG/T J21-2011, the level of the bridge's safety
289 performance (Z_j) is determined for serviceability limit states and ultimate limit states.
290 Based on the standard JTG D60-2015, in serviceability limit states, the characteristic
291 value of permanent action is combined with the quasi-permanent value of variable action
292 applied to bridges. In contrast, in ultimate limit states, the most unfavorable combination
293 of the permanent action effect and uncertainties effect is applied to bridges. The load-
294 bearing capacity of a bridge's structure or component is then calculated using Equation 6,

$$295 \quad \gamma_0 S \leq R \quad (6)$$

296 where R is the resistance value of members' load-bearing capacity, influenced by material
297 properties and the geometric dimensions of the structure; γ_0 is the coefficient for the
298 structure's importance in a road network; and S is the effect function of actions
299 combination, which varies with the combination of loads acting on the structure. If $z_i =$
300 $\gamma_0 S_i / R_i$ ($i = 1, 2, 3$), then Z_j can be inferred.

301 Due to the influence of many factors, the structural performance of in-service bridges is
302 likely to degrade to the point at which they no longer meet minimum requirements.
303 Therefore, strengthening measures are necessary and selected as appropriate to a particular
304 problem. This research uses the bonded steel plate method as an example (**Fig. 3**). In line
305 with the standard JTG/T J22-2008, the corresponding calculations are provided in
306 Equations 7-9,

$$307 \quad f_{cd} b x_1 = f_{sd} A_s + f_{sp} h_{sp} b - f'_{sd} A'_s \quad (7)$$

308 If $2a'_s \leq x_1$,

309
$$\gamma_0 M_d \leq f_{cd} b x_1 \left(h_0 - \frac{x_1}{2} \right) + f'_{sd} A'_s (h_0 - a'_s) - f_{sp} h_{sp} b a_s \quad (8)$$

310 If $x_1 < 2a'_s$,

311
$$\gamma_0 M_d \leq f_{sd} A_s (h_0 - a'_s) + f_{sp} h_{sp} b (h_0 - a'_s) \quad (9)$$

312 where b and h are the width and height of the section, respectively; f_{cd} is the design value
 313 of concrete compressive strength; f_{sd} and f'_{sd} are the design values of the tensile
 314 strength of the steel bar in the tension zone and compression zone, respectively;
 315 a_s and a'_s are the distances from the steel bar to the section in the tension zone and
 316 compression zone, respectively; A_s and A'_s are the cross-sectional area of the steel bar in
 317 the tension zone and compression zone, respectively; x_1 is the height of the compression
 318 zone; f_{sp} is the strength of the reinforced steel plate; h_{sp} is the thickness of the reinforced
 319 steel plate; and M_d is the value of the bending moment (members' load-bearing capacity)
 320 after strengthening.

321 All the evaluation results above are included in Equation 10 to obtain the multi-objective
 322 decision-making in the form of a summation of weighted reasoning results,

323
$$F_{obj} = \omega_1 D_j + \omega_2 S_j + \omega_3 Z_j \quad (10)$$

324 where ω_i is the weighting coefficient, which indicates the significance of each
 325 component from 0 to 1, with the sum being 1. The exact value of ω_i can be determined by the
 326 bridge engineer according to certain conditions. For instance, if bridge structural safety is taken
 327 as the governing consideration, then $\omega_1 = 0.2$, $\omega_2 = 0.3$, and $\omega_3 = 0.5$. Based on the
 328 resulting value of F_{obj} , maintenance decisions (daily maintenance, preventive maintenance,
 329 repair maintenance, special maintenance, and emergency maintenance) can be inferred.

330 Moreover, a Python-based OWL API was established to achieve automatic inference
331 processes. The datasets collected from Step 1 and the ontology model were loaded by
332 combining Openpyxl, a library that provides a way to read, write, and modify Excel
333 spreadsheets in Python, with Owlready2, a library that can load OWL files as Python objects,
334 modify them, save them, and perform reasoning. Subsequently, all datasets were added to the
335 BMO to permit reasoning. Finally, bridge engineers can access maintenance information that
336 satisfies certain criteria by using SPARQL queries provided by RDFLib, which is a Python
337 library allowing users to work and access OWL files. Bridge engineers can query information
338 about structural visual and material conditions, structural safety performance in different states,
339 and maintenance decisions based on multiple objectives. Different strengthening measures are
340 provided in case a bridge's safety performance does not meet requirements.

341 **A Knowledge-driven Decision-making Framework**

342 ***Bridge Maintenance Ontology (BMO) Development***

343 This section discusses the development and implementation of the ontology. As discussed
344 above, Ontology Development 101 (Noy and McGuinness 2001) was selected to build the
345 proposed knowledge base, and Protégé was employed as the ontology management system.

346 **Fig. 4** illustrates the iterative design process of the proposed ontology.

347 The domain of the proposed BMO is the bridge maintenance field. It is designed to
348 improve the maintenance knowledge management of the bridge lifecycle and provide more
349 valuable information than that of older methods, thereby enabling bridge engineers to make
350 holistic decisions. Reusing the existing ontology's critical elements can provide a knowledge

351 base that is compatible with other ontologies. Hence, several ontologies were reviewed to
352 evaluate reusability and extensibility, such as the bridge maintenance ontology (BrMontology)
353 proposed by Ren et al. (2019) and the linked open vocabularies (LOV) database (2023).
354 However, it was concluded that although these ontologies provide a solid initial foundation,
355 they use strictly static data and do not adequately cover bridge maintenance knowledge.
356 Consequently, in this research, the BMO takes those ontologies as a base for development and
357 extends them. By leveraging the FEM results, the BMO can utilize not only static knowledge
358 but also dynamic information.

359 As discussed in the literature review, terms relating to bridge maintenance were collected
360 by analyzing specifications and manuals distributed by China's Ministry of Transport. The
361 collected terms were then divided into distinct categories (classes) and properties such as object
362 properties, data properties, and annotation properties. A top-down method (Ushold and
363 Gruninger 1996) was used to define the class hierarchy. Keywords, standards, and criteria
364 analysis in these specifications were developed as classes or subclasses. Relationships were
365 defined as object or data properties. The "facets", that is, the values of properties, were also
366 added. Finally, individuals, also known as instances, were added to the class hierarchy.

367 A unified modeling language (UML) diagram of the initial version of the BMO is shown
368 in **Fig. 5**. At the highest level of abstraction, twelve core classes were defined. The "Bridge"
369 and "Organization" classes were used to describe generic information relating to bridges, such
370 as name, address, total length, and maximum span length. The classes "BridgeStructure",
371 "BridgeComponent" and "BridgeMember" were defined in detail to represent the structural

372 and non-structural elements of a bridge. Moreover, the “Material”, “MaterialSupplier”,
373 “Hazard” and “PotentialReason” classes are reused from the BrMontology ontology (Ren et al.
374 2019). They were linked together to describe knowledge relating to structural visual and
375 material conditions. In terms of structural safety performance, the “LimitStates” class and its
376 subclasses, such as “ServiceabilityLimitStates” and “UltimateLimitStates,” were defined. The
377 “MaintenanceSolution” and “StrengtheningMeasure” classes were created to provide
378 maintenance and strengthening measures.

379 Properties create connections in the above classes to form RDF triples. An RDF triple
380 consists of a subject, predicate, and object. For example, the object properties “buildBy” and
381 “managedBy” connect individuals belonging to the class “Bridge” to individuals belonging to
382 the class “Organization”, resulting in the corresponding RDF triples: “Bridge, buildBy,
383 Organization” and “Bridge, managedBy, Organization”. The object properties “hasStructure”,
384 “hasComponent” and “hasMember” are the connection and subordinate relations among the
385 structural entities; they have corresponding inverse properties such as “isStructureOf”,
386 “isComponentOf” and “isMemberOf”, and quantifier restrictions, such as “someValues”,
387 which make the ontology more complete. The object properties “hasHazard”,
388 “hasMaterialType”, “hasCapacity”, “hasMaintenanceSolution” and
389 “hasStrengtheningMeasure” belong to a design pattern to implement n-ary (n binary) relations
390 (W3C Working Group 2006). Therefore, individuals belonging to the class “Bridge” can be
391 depicted based on different properties.

392 Furthermore, data properties, which connect individuals to multiple datatypes, describe

393 the characteristics of various individuals quantitatively and qualitatively. The BMO utilizes
394 string, int, float, and Boolean datatypes. For example, the name and identification (ID) of
395 bridges are assigned as string, while the characteristics of individuals belonging to the class
396 “Material” are assigned as float. Whether the bridge needs strengthening is determined by
397 returning a Boolean type. Individuals in the BMO and their facets are also added. For example,
398 according to the standard JTG 5120-2021, individuals belonging to the class
399 “MaintenanceSolution” were added, including “DailyMaintenance”,
400 “PreventiveMaintenance”, “RepairMaintenance”, “SpecialMaintenance”, and
401 “EmergencyMaintenance”.

402 *Creation of Semantic Rules*

403 The BMO was already capable of running built-in reasoners and searching for static
404 information via SPARQL queries. However, it could not handle the complex evaluation and
405 structural safety analysis problems discussed in the methodology section. To further improve
406 its ability, five sets of semantic rules were created to support deductive reasoning using the
407 formal logic of SWRL in Protégé editor. A total of 55 SWRL rules include visual condition,
408 material condition, safety performance, maintenance decisions, and strengthening measures.
409 The workflow of the inference process is shown in **Fig. 6**. Of note, some of these rules are
410 conditional (highlighted in yellow) and rely on the dynamic FEM results.

411 **Table 3** displays several SWRL examples. An SWRL rule consists of two main parts, the
412 antecedent (body) and the consequent (head), observed at the left and right sides, respectively,
413 and connected by the symbol “ \rightarrow ”. Both the antecedent and consequent consist of zero or more

414 atoms, which are connected by ‘^’. An “atom” refers to the smallest element, serving as the
415 fundamental building block for constructing more complex logical expressions. Satisfaction of
416 the atoms in the antecedent renders the atoms in the consequent true. The SWRL provides the
417 class atom, individual property atom, and data-valued property atom. **Table 4** lists several of
418 the atoms used in this research. Atoms in SWRL rules can take the form $C(x)$, $P(x,y)$,
419 $\text{sameAs}(x,y)$, or $\text{differentFrom}(x,y)$, where C is an OWL description, P is an OWL property,
420 and x and y are either variables, OWL individuals or data values. Moreover, there are built-in
421 atoms (e.g., `swrlb:add`, `swrlb:lessThan`) in SWRL. They support many complex predicates that
422 can translate mathematical equations into semantic rules. Thus, both the mathematical
423 operations and reasoning syntaxes are implemented by exploiting SWRL.

424 *Integrating FEM with Logic-based Reasoning*

425 SWRL has limitations due to the underlying RDF/OWL syntax. Some reasoning processes
426 involve extremely complex mathematical operations that require the support of advanced
427 computer-aided tools. For instance, for various actions, the value of the combination is given
428 by the function (S_i), which can be obtained using FEM. Moreover, specific axioms relating to
429 individuals needed to be defined in some reasoning processes, e.g., the material types of the
430 bridge’s various components. Therefore, a Python-based OWL API was set up to support
431 automatic inference processes.

432 **Fig. 7** shows the overall workflow of the process. Firstly, the required data were stored in
433 an Excel (.xlsx) file in a structured way. Bridge inspection and structural property data can be
434 obtained directly from the bridge’s project report. For FEM data, APDL is applied to extract

435 ANSYS post-processing results and store them in the Excel file. Secondly, Openpyxl and
436 Owlready2 libraries were combined to load the datasets in the Excel and ontology files,
437 respectively. By using these packages, the data in the Excel sheets were converted into RDF
438 triples that map onto the relevant classes, attributes, and relationships in the proposed ontology.
439 This involved identifying the appropriate ontology classes and attributes corresponding to data
440 and associating them with RDF triples. For example, the datasets include a bridge named
441 “Changshan Bridge.” This name, “Changshan Bridge”, corresponds to an individual of the
442 class “Bridge” in the proposed ontology. By applying the proposed algorithm, the following
443 RDF triple was created: “ChangshanBridge, is_a, Bridge”.

444 Then, deductive reasoning was performed based on the as-built SWRL rules by running
445 the inference engine. New knowledge was derived through the reasoning process, which
446 enriches the original ontology; as such, an ontology can be continually updated, reasoned, and
447 searched for the timely delivery of both static and dynamic information. To give an example of
448 the enrichment, the class “Bridge” acquired a new individual “Changshan Bridge,” the safety
449 performance of the individual was good, and daily maintenance was the maintenance solution.
450 Finally, using SPARQL queries provided by the RDFLib library, the new ontology was queried
451 to retrieve maintenance information that satisfies certain criteria. The seamless connection of
452 the above steps facilitated the logical reasoning process that was supported by FEM results.

453 *Accessing the Proposed BMO on the Web*

454 The process is designed to integrate various tools to create accessible, understandable, and
455 reusable BMO on the web (**Fig. 8**). First, an OWL file of BMO with metadata and definitions

456 for terms was used as input. Wizard for documenting ontologies (WIDOCO), proposed by
457 Daniel Garijo (Garijo 2017; Garijo and Poveda-Villalón 2020), generates a set of HTML files
458 that were linked through a nexus file, a file for facilitating documentation publication through
459 content negotiation and serializations of the ontology to enable different formats of the
460 documentation and ontology. All these files were input into GitHub repositories to build and
461 deploy a web page. When publishing an ontology on the web, it is recommended to consider
462 its long-term sustainability, specifically the consequences if it becomes widely adopted.
463 Finally, the “w3id.org” website (W3C Permanent Identifier Community Group 2023), run by
464 the W3C permanent identifier community group, was used to provide a secure, permanent URL
465 re-direction service for web applications. After integrating Protégé, WIDOCO, w3id.org
466 website, and GitHub, the generated permanent URL of BMO was produced
467 (<https://w3id.org/BMO>), which is easy to access, understand, and reuse by end-users.

468 **Case Study**

469 In this section, a practical application of the physics-informed knowledge-driven
470 framework is demonstrated through the Changshan Bridge, a cable-stayed bridge with a length
471 of 540m (140m+260m+140m) located in Dalian, Liaoning Province (Jiang et al. 2020). The
472 layout of the main bridge is shown in **Fig. 9**. Its main beam is fixed to its pier and pylon.
473 Considering the geological and topographical conditions at the site, the Changshan Bridge is
474 located toward the northern end of the North Yellow Sea Fault Depression, introducing the
475 possibility of uncertain events, such as magnitude six or higher earthquakes. For structural
476 safety analysis, its loading conditions encompass not only typical load types like dead,

477 temperature, and vehicle loads but also include seismic action. **Table 5** lists the load types and
478 loading methods in FEM software for the Changshan Bridge. Additional concerns involve the
479 coastal environment and susceptibility to common defects like cracks and spalling. The service
480 scenario of the Changshan Bridge involves aspects relating to its visual and material condition,
481 as well as safety performance; therefore, inferring holistic maintenance decisions requires
482 logic-based reasoning supported by a physics-informed analysis.

483 *Generation Finite Element Model of the Changshan Bridge by integrating lifecycle data*

484 As shown in **Fig. 10**, the initial finite element model of the Changshan Bridge was
485 developed in ANSYS. Material parameters for the model were set according to the traffic and
486 environmental conditions at the bridge site. The geometric configuration of the model was
487 directly generated based on the data from the construction drawings. This model is designed as
488 a spine model, concentrating the mass and stiffness of the deck system on the main girder
489 nodes. Cables and main beam nodes are connected by steel arms. Then, the model is optimized
490 based on data from “The Annual Report on the Professional Maintenance Project of the
491 Changshan Bridge in 2019” (hereinafter referred to as the maintenance report), issued by the
492 Liaoning Provincial Transportation Planning and Design Institute. A four-factor Box-Behnken
493 design method is used to establish samples for optimization of the dynamic characteristics. The
494 change rate of the material parameter value is the correction parameter, including the elastic
495 modulus and density of the beam, as well as the elastic modulus and density of the pylon (four
496 factors). The natural frequencies of the first five orders of its structure are the correction targets.
497 The values of the coefficients in Equation 1 were calculated according to the results of samples

498 in the Box-Behnken design. The relationship between random numbers in the Monte Carlo
499 algorithm and the value of F'_{obj} in Equation 2 is listed in **Table 6**. When the total random
500 number reaches 10^6 , F'_{obj} converges, yielding dynamic optimization results.

501 For the optimization of the static characteristics, the cable forces of the initial model were
502 modified. The cable force of the initial model was assumed to be T'_i , the force from the
503 maintenance report was T_i , and the difference between the two was k_i (Equation 11).
504 According to the difference k_i , the pretension of the initial model was adjusted. The value of
505 F''_{obj} in Equation 3 was calculated after each adjustment of the pretension,

$$506 \quad k_i = \frac{(T'_i - T_i)}{T_i} \times 100\% \quad (11)$$

507 where i is the number of cables ($i= 1, 2, 3, \dots, n$), and $n=34$ for the Changshan Bridge.

508 The change of F''_{obj} , with the number of iterations, is listed in **Table 7**. After ten iterations,
509 the value of F''_{obj} converged closely, and the optimized cable force value was consistent with
510 the measured data, indicating that the characteristics of the optimized model were consistent
511 with those of the actual bridge. A more detailed description of this process is provided in our
512 previous paper (Jiang et al. 2020).

513 The structural safety analysis in two limit states was performed using the optimized
514 model, with loadings specified in **Table 5**. **Fig. 11** shows the internal force cloud diagram of
515 the bridge under the serviceability limit states. The entire section is compressed, and the
516 maximum axial compressive stress is 8.69 MPa. Under the ultimate limit states, the beam is
517 fixed to its pier and pylon; therefore, the fixed position, especially the bottom of the pylon, is
518 significantly damaged by seismic vibration (Jiang et al. 2020). The bending moment of the

519 pylon is extracted with the maximum bending moment, 11.8×10^4 kNm (**Fig. 12**).

520 *Physics-informed Inferences and Maintenance Decision-making*

521 The reasoning process and results are shown in **Fig. 13**. The datasets, including bridge
522 inspection data, the FEM analysis data, and the bridge property data, as well as the BMO
523 ontology, were loaded via the Python-based OWL API in the Python environment. Based on
524 the created Python code, these data were automatically mapped to the ontology's relevant
525 classes, attributes, and relationships. The "Changshan Bridge" was defined as an individual
526 belonging to the class "Bridge" in the ontology. Its data were added to corresponding data and
527 object property assertions. In addition, a material condition inspection of the bridge was carried
528 out on various parts of the structure, e.g., the pylon and girder. Due to the different material
529 types of the different members, the corresponding individuals and their object property
530 assertions were also added in addition to data property assertions. Running the reasoning
531 engine to execute as-built SWRL rules, the level of visual condition, material condition, and
532 structural safety performance of the "Changshan Bridge" were inferred automatically, with
533 $D_j=2$, $S_j=1$, and $Z_j=1$, respectively. The material condition and the safety performance were
534 both positive. There were areas of slight damage on the bridge but no influence on functions.
535 Following that, $\omega_i(i=1,2,3)$ are 0.2, 0.3, and 0.5, respectively, which denoted bridge structural
536 safety as the overriding consideration. The reasoning result of F_{obj} is 1.2, and it is determined
537 that the maintenance decision was daily maintenance.

538 In addition, the decision of strengthening measures was also evaluated. As shown in **Fig.**
539 **14**, under the ultimate limit states, $z_3 > 1.0$, i.e., the resistance value (8.06×10^4 kNm) is less

540 than the effect value of the combined actions (11.8×10^4 kNm), indicating that the bridge needs
541 strengthening measures. The tensile side of the pylon should be reinforced with bonded steel
542 plates. Engineers can determine the thickness of the bridge's steel plates, which is set to 4.5–
543 50 mm as the default. The as-built SWRL rules can be applied to obtain the load-bearing
544 capacity of the strengthened bridge. For example, when the Q390 plate with a thickness of 30
545 mm is selected, and the new reasoning result of $z'_3 < 1.0$, the solution meets the requirements.
546 For a more in-depth comparison, the outputs of the inferred bending moment values in different
547 solutions are illustrated in **Fig. 15**. Options for strengthening the bridge can be compared and
548 selected from the nine groups that meet the criteria. Bridge maintenance personnel can also
549 choose appropriate solutions from these options based on local steel plate types and prices.

550 Finally, rather than manually searching through information scattered across documents
551 and systems, bridge engineers can use SPARQL queries to find maintenance information that
552 satisfies their specified criteria. For example, they can query maintenance solutions for bridges
553 with overall condition as the primary consideration (**Fig. 16**). This allows engineers to better
554 understand the bridge, considering factors such as structural condition and maintenance
555 solutions.

556 **Conclusion**

557 This paper presents a knowledge-driven decision-making framework that synergistically
558 merges static knowledge reasoning with dynamic insights gained from FEM analysis to support
559 holistic bridge maintenance decisions. By following standard procedures, the research
560 developed a bridge maintenance ontology to integrate all the essential terminology and required

561 data for bridge maintenance. One of the research's main contributions is to enable complex,
562 runtime rule-based reasoning to address complex bridge maintenance scenarios. To achieve
563 this, an integrated workflow to orchestrate semantic modeling with numerical modeling
564 through a Python-based OWL API was developed, which enabled automatic, physics-informed,
565 knowledge-driven reasoning.

566 Like any research, the research acknowledges its limitations, including the fact that the
567 current validation is only relevant to one bridge scenario and that FEM necessitates substantial
568 computational resources, particularly for larger structures, where an enormous number of
569 elements are required, maintenance decision-making is computationally expensive and time-
570 consuming. Therefore, enhancing and refining the framework will require further validation of
571 different bridge scenarios. With the exponential growth in the popularity of AI, there is a
572 growing interest among researchers in utilizing machine learning (ML) techniques to evaluate
573 the structural safety performance of bridges. In forthcoming studies, an ML-based surrogate
574 model will be employed to forecast the safety performance of bridges, thereby significantly
575 reducing the time and expenses associated with the FEM analysis process.

576 The proposed knowledge base is now accessible on the internet, granting users the
577 capability to access, comprehend, and seamlessly integrate it with other management and
578 maintenance systems in the future. This framework introduces an innovative approach that
579 effectively integrates various decision-making techniques. By incorporating real-time
580 numerical analysis, the static knowledge base can be enhanced, resulting in more
581 comprehensive and semantically meaningful rule sets that are better equipped to handle

582 intricate decision scenarios.

583 **Data Availability Statement**

584 All data, models, or codes that support the findings of this research are available from the
585 corresponding author upon reasonable request.

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591 **References**

- 592 Chai, Y. T., and T. K. Wang. 2022. "Evaluation and decision-making framework for concrete
593 surface quality based on computer vision and ontology." *Engineering, Construction and*
594 *Architectural Management*, 0969-9988. <https://doi.org/10.1108/ECAM-01-2022-0064>.
- 595 Chakraborty, S., and A. Sen. 2014. "Adaptive response surface based efficient Finite Element
596 Model Updating." *Finite Elements in Analysis and Design*, 80: 33–40.
597 <https://doi.org/10.1016/j.finel.2013.11.002>.
- 598 El-Diraby, T. E., and K. F. Kashif. 2005. "Distributed Ontology Architecture for Knowledge
599 Management in Highway Construction." *J. Constr. Eng. Manag.*, 131 (5): 591–603.
600 [https://doi.org/10.1061/\(asce\)0733-9364\(2005\)131:5\(591\)](https://doi.org/10.1061/(asce)0733-9364(2005)131:5(591)).
- 601 El-Diraby, T. E., and H. Osman. 2011. "A domain ontology for construction concepts in urban
602 infrastructure products." *Autom. Constr.* 20 (8): 1120–1132.
603 <https://doi.org/10.1016/j.autcon.2011.04.014>.
- 604 Fan, W., B. Liu, X. Huang, and Y. Sun. 2019. "Efficient modeling of flexural and shear
605 behaviors in reinforced concrete beams and columns subjected to low-velocity impact
606 loading." *Eng. Struct.* 195: 22–50. <https://doi.org/10.1016/j.engstruct.2019.05.082>.
- 607 Farghaly, K., Soman, R.K., Zhou, S.A., 2023. "The evolution of ontology in AEC: A two-
608 decade synthesis, application domains, and future directions." *J. Ind. Inf. Integr.* 36,

609 100519. <https://doi.org/10.1016/j.jii.2023.100519>.

610 Federal Highway Administration, 2022. “National bridge inspection standards.”
611 <https://www.federalregister.gov/documents/2022/09/22/2022-20422/national-bridge->
612 [inspection-standards-technical-correction](https://www.federalregister.gov/documents/2022/09/22/2022-20422/national-bridge-inspection-standards-technical-correction)

613 Garijo, D. 2017. “WIDOCO: A wizard for documenting ontologies.” *Lecture Notes in*
614 *Computer Science*, 10588:94–102. https://doi.org/10.1007/978-3-319-68204-4_9.

615 Garijo, D., and M. Poveda-Villalón. 2020. “Best Practices for Implementing FAIR
616 Vocabularies and Ontologies on the Web.” *Applications and practices in ontology design,*
617 *extraction, and reasoning*, 49: 39-54, <https://doi.org/10.3233/SSW200034>.

618 Gruber, T. R. 1993. “A translation approach to portable ontology specifications.” *Knowledge*
619 *Acquisition*, 5 (2): 199–220. <https://doi.org/10.1006/knac.1993.1008>.

620 Gruber, T. R. 1995. “Toward principles for the design of ontologies used for knowledge
621 sharing?” *International Journal of Human-Computer Studies*, 43 (5-6): 907–928.
622 <https://doi.org/10.1006/ijhc.1995.1081>.

623 Hamdan, A.-H., M. Bonduel, and R. J. Scherer. 2019. “An ontological model for the
624 representation of damage to constructions.” *Proceedings of the 7th Linked Data in*
625 *Architecture and Construction Workshop - LDAC2019*. [https://ceur-ws.org/Vol-](https://ceur-ws.org/Vol-2389/05paper.pdf)
626 [2389/05paper.pdf](https://ceur-ws.org/Vol-2389/05paper.pdf).

627 Hamdan, A.-H., and R. J. Scherer. 2020. “Integration of BIM-related bridge information in an
628 ontological knowledgebase.” *Proceedings of the 8th Linked Data in Architecture and*
629 *Construction Workshop - LDAC2020*, <https://ceur-ws.org/Vol-2636/06paper.pdf>.

630 Hamdan, A.-H., J. Taraben, M. Helmrich, T. Mansperger, G. Morgenthal, and R. J. Scherer.
631 2021. “A semantic modeling approach for the automated detection and interpretation of
632 structural damage.” *Autom. Constr.* 128: 103739.
633 <https://doi.org/10.1016/j.autcon.2021.103739>.

634 Hou, S., H. Li, and Y. Rezgui. 2015. “Ontology-based approach for structural design
635 considering low embodied energy and carbon.” *Energy Build*, 102: 75–90.
636 <https://doi.org/10.1016/j.enbuild.2015.04.051>.

637 Hu, X., and K. Liu. 2022. “Structural Deterioration Knowledge Ontology towards Physics-
638 Informed Machine Learning for Enhanced Bridge Deterioration Prediction.” *Journal of*
639 *Computing in Civil Engineering*, 37 (1). [https://doi.org/10.1061/\(asce\)cp.1943-](https://doi.org/10.1061/(asce)cp.1943-)
640 [5487.0001066](https://doi.org/10.1061/(asce)cp.1943-5487.0001066).

641 Jiang, Y. L., G. Yang, and H. H. Song. 2020. “Dynamic optimization design of extradosed
642 cable-stayed bridge under earthquake excitation.” [In Chinese.] *Engineering Mechanics*,

643 37: 313–319. Tsinghua University. <https://doi.org/10.6052/j.issn.1000-4750.2019.04.S060>.

644 Jiang, Y., G. Yang, H. Li, and T. Zhang. 2023a. “Knowledge driven approach for smart bridge
645 maintenance using big data mining.” *Autom. Constr.* 146:104673,
646 <https://doi.org/10.1016/j.autcon.2022.104673>.

647 Jiang, Y., H. Li, G. Yang, C. Zhang, and K. Zhao. 2023b. “Machine Learning-driven
648 Ontological Knowledge Base for Bridge Corrosion Evaluation.” *IEEE Access*, 11:
649 144735–144746, <https://doi.org/10.1109/access.2023.3344320>.

650 Jung, S.-Y., S. Lee, and J. Yu. 2020. “Ontological Approach for Automatic Inference of
651 Concrete Crack Cause.” *Applied sciences*, 11 (1): 252–252.
652 <https://doi.org/10.3390/app11010252>.

653 Kartal, M. E., H. B. Başağa, and A. Bayraktar. 2011. “Probabilistic nonlinear analysis of CFR
654 dams by MCS using Response Surface Method.” *Appl Math Model*, 35 (6): 2752–2770.
655 <https://doi.org/10.1016/j.apm.2010.12.003>.

656 Khudhair, A., H. Li, G. Ren, and S. Liu. 2021. “Towards future BIM technology innovations:
657 A bibliometric analysis of the literature.” *Applied Sciences*.
658 <https://doi.org/10.3390/app11031232>.

659 Kim, S. J., E. J. Park, S. Y. Jung, and Y. J. Kim. 2017. “Optimization of the pole piece in coaxial
660 magnetic gears for transfer torque ripple improvement.” *International Journal of Applied*
661 *Electromagnetics and Mechanics*, 55 (2): 223–234. <https://doi.org/10.3233/JAE-170079>.

662 Li, R., T. Mo, J. Yang, S. Jiang, T. Li, and Y. Liu. 2021. “Ontologies-Based Domain Knowledge
663 Modeling and Heterogeneous Sensor Data Integration for Bridge Health Monitoring
664 Systems.” *IEEE Trans Industr Inform*, 17 (1): 321–332.
665 <https://doi.org/10.1109/TII.2020.2967561>.

666 Linked open vocabularies (lov), 2023. <https://lov.linkeddata.es/dataset/lov/>.

667 Liu, K., and N. El-Gohary. 2016. “Semantic Modeling of Bridge Deterioration Knowledge for
668 Supporting Big Bridge Data Analytics.” *Construction Research Congress 2016*.
669 <https://doi.org/10.1061/9780784479827.094>.

670 Liu, K., and N. El-Gohary. 2017. “Ontology-based semi-supervised conditional random fields
671 for automated information extraction from bridge inspection reports.” *Autom. Constr.* 81:
672 313–327. <https://doi.org/10.1016/j.autcon.2017.02.003>.

673 Liu, K., and N. El-Gohary. 2022. “Bridge Deterioration Knowledge Ontology for Supporting
674 Bridge Document Analytics.” *J. Constr. Eng. Manag.* 148 (6): 04022030.
675 [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002210](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002210).

676 Mancini, F., H. Remes, J. Romanoff, and P. Gallo. 2021. “Influence of weld rigidity on the non-

677 linear structural response of beams with a curved distortion.” *Eng. Struct.* 246:113044.
678 <https://doi.org/10.1016/j.engstruct.2021.113044>.

679 Ministry of Transport of the People’s Republic of China. 2021. “Important traffic news from
680 the Ministry of Transport of the People’s Republic of China.”
681 https://www.mot.gov.cn/jiaotongyaowen/202111/t20211111_3625593.html.

682 Ministry of Transport of the People’s Republic of China. 2023. “The current industry standards
683 (quota) and daily management group information for highway engineering.”
684 https://xxgk.mot.gov.cn/2020/jigou/glj/202304/t20230407_3790364.html.

685 Noy, N.F., and D.L., McGuinness. 2001. “Ontology Development 101: A Guide to Creating
686 Your First Ontology”. *Stanford Knowledge Systems Laboratory Technical Report KSL-01-*
687 *05 and Stanford Medical Informatics Technical Report SMI-2001-0880.*
688 <https://protegewiki.stanford.edu/wiki/Ontology101>.

689 Osman, H., and T. El-Diraby. 2006. “Ontological Modeling of Infrastructure Products and
690 Related Concepts.” *Transportation Research Record: Journal of the Transportation*
691 *Research Board*, 1984 (1): 159–167. <https://doi.org/10.1177/0361198106198400115>.

692 Pauwels, P., Zhang, S., Lee, Y.C., 2017. “Semantic web technologies in AEC industry: A
693 literature overview.” *Autom. Constr.* 73, 145–165.
694 <https://doi.org/10.1016/j.autcon.2016.10.003>.

695 Ren, G., R. Ding, and H. Li. 2019. “Building an ontological knowledgebase for bridge
696 maintenance.” *Adv. Eng. Softw.* 130: 24–40.
697 <https://doi.org/10.1016/j.advengsoft.2019.02.001>.

698 Saba, F., and Y. Mohamed. 2013. “An ontology-driven framework for enhancing reusability of
699 distributed simulation modeling of industrial construction processes.” *Can. J. Civil Eng.*
700 40 (9): 917–926. <https://doi.org/10.1139/cjce-2011-0489>.

701 Smiroldo, F., I. Giongo, and M. Piazza. 2021. “Use of timber panels to reduce the seismic
702 vulnerability of concrete frame structures.” *Eng. Struct.* 244:112797.
703 <https://doi.org/10.1016/j.engstruct.2021.112797>.

704 Studer, R., V. Richard. Benjamins, and D. Fensel. 1998. “Knowledge engineering: Principles
705 and methods.” *Data & Knowledge Engineering*, 25 (1-2): 161–197.
706 [https://doi.org/10.1016/s0169-023x\(97\)00056-6](https://doi.org/10.1016/s0169-023x(97)00056-6).

707 The World Wide Web Consortium. 2024. “About W3C web standards.”
708 <https://www.w3.org/standards/about/>.

709 Uschold, M., and M. Gruninger. 1996. “Ontologies: Principles, methods and applications.”
710 *Knowledge Engineering Review*, 11 (2): 93–136.

711 <https://doi.org/10.1017/s0269888900007797>.

712 Wu, C., P. Wu, J. Wang, R. Jiang, M. Chen, and X. Wang. 2021a. “Critical review of data-
713 driven decision-making in bridge operation and maintenance.” *Struct. Infrastruct. E.* 18
714 (1): 47–70. <https://doi.org/10.1080/15732479.2020.1833946>.

715 Wu, C., P. Wu, J. Wang, R. Jiang, M. Chen, and X. Wang. 2021b. “Ontological knowledge base
716 for concrete bridge rehabilitation project management.” *Autom. Constr.* 121: 103428.
717 <https://doi.org/10.1016/j.autcon.2020.103428>.

718 W3C Permanent Identifier Community Group. 2023. “Permanent identifiers for the web.”
719 <https://w3id.org/>.

720 W3C Working Group. 2006. “Defining N-ary Relations on the Semantic Web.”
721 <https://www.w3.org/TR/swbp-n-aryRelations/>.

722 Xu, X., and H. Cai. 2020. “Semantic approach to compliance checking of underground utilities.”
723 *Autom. Constr.* 109:103006. <https://doi.org/10.1016/j.autcon.2019.103006>.

724 Zhang, J., H. Li, Y. Zhao, and G. Ren. 2018. “An ontology-based approach supporting holistic
725 structural design with the consideration of safety, environmental impact and cost.” *Adv.*
726 *Eng. Softw.* 115: 26–39. <https://doi.org/10.1016/j.advengsoft.2017.08.010>.

727 Zhou, X., and X. Zhang. 2019. “Thoughts on the Development of Bridge Technology in China.”
728 *Engineering*, 5 (6): 1120-1130. <https://doi.org/10.1016/j.eng.2019.10.001>.

729 Zhang, Y., J. Liu, and K. Hou. 2023. “Building a Knowledge Base of Bridge Maintenance
730 Using Knowledge Graph.” *Advances in Civil Engineering*, 2023: 1–16.
731 <https://doi.org/10.1155/2023/6047489>.

732

733 **Table 1.** KPIs for bridge maintenance

Category	Key Performance Indicators	Data needs
Visual condition	Indicator of technical condition level	Bridge inspection data
Material condition	Indicator of concrete strength level	Non-destructive inspection data
Safety performance	Indicator of load-bearing capacity	Material property data
	Indicator of strengthening design	Structural property data FEM analysis results

734

735 **Table 2.** Ontologies in bridge maintenance

Name	Acronym	Concepts								URI	Language
		T	E	M	D	C	S	A	P		
Bridge Deterioration Ontology (Liu and El-Gohary 2016; Liu and El-Gohary 2022)	BridgeOnto	X	XX	O	XX	XX	O	XX	O	/	OWL; SWRL
Damage Topology Ontology (Hamdan et al. 2019)	DOT	O	O	O	X	X	O	O	O	https://www.w3id.org/dot	OWL; SPARQL; SHACL
Bridge Maintenance Ontology (Ren et al. 2019)	BrMontology	O	X	O	X	X	O	X	O	/	OWL; SQWRL; SWRL
Bridge Topology Ontology (Hamdan et al. 2020)	BROT	X	X	X	O	O	O	O	O	https://www.w3id.org/brot	OWL; SWRL
Crack Type Ontology (Jung et al. 2020)	CTO	O	O	O	XX	O	O	O	O	/	OWL
Crack Cause Ontology (Jung et al. 2020)	CCO	O	O	O	O	XX	O	O	O	/	OWL
Bridge Structure and Health Monitoring Ontology (Li et al. 2021)	BSHM	X	X	O	O	O	XX	O	O	https://github.com/chongqing-jiaotong-university-ai-lab/BridgeHealthMonitoring	OWL; SPARQL; SWRL
Concrete Bridge Rehabilitation Project Management Ontology (Wu et al. 2021b)	CBRPMO	O	X	O	O	O	O	XX	XX	/	OWL; SQWRL; SPARQL; SWRL
Concrete Surface Defect Ontology (Chai and Wang 2022)	/	O	X	O	XX	XX	O	X	X	/	OWL; SWRL

Structural Deterioration Knowledge Ontology (Hu and Liu 2022)	DT-KL- Onto	o	o	o	xx	xx	o	o	o	/	OWL
Bridge Corrosion Evaluation Ontology (Jiang et al. 2023b)	BCEO	x	x	x	x	x	o	o	x	https://w3id.org/BCEO (Invalid link)	OWL; SWRL
Bridge Maintenance Domain Ontology (Zhang et al. 2023)	BMDO	x	xx	o	xx	o	o	xx	o	http://www.semanticeweb.org/kert/ontologies/2022/6/BMDO (Invalid link)	OWL; SWRL

736 Note: T = Bridge Type; E = Bridge Element; M = Material Properties; D = Deficiency (or Defects); C = Deficiency (or
737 Defects) Cause; S = Sensors Configuration; A = Maintenance Action; P = Project Participation. O= not covered; X = rarely
738 covered; and XX = moderately covered.

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740 **Table 3.** Examples of SWRL rules

Rules for calculating the value of visual condition, $D_r = BDCI \times W_D + SPCI \times W_{SP} + SBCI \times W_{SB}$
VisualCondition(?B)^BDCI(?B,?Bbd)^SPCI(?B,?Bsp)^SBCI(?B,?Bsb)^Wd(?B,?Bwd)^Wsp(?B,?Bwsp)^Wsb(?B,?Bwsb)^swrlb:multiply(?k1,?Bbd,?Bwd)^swrlb:multiply(?k2,?Bsp,?Bwsp)^swrlb:multiply(?k3,?Bsb,?Bwsb)^swrlb:add(?Bdr,?k1,?k2,?k3)->Dr(?B,?Bdr)
Rules for calculating the uniformity coefficient of inferred strength of concrete, $K_{bt} = R_{it}/R_d$
BridgeMember(?B)^Rit(?B,?Brit)^Rd(?B,?BRd)^swrlb:divide(?Bkbt,?Brit,?BRd)->Kbt(?B,?Bkbt)
Under ultimate limit states, rules for calculating safety performance coefficient. $z_i = \gamma_0 S_i / R_i$ ($i = 1, 2, 3$)
Bridge(?B)^r0(?B,?Br0)^S3(?B,?BS3)^swrlb:multiply(?Bk,?Br0,?BS3)^R3(?B,?BR3)^swrlb:divide(?Bz,?Bk,?BR3)->z3(?B,?Bz)
Rules for calculating the value of objective function, $F_{obj} = \omega_1 D_j + \omega_2 S_j + \omega_3 Z_j$
Bridge(?B)^Dj(?B,?BDj)^Sj(?B,?BSj)^Zj(?B,?BZj)^w1(?B,?Bw1)^w2(?B,?Bw2)^w3(?B,?Bw3)^swrlb:multiply(?k1,?BDj,?Bw1)^swrlb:multiply(?k2,?BSj,?Bw2)^swrlb:multiply(?k3,?BZj,?Bw3)^swrlb:add(?sum,?k1,?k2,?k3)->Fobj(?B,?sum)
If $1.5 \leq F_{obj} < 2.5$, rules for reasoning about maintenance decisions.
Bridge(?B)^Fobj(?B,?Bj)^swrlb:greaterThanOrEqualTo(?Bj,1.5)^swrlb:lessThan(?Bj,2.5)->hasMaintenanceSolution(?B,PreventiveMaintenance)^maintenancePlaning(?B,"Protective measures need to be taken to delay the degradation of structural performance and prolong the service life of the bridge.")
If $z_3 \leq 1$, rules for reasoning about the result of strengthening demands.
Bridge(?B)^z3(?B,?Bz3)^swrlb:lessThanOrEqualTo(?Bz3,1)->needStrengthening(?B,false)
Rules for calculating the height of compression zone, $f_{cd} b x_1 = f_{sd} A_s + f_{sp} h_{sp} b - f'_{sd} A'_s$
StrengtheningMeasure(?B)^hsp(?B,?Bhsp)^b(?B,?Bb)^swrlb:multiply(?BAsp,?Bhsp,?Bb)^fsp(?B,?Bfsp)^swrlb:multiply(?BFsp,?BAsp,?Bfsp)^fcd(?B,?BFcd)^fsd1(?B,?BFsd1)^fcd2(?B,?BFsd2)^f_sd1(?B,?BFsd1)^f_sd2(?B,?BFsd2)^swrlb:add(?k1,?BFsd1,?BFsd2,?BFsp)^swrlb:add(?k2,?BFsd1,?BFsd2)^swrlb:subtract(?k3,?k1,?k2)^swrlb:divide(?k4,?k3,?BFcd)->x1(?B,?k4)

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743 **Table 4.** Examples of atoms used in this research

Atom type	Atom	Corresponding OWL element
Class atom	Bridge (?B)	Bridge (class)
	BridgeMember (?Bm)	BridgeMember (class)
Data valued property atom	Dj (?B,?Bdj)	Dj (data-type property)
	Sj (?B,?BSj)	Sj (data-type property)
	Zj (?B,?BZj)	Zj (data-type property)
	Fobj(?B,?Bj)	Fobj (data-type property)
Object property atom	hasMaterialType(?B,?BM)	hasMaterialType (object property)
	hasStrengtheningMaterial(?B,?BSM)	hasStrengtheningMaterial (object property)
Built-in atom	swrlb:add(?Bdr,?k1,?k2,?k3)	
	swrlb:greaterThanOrEqual(?Bdr,95)	
	swrlb:lessThan(?Bdr,60)	

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745 **Table 5.** The load types and loading methods

Name	Load types	Description	Loading methods	APDL script
Dead load	Permanent action	The weight of concrete beam, main pylon and stay cables.	Add to the concrete material properties	MP,DENS,1, 2678
		10cm asphalt concrete bridge deck pavement, 7cm cement concrete bridge deck pavement, anti-collision guardrail, marking signs, lamp posts, cable pipelines and water pipes.	Loaded as MASS21 mass element	ET,4,MASS21 R,35,4.898E3,4.898E3,4.898E3
Temperature load	Variable action	The annual average temperature is 9.7°C.	Loaded in the form of element load	BF,all,TEMP,9.7
Vehicle load	Variable action	The vehicle load level is class I, and the design speed is 60 km/h.	Loaded in the form of lane load	SFBEAM,all,1,PRES,10500 F,52,FY,-360000
Seismic action	Seismic action	There is a probability of an earthquake of magnitude-6 or higher.	The EI-Centro wave (Seismic action E2) conducts the co-excitation along the axial and vertical axes.	*dim,ACCEXY,TABLE,1000,4 *tread,ACCEXY,E2-EI,txt,, *dim,ACCEX,array,1000 *dim,ACCEY,array,1000

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747 **Table 6.** The relationship between random numbers and the objective function

Number of random numbers	10 ¹	10 ²	10 ³	10 ⁴	10 ⁵	10 ⁶
F'_{obj}	0.0815	0.0776	0.0296	0.0159	0.0037	0.0033

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749 **Table 7.** The change of the objective function with the number of iterations

Number of iterations	1	2	3	4	5	6	7	8	9	10	11	12	13
F''_{obj}	6.2	2.2	1.5	1.4	1.3	1.2	1.2	1.1	1.0	1.0	0.9	0.9	0.9

