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Citation for final published version:

Jiang, Yali, Yang, Gang, Li, Haijiang , Zhang, Tian and Khudhair, Ali 2024. Physics-informed knowledge driven decision-making framework for holistic bridge maintenance. *Journal of Construction Engineering and Management* 10.1061/JCEMD4/COENG-13593

Publishers page: <https://doi.org/10.1061/JCEMD4/COENG-13593>

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

3  
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## 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;  $\gamma_0$  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  $\omega_i$  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  $\omega_i$  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 (Uschold 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,  $11.8 \times 10^4$  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 ( $8.06 \times 10^4$  kNm) is less

540 than the effect value of the combined actions ( $11.8 \times 10^4$  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.

### 586 **Acknowledgment**

587 This research was supported by Research Funds for the Central Universities of China  
588 (grant number 3132019349), China Scholarship Council (CSC No.202006570025), and BIM  
589 for Smart Engineering Centre in Cardiff University, UK. The author would like to thank them  
590 for their support.

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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	<a href="https://www.w3id.org/dot">https://www.w3id.org/dot</a>	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	<a href="https://www.w3id.org/brot">https://www.w3id.org/brot</a>	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	<a href="https://github.com/chongqing-jiaotong-university-ai-lab/BridgeHealthMonitoring">https://github.com/chongqing-jiaotong-university-ai-lab/BridgeHealthMonitoring</a>	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	<a href="https://w3id.org/BCEO">https://w3id.org/BCEO</a> (Invalid link)	OWL; SWRL
Bridge Maintenance Domain Ontology (Zhang et al. 2023)	BMDO	x	xx	o	xx	o	o	xx	o	<a href="http://www.semantweb.org/kert/ontologies/2022/6/BMDO">http://www.semantweb.org/kert/ontologies/2022/6/BMDO</a> (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.

739

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

<b>Rules for calculating the value of visual condition, <math>D_r = BDCI \times W_D + SPCI \times W_{SP} + SBCI \times W_{SB}</math></b>
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)
<b>Rules for calculating the uniformity coefficient of inferred strength of concrete, <math>K_{bt} = R_{it}/R_d</math></b>
BridgeMember(?B)^Rit(?B,?Brit)^Rd(?B,?BRd)^swrlb:divide(?Bkbt,?Brit,?BRd)->Kbt(?B,?Bkbt)
<b>Under ultimate limit states, rules for calculating safety performance coefficient. <math>z_i = \gamma_0 S_i / R_i</math> (<math>i = 1, 2, 3</math>)</b>
Bridge(?B)^r0(?B,?Br0)^S3(?B,?BS3)^swrlb:multiply(?Bk,?Br0,?BS3)^R3(?B,?BR3)^swrlb:divide(?Bz,?Bk,?BR3)->z3(?B,?Bz)
<b>Rules for calculating the value of objective function, <math>F_{obj} = \omega_1 D_j + \omega_2 S_j + \omega_3 Z_j</math></b>
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)
<b>If <math>1.5 \leq F_{obj} &lt; 2.5</math>, rules for reasoning about maintenance decisions.</b>
Bridge(?B)^Fobj(?B,?Bj)^swrlb:greaterThanOrEqual(?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.")
<b>If <math>z_3 \leq 1</math>, rules for reasoning about the result of strengthening demands.</b>
Bridge(?B)^z3(?B,?Bz3)^swrlb:lessThanOrEqual(?Bz3,1)->needStrengthening(?B,false)
<b>Rules for calculating the height of compression zone, <math>f_{cd} b x_1 = f_{sd} A_s + f_{sp} h_{sp} b - f'_{sd} A'_s</math></b>
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)

741

742

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)	

744

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

746

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

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

748

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

