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AUTOMATED GENERATION OF IFC-COMPLIANT BRIDGE INFORMATION MODELS FROM STRUCTURED DESIGN DATA

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Yu Chen, Ph.D., Assistant Professor
Hirosaki University, Japan
https://orcid.org/0000-0002-1187-4761
yu.chen@hirosaki-u.ac.jp

Chao Lin, Ph.D Candidate
The University of Tokyo, Japan
https://orcid.org/0000-0002-1517-8392
chao-lin@g.ecc.u-tokyo.ac.jp

Haitong Sui, Ph.D., Project Assistant Professor
Nagoya University, Japan
https://orcid.org/0009-0001-1373-1596
sui.haitong.y4@f.mail.nagoya-u.ac.jp

Ryota Okauchi
The University of Tokyo, Japan
https://orcid.org/0009-0001-5391-7133
ryoutaokauchi@g.ecc.u-tokyo.ac.jp

Aya Akita
IMG Inc., Japan
akita.aya@e-img.co.jp

Pang-jo Chun*, Ph.D., Project Professor (corresponding author)
The University of Tokyo, Japan
https://orcid.org/0000-0002-9755-8435
chun@g.ecc.u-tokyo.ac.jp

SUMMARY: *This paper presents an automated framework for generating high-fidelity bridge information models based on the IFC4x3 standard. Addressing the challenges of manual modeling and data consistency in bridge engineering, the proposed solution enables the seamless transformation of structured design data (e.g., Excel tables) as input into detailed and semantically rich IFC models as output through programmatic generation. The workflow integrates a JSON intermediary layer to facilitate flexible data exchange and supports the rapid assembly of complex bridge components, including main girders, secondary beams, connections, bolts, stiffeners, and diaphragms. A key innovation lies in the system's parameter-driven geometry generation, which allows for efficient adjustment and iteration of bridge designs. The framework ensures both geometric precision and semantic completeness, providing the geometric and semantic foundation for downstream workflows including structural modeling, asset management, and maintenance planning. Furthermore, the architecture is designed with future AI integration in mind, enabling large language models to interact with and modify bridge parameters via natural language commands. Case studies on steel plate girder and box girder bridges demonstrate the system's capability to handle intricate structural details and generate models swiftly, with performance scaling linearly with complexity. While current limitations include a focus on steel structures and reliance on comprehensive metadata, the paper outlines future directions such as expanding to other bridge types, implementing automated design rule checks, and enhancing AI-driven design support. Overall, this research advances the digitalization and automation of bridge modeling, providing a robust foundation for intelligent design, analysis, and lifecycle management within the civil engineering domain.*

KEYWORDS: *bridge information model (BrIM), digital twin, bridge engineering, computer-aided design, steel construction.*

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1. INTRODUCTION

Bridges represent critical assets in transportation infrastructure, serving as essential links in regional and national mobility networks (Chen et al., 2023). Their structural complexity, long service life, and high maintenance requirements demand precise, information-rich digital models to support planning, design, construction, and lifecycle management. In recent years, the rapid advancement of digital technologies in civil engineering has fundamentally transformed the way bridge infrastructure is managed (Lin et al., 2025). Bridge Information Model (BrIM), as an extension of Building Information Model (BIM) tailored to the bridge domain, has emerged as a powerful paradigm for integrating geometric, semantic, and engineering data into a single interoperable digital representation (Mafipour et al., 2023). By enabling accurate visualization, multidisciplinary collaboration, and data-driven decision-making, BrIM plays a crucial role in improving the efficiency, safety, and sustainability of bridge projects throughout their lifecycle (Yan and Hajjar, 2022).

A key enabler of BrIM's interoperability is the Industry Foundation Classes (IFC) standard (buildingSMART International, 1999). IFC provides an open, vendor-neutral data schema capable of representing bridge geometry, semantics, and engineering attributes in a software-independent format. Its adoption allows consistent data exchange between design, analysis, and asset management platforms, thereby strengthening cross-disciplinary collaboration, ensuring long-term data accessibility, supporting compliance with regulatory requirements, and enabling seamless integration into emerging digital twin environments. Moreover, the release of IFC4x3 (Justo et al., 2021; buildingSMART International, 2024) has further expanded the standard's applicability to bridges, introducing entities such as IfcBridge and IfcBridgePart, enhanced alignment modeling, and improved support for long-span and segmented structures, making it especially relevant to BrIM workflows.

Despite these advances, the generation of IFC-based BrIMs remains a labor-intensive and error-prone process in most engineering workflows (Justo et al., 2021; Fang et al., 2025). Conventional approaches typically rely on manual three-dimensional (3D) modeling or semi-automated tools that still require significant user intervention (Romero-Jarén and Arranz, 2021). This dependency not only increases the risk of human error but also limits scalability for large and complex infrastructure projects. Moreover, maintaining semantic richness and geometric fidelity—essential for advanced applications such as structural analysis, construction sequencing, and asset management—remains challenging (Tang et al., 2022). Another persistent bottleneck lies in transforming structured design data, often stored in tabular or spreadsheet formats, into semantically rich and geometrically accurate IFC models. Although some commercial and research tools provide partial automation, establishing a direct, fully automated mapping between raw design parameters and IFC-compliant entities without manual modeling is still a complex and underdeveloped area of research.

In addition to the growing adoption of BIM for bridge infrastructure, there has been increasing attention on the automation of digital model creation from physical assets through Scan-to-BIM technologies(Chen et al., 2025). Scan-to-BIM aims to convert laser-scanned point cloud data into comprehensive and up-to-date digital representations, thereby enabling efficient renovation, maintenance, and lifecycle management for existing structures (Bosché et al., 2015; Son et al., 2015). In industrial and infrastructural environments, the process faces significant challenges due to complex geometries, dense layouts (Sui et al., 2025), and the presence of occlusions and noise in raw point cloud data (Patraucean et al., 2015; Sui et al., 2025). Especially for elongated steel elements such as beams and columns, manual modeling is labor-intensive and prone to errors, while traditional automated approaches may struggle with the identification and accurate reconstruction of non-standard cross-sections or may only generate simplified geometric representations (Agapaki et al., 2018; Smith and Sarlo, 2021; Justo et al., 2023).

Recent advances in point cloud processing have sought to address these limitations by developing methods capable of segmenting and fitting standardized profiles to individual structural components, even in the presence of significant occlusions and clutter (Yang et al., 2020; Yan and Hajjar, 2022). Noichl et al. (2025) proposed a method that combines geometric feature analysis and skeleton-based topology preservation to achieve accurate instance segmentation and parametric shape fitting of steel structures, generating complete IFC-format models. However, achieving fully automated, high-fidelity BIM model generation that preserves both geometric detail and semantic richness, and that outputs in industry-standard formats such as IFC, remains a critical research gap.

Against this backdrop, this study addresses these gaps by proposing a comprehensive, fully automated framework for IFC-based BrIM generation from structured bridge design data. Specifically, this research seeks to enable the direct generation of IFC models from bridge design data stored as numerical values in spreadsheets such as Excel

(Microsoft, 2025), thereby avoiding reliance on conventional visualization-based or manually intensive modeling workflows. The study is based on the premise that properly structured design parameters contain sufficient geometric and semantic information to drive IFC model generation directly. Accordingly, the proposed framework takes structured bridge design data (e.g., Excel tables) as input and programmatically generates detailed, semantically rich IFC bridge models as output. The proposed methodology adopts a data-driven geometric modeling approach, in which design parameters are systematically processed through mathematical algorithms to produce IFC4x3-compliant bridge models. The framework introduces a multi-stage transformation pipeline—from Excel-based design inputs, through an intermediate JSON-based (JSON, 2025) representation, to final IFC entity assembly—ensuring that both semantic integrity and geometric precision are preserved throughout the process. By integrating hierarchical component categorization, robust data validation, parametric geometric processing, and systematic IFC mapping, the methodology eliminates the need for manual modeling while enhancing interoperability with other BIM platforms.

The proposed framework ensures a high degree of parametric flexibility, allowing for the straightforward modification of component dimensions and quantities. This capability not only facilitates rapid design iterations but also enables efficient adaptation of models to accommodate project-specific requirements or to be transferred across analogous structural systems with minimal revision. In addition, the framework supports the detailed representation of intricate structural components, including bolts, studs, stiffeners, and diaphragms. Such granularity enhances the fidelity of the digital models, thereby enabling advanced analyses and providing a more accurate basis for structural evaluation. A further impact of the framework lies in its emphasis on structuring design data in a machine-readable and semantically consistent format. This characteristic establishes a robust foundation for the integration of Large Language Models (LLMs) within the design workflow. Leveraging LLMs in this context facilitates the automated generation of alternative design options, verification of compliance with design codes, and recommendation of optimized parameter sets informed by historical project data and performance objectives (Forth and Borrmann, 2024). Collectively, these features allow the framework to transcend conventional automation, fostering an AI-assisted environment in which engineers can iteratively explore, refine, and validate bridge designs with enhanced efficiency and reliability (Hattori et al., 2024; Matzakos and Moundridou, 2025).

To demonstrate the applicability and performance of the proposed workflow, two representative structural typologies—a steel plate girder and a steel box girder—were modeled and implemented within the framework. The resulting BrIMs encapsulate not only precise geometric representations and detailed structural features but also comprehensive semantic information and material properties. This integration ensures that the digital models are enriched with the contextual knowledge required for advanced engineering analysis and lifecycle management. Furthermore, the models were systematically decomposed into distinct spatial and functional regions, a strategy that facilitates modularity and opens the possibility for subsequent incorporation of damage detection, inspection records, and maintenance data. This design enables the BrIMs to evolve dynamically over the service life of the structure, thereby supporting asset management tasks such as condition assessment and rehabilitation planning. As a result, the proposed framework establishes itself as a scalable, repeatable, and robust methodology for bridge modeling. By streamlining the transition from design concepts to information-rich digital models, it holds significant potential to enhance efficiency, consistency, and reliability across the design-to-model workflow in contemporary bridge engineering practice.

The key contributions of this paper are:

1. Direct generation of IFC4x3-compliant BrIMs from structured bridge design data, reducing manual modeling effort and enhancing design consistency.

2. Straightforward modification of component dimensions and quantities, facilitating rapid design iteration and efficient adaptation to project-specific requirements.

3. Detailed semantic and geometric representation of complex structural components, ensuring high modeling fidelity and providing the geometric and semantic basis for downstream structural modeling and lifecycle management.

4. Solid basis for integration with LLMs, enabling automated design generation, compliance verification, and data-driven optimization of design parameters.

The remainder of this paper is structured as follows. Section 2 details the methodological framework, including the overall system architecture, data structure design, geometric processing algorithms, and IFC model assembly procedures. Section 3 describes the implementation and application of the proposed methodology, illustrating the BrIM generation of a steel plate girder and a steel box girder. Section 4 presents conclusions, discusses limitations, and outlines potential directions for future research.

2. METHODOLOGY

2.1 Overall framework for automated BrIM generation

This research proposes a comprehensive framework for automated BrIM generation from structured design data (See Figure 1). The methodology addresses the fundamental challenge of transforming tabular bridge design information into semantically rich, geometrically accurate IFC models without manual intervention. The framework operates on a clear parameter-to-geometry principle: all design parameters—alignment control coordinates, component cross-sections, material specifications, and connection details—are explicitly specified by the engineer in spreadsheet or JSON format; all 3D geometry, inter-component connectivity, and IFC entity assembly are derived automatically by the framework from these parameters, requiring no manual 3D modelling at any stage. Where extension parameters (E1–E4) are set to 'Auto', the framework computes the required edge offsets programmatically from adjacent component geometry.

The core innovation lies in the development of a multi-stage conversion process that preserves both geometric accuracy and semantic information throughout the transformation pipeline. Unlike conventional approaches that require manual 3D modeling or semi-automated tools with significant user intervention, this methodology enables fully automated BrIM generation by establishing a direct mapping between design parameters and IFC geometric entities. Throughout this paper, 'the system' refers to this integrated framework as a whole—encompassing the structured spreadsheet/JSON input interface, the data processing and normalization module, and the IFC generation engine.

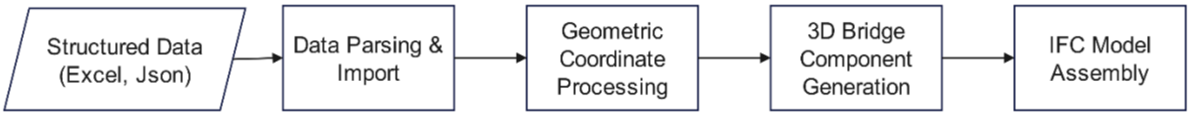


Figure 1: IFC model generation flow.

2.2 Hierarchical component categorization

The methodology implements a comprehensive component categorization scheme that organises bridge structures into functional groups while maintaining computational efficiency. As shown in Figure 2 the hierarchical structure begins with Bridge Information Metadata encompassing project identification, coordinate system parameters, and export configuration settings that govern the scope and format of model generation.

Table 1: The abbreviations used to denote panel types, boundary parameters, and connection positions.

Abbreviation	Full Term	Context
UF / LF	Upper Flange / Lower Flange	Main panel face type
W	Web	Main panel face type
E1 – E4	Edge extension offset (E1=Left, E2=Right, E3=Top, E4=Bottom)	Geometric offset applied to each panel edge for inter-component connection interface; positive values extend outward, negative values retract inward
SEC	Section	Panel block section index
SPL	Splice plate	Connection member type
TL / TR	Top-left / Top-right	Gusset plate mounting position
BL / BR	Bottom-left / Bottom-right	Gusset plate mounting position
MID	Middle	Gusset plate mounting position
VS / HS	Vertical Stiffener / Horizontal Stiffener	Stiffening element type

Geometric alignment data forms the spatial foundation of the bridge model through centerline geometry control points, cross-section definitions, and spatial reference coordinates. This information establishes the global coordinate system and ensures spatial consistency across all bridge components. The alignment data directly influences the positioning and orientation of all structural elements within the 3D bridge model.

Structural components are organized into three primary categories based on their engineering function and geometric complexity. Main panels represent primary structural elements such as deck slabs and girders, characterized by geometric properties including line definitions, section types, material specifications, and boundary extension offsets (E1–E4, denoting Left, Right, Top, and Bottom edge adjustments respectively) that enable proper inter-component connection interfaces. Sub panels encompass secondary elements including splice connections, stiffening ribs, and detailed components with cutouts and attachments. Connection members define joints and fasteners through bolt connection details, weld specifications, and assembly relations that establish connectivity between adjacent components. The abbreviations used to denote panel types, boundary parameters, and connection positions throughout this paper are defined in Table 2.

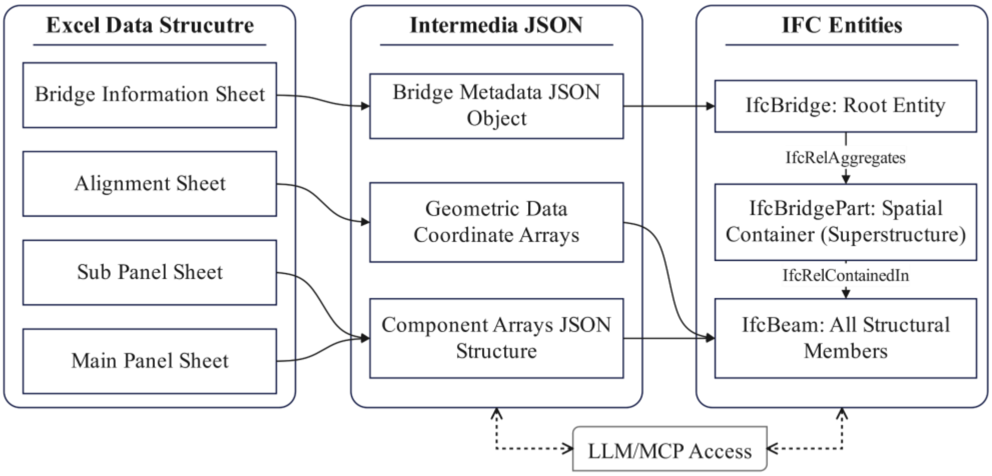


Figure 2: Data schema mapping diagram.

2.3 Data structure design and processing

The proposed methodology employs a three-tier data transformation architecture that systematically converts Excel-based design data into IFC-compliant bridge models (see Figure 3). The Excel data structure consists of four primary worksheets: (1) Bridge Information Sheet containing project metadata and coordinate system parameters, (2) Alignment Sheet defining the bridge centerline geometry and spatial references, (3) Main Panel Sheet specifying primary structural elements, and (4) Sub Panel Sheet detailing secondary components and connections.

The JSON layer serves as the canonical internal representation of the framework, with three roles that justify its presence as a dedicated architectural tier. First, it decouples the input format from the processing pipeline: while Excel is the primary design interface, JSON can also be supplied directly—enabling programmatic parameter injection without spreadsheet involvement and supporting the Model Context Protocol (MCP) interface described in Section 3.3. Second, it performs multi-sheet normalisation: a single component's definition spans three Excel worksheets (geometry lines, material records, and attachment marks), which the conversion function merges into a single typed object and supplements with validated default values for any absent fields. Third, the resulting JSON is cached to disk on first conversion, so repeated IFC exports reuse the parsed representation without re-reading the source spreadsheet.

The final transformation stage maps the processed JSON data to appropriate IFC entities following the IFC4x3 standard. Bridge-level information generates the IfcBridge root entity. Spatial organisation of the superstructure is represented by an IfcBridgePart element (PredefinedType = SUPERSTRUCTURE), which acts as the spatial container for all structural members via IfcRelContainedInSpatialStructure—consistent with its role as a spatial structuring element in IFC4x3, analogous to IfcBuildingStorey in building models. Individual structural members are instantiated as IfcBeam entities.This systematic mapping ensures that the resulting BrIM maintains both geometric accuracy and semantic richness required for interoperability with other BIM applications.

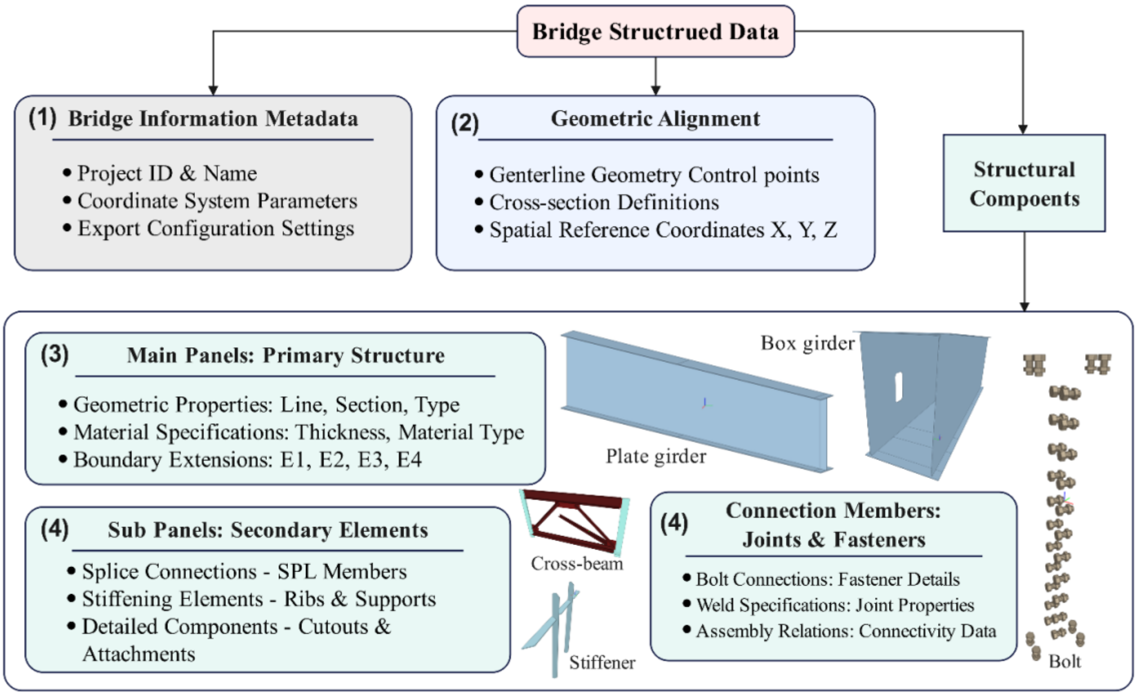


Figure 3: Hierarchical Data Structure Diagram.

2.4 Geometric processing and coordinate transformation

The geometric processing module transforms structural component definitions from the bridge-local reference frame—in which parameters describe cross-sectional geometry and longitudinal placement relative to the alignment centerline—into absolute survey coordinates used throughout the IFC model. Although IFC natively supports relative element positioning via IfcLocalPlacement, the framework deliberately adopts absolute global coordinates (PlacementRelTo = None) so that the generated BrIM is geospatially anchored in the real-world survey coordinate system, enabling direct integration with GIS datasets, point cloud inspection data, and asset management systems referenced in the same frame.

The methodology incorporates sophisticated algorithms for boundary extension calculations that automatically determine the geometric adjustments required for proper component connections. Panel edge extension offsets (E1–E4) are systematically applied to generate the precise geometric interfaces needed for structural continuity. These calculations account for material thickness, connection tolerances, and assembly requirements that are critical for accurate bridge representation.

Surface generation employs parametric modeling techniques that create 3D solid geometries from discrete coordinate points and section definitions. The algorithm ensures geometric continuity across component boundaries while maintaining clear semantic distinctions between different structural elements. Boolean operations are applied to create complex geometries including cutouts, penetrations, and connection details that reflect actual construction requirements.

2.5 IFC model assembly and validation

The final methodology stage involves systematic assembly of processed geometric data into IFC-compliant BIMs. The process establishes a comprehensive entity hierarchy beginning with the IfcBridge root entity that contains all project-level information and spatial context. Individual bridge components are instantiated as appropriate IFC entities based on their structural function and geometric characteristics.

Geometric representation utilizes IFC geometric modeling capabilities including IfcExtrudedAreaSolid for linear structural elements, IfcBooleanResult for complex geometries with cutouts and penetrations, and IfcFacetedBrep for detailed surface representations. Material properties and cross-sectional definitions are assigned through IfcMaterial and IfcProfileDef entities that maintain the engineering specifications required for import into structural analysis and construction planning applications.

The core data flow of the automated bridge IFC modeling system is summarized in Algorithm 1. The process begins with importing design data from Excel, configuration files, and alignment information, followed by comprehensive validation of all input formats and completeness. The workflow then converts the Excel data into a structured JSON format, normalizes units and data types, and extracts alignment coordinates that serve as spatial references for the bridge model. Main and sub panels, along with other structural components, are identified and iteratively processed: for each panel, the algorithm validates geometry, computes 3D coordinates, and generates solid geometry. Additional features such as ribs, stiffeners, and cutouts are applied to each panel as needed. All generated solids are collected and assembled into the overall bridge model. Finally, the internal data is mapped to IFC4x3 entities and relationships, schema compliance and geometric connectivity are validated, and the completed model is exported as an IFC file. This structured workflow ensures both semantic richness and geometric fidelity throughout the automated modeling process.

Algorithm 1: Automated Bridge IFC Modeling Data Flow

```
Input: Excel file with bridge specifications;
JSON configuration file;
Alignment data (Excel/JSON)
Output: IFC4x3-compliant bridge BIM model
Import design data from Excel, configuration from JSON, and
  alignment data;
Validate formats and completeness of all inputs;
Convert Excel to structured JSON;
Normalize data fields (units, types);
Extract alignment coordinates;
Identify main and sub panels, and other components;
foreach panel in all panels do
    Validate panel geometry;
    Compute 3D coordinates;
    Generate 3D solid geometry;
    foreach feature in panel do
        Apply feature to geometry (e.g., rib, stiffener, cutout);
    Store solid in assembly list;
Assemble all solids into bridge model;
Map internal data to IFC4x3 entities and relationships;
Validate IFC schema compliance;
Check geometric integrity and connectivity;
Export bridge model as IFC file;
```

The methodology incorporates comprehensive validation mechanisms that verify model completeness and geometric consistency before export. Validation procedures include geometric intersection detection, connectivity verification between adjacent components, and material property validation against engineering standards. These quality assurance measures ensure that the generated BrIMs meet the accuracy and reliability requirements for professional engineering applications while maintaining full compliance with IFC4x3 standards.

3. SYSTEM IMPLEMENTATION

3.1 Steel plate girder

The proposed automated BrIM generation framework has been implemented and validated through the development of a comprehensive steel plate girder bridge model. The test case consists of a 60-meter span steel plate girder bridge featuring four main girders with complete structural detailing including secondary members and connection elements (Figure 4). The generated model demonstrates the system's capability to automatically produce geometrically accurate and semantically rich BrIMs from tabular design data.

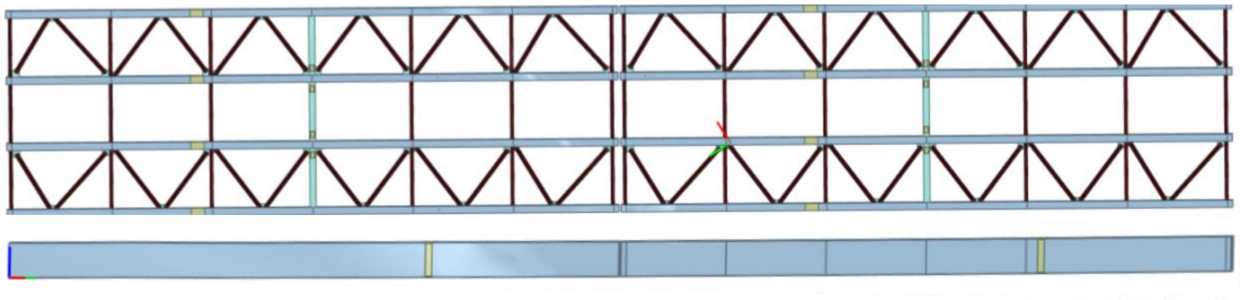
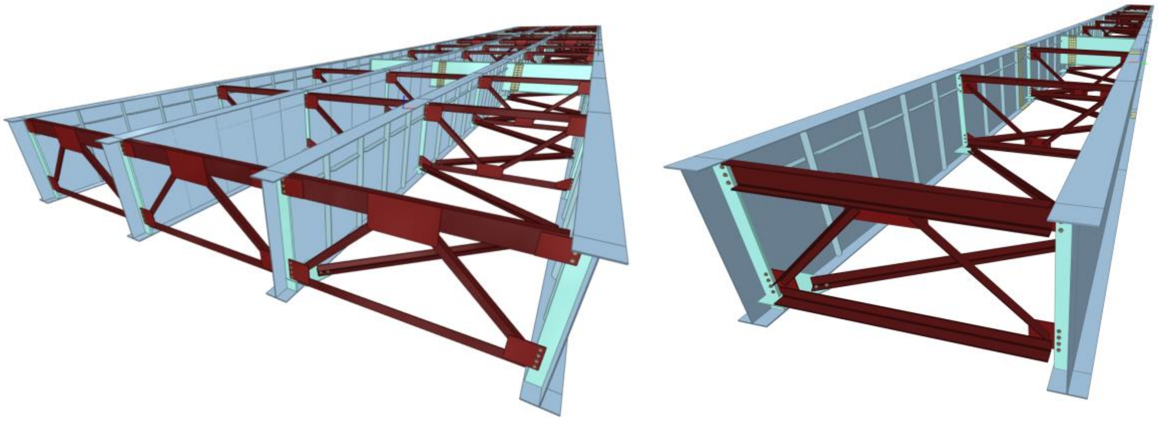


Figure 4: Aerial view and side view of steel plate girder bridge information model.

The automated system successfully generates all essential bridge components including main girders, cross-beam, sway bracing, vertical stiffeners, horizontal stiffeners, connections with bolts and connection plates, and gusset plates. Each component is systematically positioned according to the input design parameters and assigned appropriate material properties for direct integration with structural analysis applications.

The implementation demonstrates system flexibility through its ability to generate bridge models with varying configurations. Figure 5 illustrates the automated generation of steel plate girder bridges with different main girder quantities, comparing a four-girder configuration with a two-girder alternative. This adaptability showcases the robustness of the underlying data processing algorithms, which accommodate varying bridge geometries while maintaining structural and semantic consistency throughout the automated model generation process.



a) 4 main girder *b) 2 main girder*

Figure 5: View of steel plate girder bridge with different girder number.

Component visualization employs a systematic color-coding scheme that facilitates model interpretation and quality verification. Primary structural elements including main girders and deck components are distinguished through distinct color assignments, while secondary members such as bracing systems and stiffeners utilize complementary color schemes. Connection details including bolts, splice plates, and gusset plates are highlighted through contrasting colors that enable rapid identification during model review and validation processes. This visual organization enhances the practical utility of the generated BrIMs for engineering review and construction planning applications.

3.1.1 Metadata structures

The automated BrIM generation system employs a comprehensive metadata framework consisting of thirteen structured worksheets that systematically define all bridge components and their geometric relationships (Table 2). This metadata structure serves as the foundational data layer that enables the automated transformation of design parameters into IFC-compliant BrIMs. All fields within these worksheets constitute engineer-specified inputs; spatial coordinates, solid geometry, and IFC entity relationships are derived entirely by the processing pipeline.

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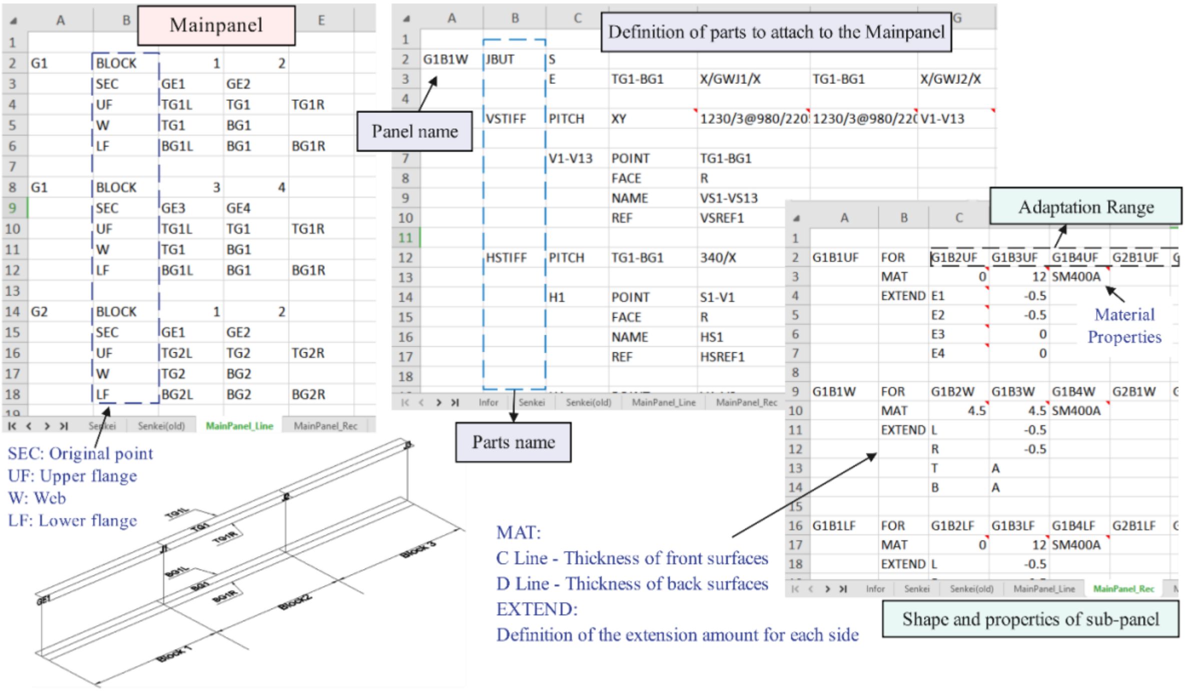
Table 2: Metadata sheet structure and definitions.

Sheet name	Contents
Infor	Basic project and bridge information
Alig	Alignment data
MainPanel_Line	Main panel block and boundary line definitions
MainPanel_Rec	Main panel material and gap settings
MainPanel_Mark	Main panel attached member definitions
SubPanel_Line	Cross-section nomenclature and boundary line definitions
SubPanel_Rec	Sub-panel geometry and properties
SubPanel_Mark	Sub-panel component placement definitions
Cross-Beam	Cross-frame system definitions
Bracing	Lateral bracing system definitions
Member_Rib	Rib and stiffener reinforcement definitions
Member_SPL	Splice connection definitions
Member_Data	Attachment member definitions

The metadata framework encompasses three primary categories of information: a) project-level data including basic bridge information and alignment parameters, b) structural component definitions covering main panels and c) sub-panels with their geometric and material properties, and connection system specifications including cross-beams, bracing elements, and splice connections. Each worksheet follows a standardized format that ensures consistent data interpretation and processing throughout the automated model generation workflow.



Mainpanel

	A	B	C	D	E
1					
2	G1	BLOCK	1	2	
3		SEC	GE1	GE2	
4		UF	TG1L	TG1	TG1R
5		W	TG1	BG1	
6		LF	BG1L	BG1	BG1R
7					
8	G1	BLOCK	3	4	
9		SEC	GE3	GE4	
10		UF	TG1L	TG1	TG1R
11		W	TG1	BG1	
12		LF	BG1L	BG1	BG1R
13					
14	G2	BLOCK	1	2	
15		SEC	GE1	GE2	
16		UF	TG2L	TG2	TG2R
17		W	TG2	BG2	
18		LF	BG2L	BG2	BG2R

SEC: Original point
UF: Upper flange
W: Web
LF: Lower flange

Definition of parts to attach to the Mainpanel

	A	B	C	D	E	F	G
1							
2	G1B1W	JBUT	S				
3			E	TG1-BG1	X/GWJ1/X	TG1-BG1	X/GWJ2/X
4							
		VSTIFF	PITCH	XY	1230/3@980/220	1230/3@980/22(	V1-V13
7			V1-V13	POINT	TG1-BG1		
8				FACE	R		
9				NAME	VS1-VS13		
10				REF	VSREF1		
11							
12		HSTIFF	PITCH	TG1-BG1	340/X		
13							
14			H1	POINT	S1-V1		
15				FACE	R		
16				NAME	HS1		
17				REF	HSREF1		
18							

Panel name

Parts name

Adaptation Range

	A	B	C	D	E	F
1						
2	G1B1UF	FOR	G1B2UF	G1B3UF	G1B4UF	G2B1UF
3		MAT	0	12	SM400A	
4		EXTEND	E1	-0.5		
5			E2	-0.5		
6			E3	0		
7			E4	0		
8						
9	G1B1W	FOR	G1B2W	G1B3W	G1B4W	G2B1W
10		MAT	4.5	4.5	SM400A	
11		EXTEND	L	-0.5		
12			R	-0.5		
13			T	A		
14			B	A		
15						
16	G1B1LF	FOR	G1B2LF	G1B3LF	G1B4LF	G2B1LF
17		MAT	0	12	SM400A	
18		EXTEND	L	-0.5		

Material Properties

MAT:
C Line - Thickness of front surfaces
D Line - Thickness of back surfaces
EXTEND:
Definition of the extension amount for each side

Shape and properties of sub-panel

Figure 6: Detailed structure of representative metadata sheets.

Figure 6 illustrates the detailed structure of representative metadata sheets, demonstrating how bridge components are systematically defined through coordinate-based geometric parameters and material specifications. The MainPanel worksheet exemplifies the methodology's approach to component definition, where structural elements are characterized through block sectioning (SEC), geometric boundaries (UF, W, LF), and extension parameters (E1-E4) that facilitate automated connection generation. Material properties and cross-sectional definitions are integrated directly within the metadata structure, enabling seamless propagation of engineering specifications throughout the generated BrIM.

The metadata architecture supports flexible bridge configurations through parametric definitions that accommodate varying component quantities and arrangements. Component naming conventions follow systematic patterns that enable automated recognition and processing of related elements, while geometric definitions utilize relative positioning and extension parameters that ensure proper connectivity between adjacent components. This structured approach provides the foundation for robust automated model generation while maintaining the flexibility required for diverse bridge design applications.

3.1.2 Bracing system parametric generation

The automated generation of cross bracing systems represents a critical component of the proposed BrIM framework, requiring precise parametric control of geometric relationships and connection details (Figure 7, Table 3). The system implements a comprehensive parametric definition approach that captures the complex spatial relationships between bracing members, gusset plates, and primary structural elements through systematically defined geometric parameters.

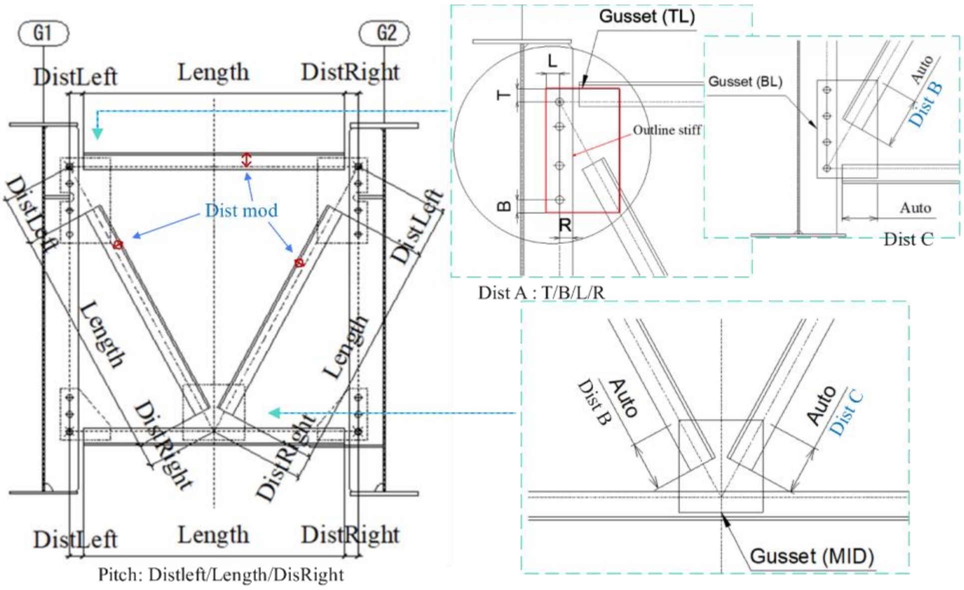


Figure 7: Parametric definition and geometric configuration of bracing system components.

Table 3: Material specifications and dimensional parameters for bracing elements.

	Position	**Type**	**Material**	**Shape**	**Direction**	**Dist mod**	**Pitch**
SHAPE	T	C	SS400	250x90x9	U	62	75/X/75
	B	L	SS400	130x130x9	D	70	75/X/75
	L	L	SS400	90x90x10	U	45	159/X/350
	R	L	SS400	90x90x10	U	45	171/X/350
	Position	**Thickness**	**Material**	**Dist A**	**Dist B**	**Dist C**	
GUSS	TL	9	SM400A	40/40/40/40	200	0	
	TR	9	SM400A	40/40/40/40	200	0	
	BL	9	SM400A	40/40/40/40	Auto	Auto	
	BR	9	SM400A	40/40/40/40	Auto	Auto	
	MID	9	SM400A	40/40/40/40	175	175	62

The bracing generation methodology employs a sophisticated gusset plate positioning system that accommodates five distinct mounting configurations including top-left (TL), top-right (TR), bottom-left (BL), bottom-right (BR), and middle (MID) positions. Each gusset plate configuration utilizes a four-parameter distance specification system (Dist A, Dist B, Dist C, and Dist D for middle configurations) that precisely controls the geometric relationship between connection plates and adjacent structural elements. The Dist A parameter defines the distance from the outermost bolt hole centers to the gusset plate edges in four directions (Top, Bottom, Left, Right), enabling precise control of connection geometry and load transfer characteristics.

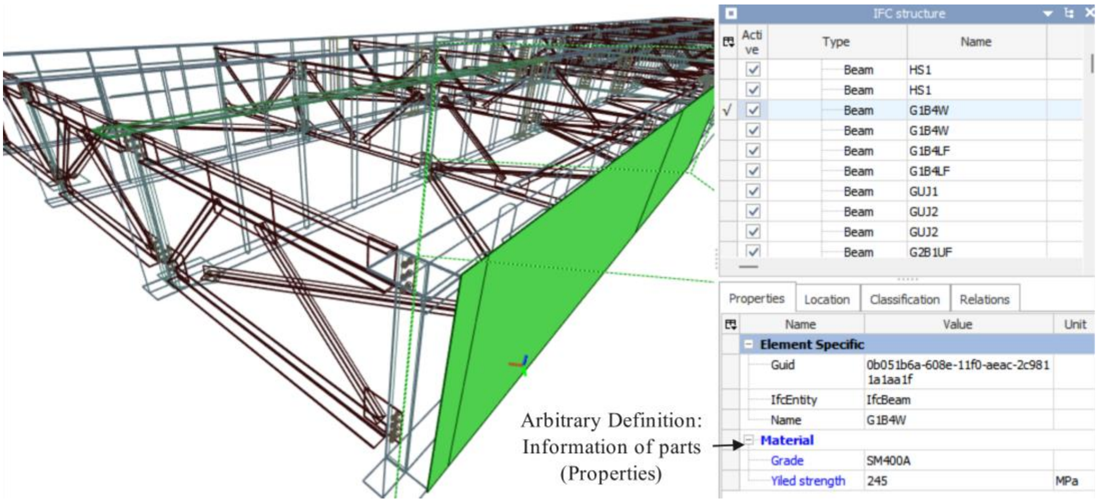
The geometric processing algorithm incorporates intelligent automation capabilities that calculate optimal gusset plate dimensions when multiple structural shapes intersect at a single connection point. When both Dist B and Dist C parameters are set to "Auto" mode, the system automatically computes the required geometric clearances based on the intersecting member profiles and standard connection practices. This automation significantly reduces the manual input requirements while ensuring structural adequacy and geometric consistency throughout the bracing system.

Material specifications and cross-sectional properties are systematically assigned through the integrated SHAPE command structure that defines steel section types, dimensions, and material grades for each bracing member. The system accommodates various structural steel sections including equal angle sections (L-shapes), channel sections (C-shapes), and custom profiles with corresponding material specifications ranging from SS400 to SM400A grades. Orientation parameters (U for upward, D for downward) control the installation direction of angle sections relative to the structural background, ensuring proper load transfer and connection alignment.

The parametric framework incorporates pitch control mechanisms that define the longitudinal spacing and distribution of bracing elements along the bridge span through DistLeft, Length, and DistRight parameters. This systematic approach enables the generation of uniform bracing patterns while accommodating varying span configurations and structural requirements. The Dist mod parameter controls the offset distance from the structural steel background to the working line, ensuring proper geometric relationships between theoretical design lines and actual fabrication requirements for construction accuracy and quality control.

3.1.3 Properties and semantic attribution

The implemented BrIM framework incorporates comprehensive material property assignment mechanisms that enable precise engineering specification during the model generation phase (Figure 8). Each structural component is systematically assigned material properties including steel grade classifications (SM400A, SS400), yield strength specifications (245 MPa), and relevant mechanical characteristics through the integrated material definition system. The methodology ensures that all generated IFC entities maintain complete material property sets that support downstream structural analysis and engineering verification processes, with properties directly accessible through standard IFC property interfaces for seamless integration with analysis software platforms.



	Active	Type	Name
	☑	Beam	HS1
	☑	Beam	HS1
√	☑	Beam	G1B4W
	☑	Beam	G1B4W
	☑	Beam	G1B4LF
	☑	Beam	G1B4LF
	☑	Beam	GUJ1
	☑	Beam	GUJ2
	☑	Beam	GUJ2
	☑	Beam	G2B1UF

Name	Value	Unit
Element Specific		
Guid	0b051b6a-608e-11f0-aeac-2c9811a1aa1f	
IfcEntity	IfcBeam	
Name	G1B4W	
Material		
Grade	SM400A	
Yiled strength	245	MPa

Arbitrary Definition:
Information of parts
(Properties)

Figure 8: Material property assignment and IFC entity structure in generated BrIM.

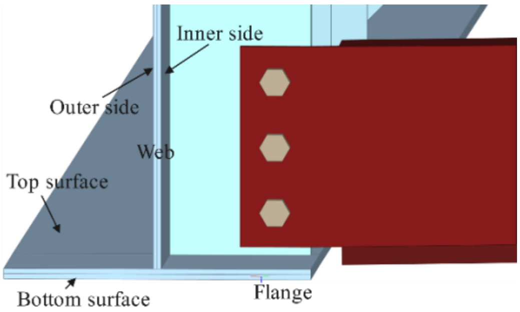


Figure 9: Dual-surface representation of plate elements for inspection documentation.

CC BY

The system implements a dual-surface geometric representation approach for all primary plate elements including web plates, flange components, and deck structures (Figure 9). In the proposed BrIM workflow, each physical plate element (such as a girder web) is intentionally represented by two distinct IfcBeam instances, corresponding to its outer and inner exposed surfaces respectively. While both instances share the same component identifier and geometric extent, they are assigned independent semantic identities to enable unambiguous surface-specific referencing during bridge inspection. This design is motivated by practical inspection needs: damage annotations, such as the corrosion zone, must be attributed to a specific surface (e.g., the outer face of web G1) rather than the plate as a whole, which is essential for condition assessment and maintenance planning. It should be noted that these paired instances together represent a single physical plate; practitioners performing quantity take-off or material estimation should treat each surface pair as one component to avoid double-counting of material volume.

3.2 Steel box girder

In addition to the plate girder modeling capabilities demonstrated in the previous section, the BrIM framework provides comprehensive steel box girder generation functionality with equivalent geometric precision and semantic completeness (Figure 10). The system systematically reproduces complex box girder assemblies including precise stud distributions, diaphragm configurations, longitudinal and transverse stiffening systems, and bolted connection details. Each structural component maintains accurate spatial relationships and engineering specifications, enabling the automated generation of complete box girder models that reflect actual fabrication and construction practices through parametric control mechanisms.

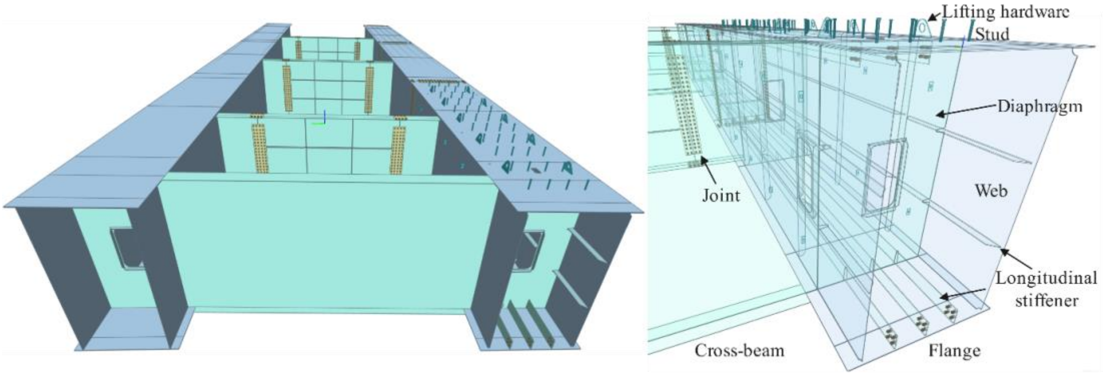


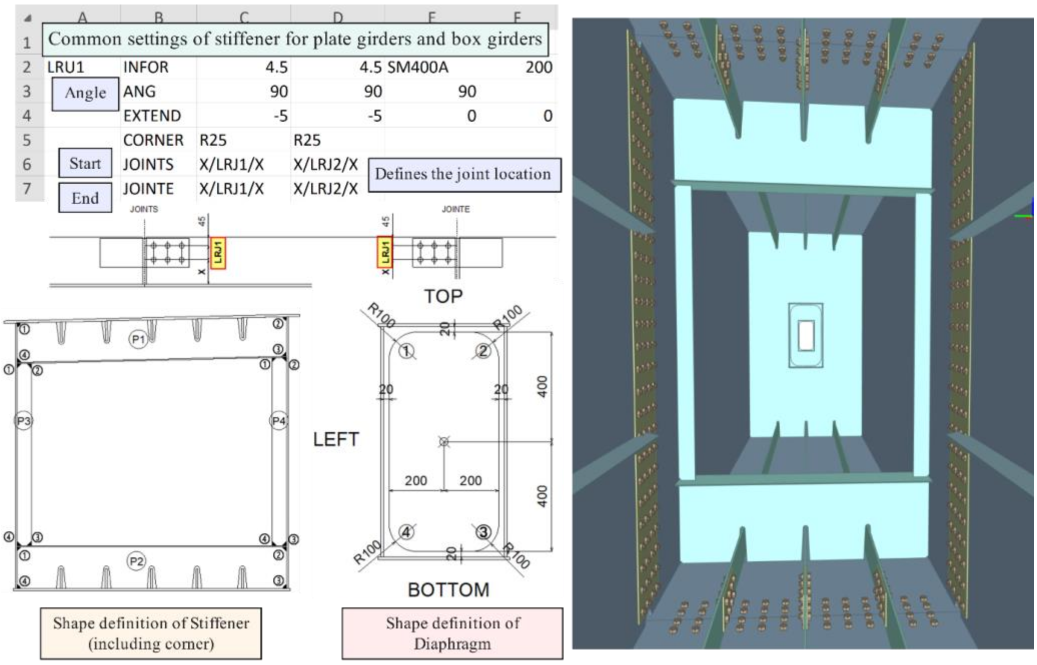
Figure 10: Automated steel box girder generation with detailed internal component configuration.

The stiffener and diaphragm generation subsystem employs structured data tables that provide comprehensive parametric control over geometric configurations and connection details (Figure 11). The system enables precise definition of stiffener profiles including angle specifications, extension parameters, and corner radius treatments (R25 configurations) through standardized input protocols. Joint location specifications (LRJ1/LRJ2 positioning systems) facilitate accurate connection placement between stiffening elements and primary structural components, while diaphragm shape definitions accommodate complex geometric requirements including strategic cutouts and filleted transitions that optimize structural performance and fabrication efficiency.

The automated box girder generation methodology incorporates intelligent geometric processing algorithms that calculate optimal stiffener spacing, diaphragm positioning, and connection hardware placement based on structural engineering principles and standard design practices. This systematic approach ensures that generated box girder models maintain structural integrity requirements while providing the geometric precision necessary for downstream fabrication planning, construction sequencing, and long-term asset management applications within the integrated BrIM framework.

3.3 Experimental integration of an LLM via MCP for BrIM parameter updates

This section presents an experimental (prototype) workflow that connects the automated BrIM framework to a LLM through the MCP. As illustrated in Figure 12, an MCP host environment (e.g., a desktop LLM client) acts as the orchestration layer, while local BrIM subsystems—the Excel-based structured input, the intermediate JSON representation, and the IFC generation/adjustment engine—are exposed as callable tools via an MCP server. The server mediates standardized requests for parameter retrieval, modification, and controlled regeneration of affected model components rather than triggering a full rebuild.



	A	B	C	D	E	F
1	Common settings of stiffener for plate girders and box girders					
2	LRU1	INFOR	4.5	4.5	SM400A	200
3		ANG	90	90	90	
4		EXTEND	-5	-5	0	0
5		CORNER	R25	R25		
6		JOINTS	X/LRJ1/X	X/LRJ2/X		
7		JOINTE	X/LRJ1/X	X/LRJ2/X		

Figure 11: Parametric configuration interface for stiffener and diaphragm geometric specifications.

In its current prototype form, the workflow supports limited, parameter-scoped modification scenarios expressed in natural language (e.g., “Add vertical stiffeners to the main girder in span 3”). A mediated sequence is then executed: (i) target parameter fields in the Excel sheets (or their JSON equivalents) are located and edited; (ii) the intermediate JSON layer is updated with consistency checks (component existence, span indexing, attachment compatibility); and (iii) selective geometric regeneration is invoked for the impacted girders, stiffeners, or connection assemblies. The process preserves previously established alignment and semantic relationships while avoiding unnecessary recomputation of unrelated assemblies. CRUD-style operations on certain component classes (stiffeners, splice plates, bolts) are partially implemented; however, broader semantic transformations (e.g., cross-frame system redesign, load-path reconfiguration) remain outside the current prototype scope.

Rather than representing a completed module, this integration is intended as a foundation for incremental, AI-assisted model editing. It lowers the operational barrier for structured BrIM adjustments, but substantial technical challenges must still be addressed before reliable deployment in production design or asset management contexts. Key ongoing and future research tasks include:

- Natural-language intent grounding and disambiguation: User queries often omit explicit span indices, girder identifiers, or component types; resolving synonyms (“web stiffener” vs “vertical stiffener”) and implicit scope requires a controlled vocabulary, ontology mapping, and dialog-based clarification.
- Automation precision and semantic consistency: Local edits (e.g., inserting stiffeners) can cascade into spacing rules, fastener patterns, and diaphragm clearances; a more rigorous dependency graph is needed to ensure that propagated updates do not introduce misalignments or silent semantic drift.
- Large-scale IFC context handling: A fully detailed four-girder plate girder model produces an IFC file approaching 200,000 lines, exceeding practical LLM attention for holistic reasoning. Hierarchical indexing, structured retrieval (component-level views, relationship graphs), and summary caching are required to maintain global coherence across iterative edits.
- Spatial and relational understanding: Current generic language models have limited native grasp of 3D topological relationships (girder–stiffener–connection plate adjacency, coordinate frames, orientation conventions). Fine-tuning or adapter strategies using graph- or scene-structured representations, plus enriched embeddings for spatial keys, are needed to reduce misinterpretation of placement instructions.

Secondary topics (multi-user concurrency, security and access control, integration of condition or inspection data, lifecycle state evolution) are deferred to future phases. Even in its preliminary form, the prototype indicates the feasibility of coupling structured parametric BrIM data with an LLM-mediated editing layer, while making clear that advances in semantic disambiguation, scalable context management, spatial reasoning, and rule-constrained regeneration are essential for reliable deployment.

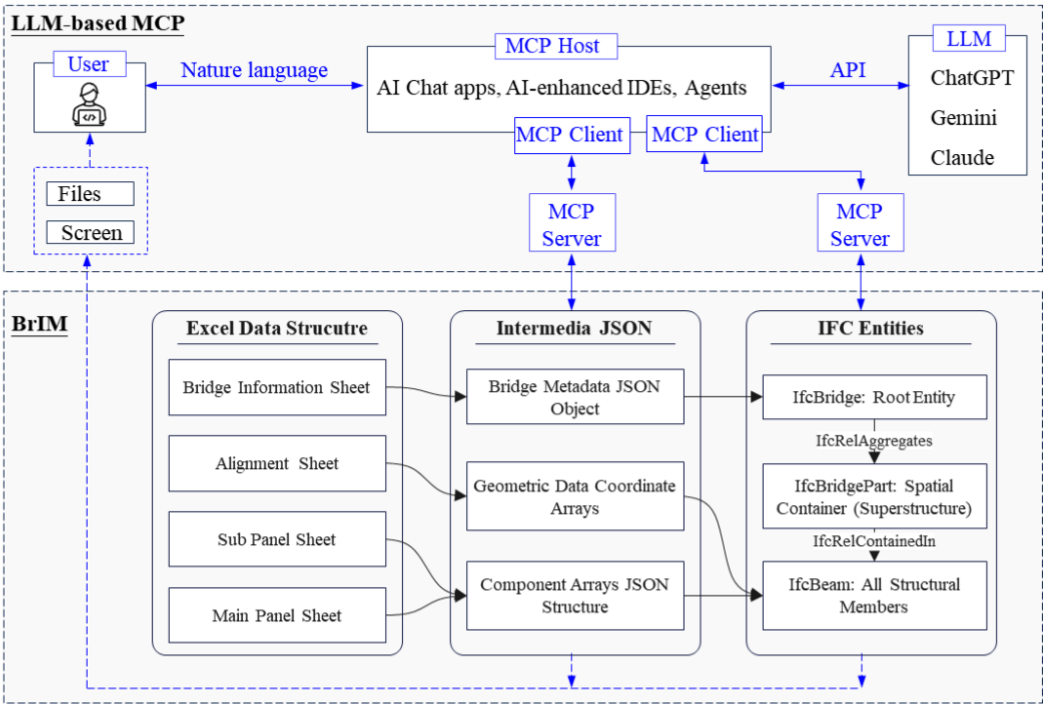


Figure 12: MCP-mediated linkage between BrIM and a large language model.

3.4 Implementation

The automated BrIM generation system demonstrates efficient computational performance across different bridge configurations, with generation times directly correlated to model complexity and component density (Table 4). Comprehensive bridge models including complete geometric and semantic information are generated within seconds on standard high-performance computing platforms, enabling practical integration into routine design workflows. The system exhibits linear scaling characteristics, with 4-girder plate bridge models requiring approximately twice the computational time of 2-girder configurations (10.78 s vs 4.98 s), while box girder models demonstrate comparable efficiency to simple plate girder assemblies despite their increased geometric complexity.

For comparison, manual creation of detailed BIM models for bridges using general-purpose software such as Revit typically requires several hours to multiple days, depending on the complexity of the structure and the experience of the technician (Volk et al., 2014). In contrast, our automated workflow generates a fully detailed IFC4x3-compliant bridge model in under 20 seconds, demonstrating a substantial improvement in modeling efficiency.

Table 4: BrIM generation performance for different bridge configurations.

Type of the girder	Plate girder (2 girder)	Plate girder (4 girder)	Box girder (2 box)
Generation Time (s)	4.98	10.78	5.05

The implemented framework operates within standard software environments requiring Python 3.8+ (Python, 2019) with specialized libraries including IfcOpenShell (IfcOpenShell, 2025) for IFC standard compliance, NumPy (NumPy, 2025) for mathematical operations, and pandas (pandas, 2025) for data processing workflows. System validation was conducted on a high-performance workstation equipped with AMD Ryzen 9 9950X processor (16-core, 4.30 GHz) and 192 GB RAM running Windows 11 Pro, demonstrating reliable performance characteristics suitable for practical engineering applications. The CPU-intensive computational approach ensures broad compatibility with standard engineering workstations without requiring specialized graphics processing units, facilitating widespread adoption across bridge design and construction organizations with existing computing infrastructure.

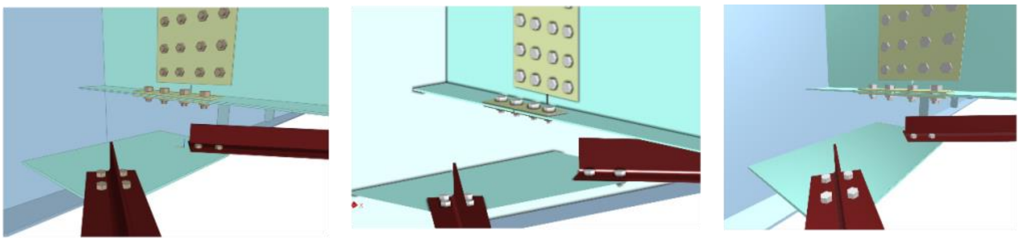
3.5 IFC model compatibility and visualization across software platforms

To evaluate the interoperability of the generated IFC4x3 bridge models, schema conformance validation was first conducted using the ifcopenshell.validate module (IfcOpenShell v0.8.1), followed by cross-platform visualization tests across mainstream software platforms as shown in Figure 13. The plate girder model, comprising 289,000 IFC entities and 6,416 structural members, achieved zero schema violations against the IFC4x3 ADD2 EXPRESS schema across all syntax, attribute cardinality, and type conformance checks, as summarised in Table 5. Visualization platforms were divided into two categories: specialized IFC visualization tools (BIM Vision, Open IFC Viewer, BIMcollab Zoom) (BIM vision, 2025; Open IFC Viewer, 2025; BIMcollab, 2025) and general BIM platforms (Autodesk Viewer, Revit, 2026, Solibri Anywhere (Solibri, 2024)).

Table 5: IFC Schema Validation and Geometry Summary.

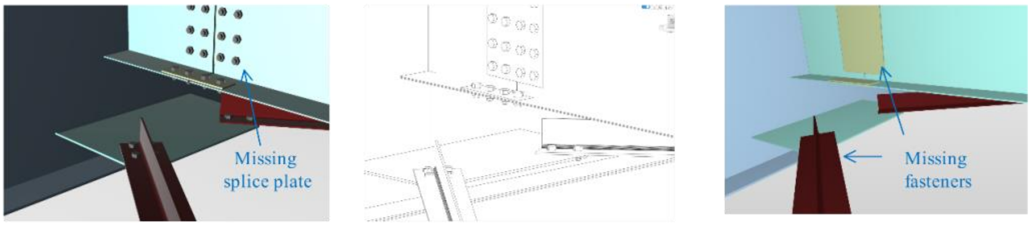
Item	Value
Schema	IFC4X3 ADD2
Total entities	289,000
Structural members (IfcBeam)	6,416
Schema violations	0 (PASS)
Geometry: IfcBooleanResult	5,522 (86.1%)
Geometry: IfcExtrudedAreaSolid	540 (8.4%)
Geometry: IfcFacetedBrep	354 (5.5%)

The specialized IFC visualization tools demonstrated robust compatibility with the exported IFC models. All structural details—including splice plates and fasteners—were rendered accurately and consistently across these viewers, corroborating the schema validation result and confirming that the generated IFC files fully conform to the IFC4x3 standard.



BIM Vision Open IFC Viewer BIMcollab Zoom

a) Specialized IFC Visualization Tools



Autodesk viewer (Web) Revit 2026 Solibri Anywhere

b) General BIM Platforms

Figure 13: Compatibility and visualization across software platforms.

In contrast, the general BIM platforms exhibited certain limitations in IFC data interpretation. While Autodesk Viewer and Revit 2026 successfully displayed the overall geometry, Autodesk Viewer failed to visualize the splice plate, and Solibri Anywhere did not render the fastener entities as shwon in Figure 13. Since schema conformance has been independently verified, these omissions are attributable to software-side rendering scope rather than model defects. Specifically, splice plates incorporate IfcBooleanResult geometry (Boolean difference operations for bolt holes), which requires full B-Rep kernel support unavailable in Autodesk Viewer's lightweight cloud renderer; bolt elements rendered as IfcBeam with small circular cross-sections fall below Solibri's default level-of-detail threshold. These results highlight the varying degrees of IFC geometry support among platforms and underscore the value of independent schema validation when diagnosing cross-platform discrepancies. Overall, the tests confirm that the proposed modeling framework achieves high compatibility with dedicated IFC viewers, while partial feature loss may occur in some general BIM software.

The cross-platform visualization results in this section—where dedicated IFC viewers consistently rendered splice plates and fasteners, while some general BIM platforms omitted certain entities—highlight the practical need for an attribute-preserving, lightweight web pathway for IFC model viewing. As a concrete direction, co-author Okauchi is prototyping a browser-based viewer that converts IFC to glTF while preserving essential identifiers and property sets (e.g., GUIDs and Psets). Although mesh compression and progressive streaming are not yet implemented, the resulting glTF assets already render reliably in modern browsers, including on tablet-class devices such as the iPad, enabling convenient field and review use without desktop licenses or OS dependencies. We do not present implementation details here; rather, we note that a standards-aligned, device-agnostic web viewer that maintains IFC semantics via glTF is a promising means to close the last-mile gap between rich IFC models and everyday consumption in design coordination, inspections, and stakeholder communication.

4. CONCLUSION

This paper introduced an automated workflow that transforms structured bridge design data (Excel) into IFC4x3-compliant BrIMs through an intermediate JSON layer and systematic entity assembly. The framework handles hierarchical component categorization, parametric geometry generation, and validation of connectivity and representation. Two steel typologies—a plate girder bridge (with variable girder counts) and a box girder bridge—were generated with full detailing of stiffeners, diaphragms, bracing, ribs, splice connections, bolts, and studs. Typical end-to-end generation times ranged from about five to eleven seconds on a 16-core workstation, showing predictable scaling with model complexity and comparable efficiency between plate and box configurations.

The resulting models preserve geometric fidelity and semantic richness sufficient as structured input for downstream structural modeling workflows and asset management integration; generation of IFC-native structural analysis entities (IfcStructuralAnalysisModel, IfcStructuralMember) is identified as a future extension, and prospective digital twin linkage. The parameterized data structure also enables rapid configuration changes and provides a clear pathway for coupling with emerging AI methods for design variation, code-related querying, and model auditing.

Current limitations include: restriction to steel superstructures; reliance on clean, fully populated metadata; absence of embedded design code rule checking or structural consistency verification; no exploitation of GPU or parallel acceleration for further runtime reduction; and only conceptual (not yet implemented) linkage to inspection and condition data. Future work will extend to additional structural systems (e.g., composite (Zvierieva et al., 2025), prestressed (Bai et al., 2025), cable-supported (Chen et al., 2025)), implement automated rule and ontology-based validation (Lee et al., 2025; Cerovšek and Omar, 2025), integrate AI-assisted design and checking agents (L. Liu and Y. Liu, 2025; Xu and Guo, 2025), incorporate temporal condition updates for digital twins (Fan et al., 2025; Yang et al., 2025), and benchmark against existing commercial and open-source BrIM authoring tools.

Overall, the framework consolidates data structuring, parametric geometric synthesis, and standards-based IFC assembly into a reproducible process, reducing manual modeling effort and providing a scalable base for next-stage, data-driven and AI-supported bridge engineering workflows.

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DATA AVAILABILITY STATEMENT

The sample Excel input files and IFC4x3 output files for both case studies presented in this paper are publicly available at Zenodo: https://doi.org/10.5281/zenodo.18920226. The source code is not publicly available due to proprietary constraints.

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