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Generative Artificial Intelligence for Structural Design of Tall Buildings

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Abstract The implementation of artificial intelligence (AI) design for tall building structures is an essential solution for addressing critical challenges in the current structural design industry. Generative AI technology is a crucial technical aid because it can acquire knowledge of design principles from multiple sources, such as architectural and structural design data, empirical knowledge, and mechanical principles. This paper presents a set of AI design techniques for building structures based on two types of generative AI: generative adversarial networks and graph neural networks. Specifically, these techniques effectively master the design of vertical and horizontal component layouts as well as the cross-sectional size of components in reinforced concrete shear walls and frame structures of tall buildings. Consequently, these approaches enable the development of high-quality and high-efficiency AI designs for building structures.

Keywords Tall building structures, Generative artificial intelligence (AI), Generative adversarial network (GAN), Graph neural network (GNN)

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1. Introduction

The building structural design industry primarily relies on manual workflows, which results in significant obstacles such as limited design efficiency, low data reuse rates, and over-reliance on the experience of senior engineers. Hence, a more automated and intelligent approach to structural design is urgently required.

Engineers have endeavored to develop efficient, automated, and intelligent computer-aided design methods. Automatic design methods have been primarily investigated based on expert systems and heuristic algorithms (Zhang et al., 2017; Tafraout et al., 2019; Lou et al., 2021; Zhou et al., 2022). However, the automated design methods mentioned above encounter challenges in learning from design data, empirical knowledge, and mechanical principles; they exhibit relatively low optimization efficiency and typically require more than 10 h of processing time. Hence, the intelligence of building structural design must be enhanced by developing efficient and intelligent methods that can learn from available design data to satisfy the efficiency requirements of scheme design and provide more diverse design scheme references.

Deep learning, particularly generative artificial intelligence (AI), has demonstrated remarkable proficiency in acquiring design data features and generating new content, thereby effectively addressing the challenges of structural design data learning and intelligent design generation. Deep learning has become a novel production tool for researchers and fosters new scientific research paradigms (Alibaba DAMO Academy, 2021). In recent years, generative AI has garnered significant attention in research owing to its high content-generation abilities (Alibaba DAMO Academy, 2023).

In this study, AI design technologies developed for building structures that utilize generative AI are proposed. Based on generative AI algorithms such as generative adversarial networks (GANs) and graph neural networks (GNNs), data feature extraction and representation methods are proposed, and AI generation methods that integrate constraints such as architectural design images, design specification texts, mechanics principles, and the corresponding design evaluation methods are developed. These proposed methods facilitate the AI design of vertical and horizontal component layouts, as well as the cross-sectional size of the components in reinforced concrete (RC) shear walls and frame structures of tall buildings.

2. Generative AI-driven design for building structures

Figure 1 shows the generative intelligent design process

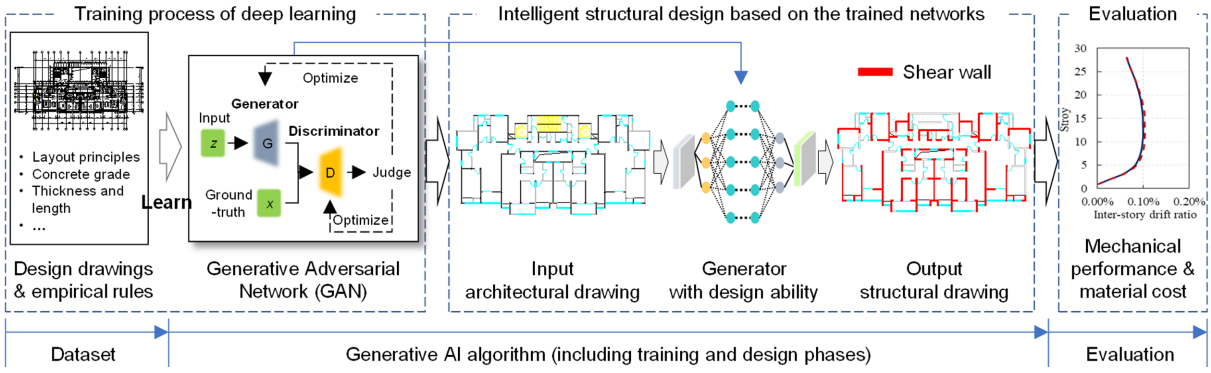


Figure 1. Generative intelligent design for building structures.

of building structures. By leveraging advanced deep learning algorithms, the system can learn from the drawing data of existing structural design data and empirical knowledge, thereby acquiring structural design abilities. The trained deep neural network can subsequently intelligently generate structural designs based on the architectural drawing input (Liao et al., 2021 & 2022 & 2023; Lu et al., 2022; Zhao et al., 2022 & 2023a & 2023b & 2023c; Fei et al., 2022a & 2022b; Pizarro et al., 2021a & 2021b).

The authors developed a series of AI design methods and investigated the extraction and representation of data features, the implementation of AI generation algorithms, and the evaluation methodologies. The result shows that the methodologies investigated effectively facilitated the intelligent design of vertical and horizontal component layouts, cross-sectional sizes of structural components, and isolation bearings in RC shear walls and frame structures of tall buildings.

3. Generative AI-driven layout design of vertical components

3.1. GAN-based shear wall structure design

A design methodology for shear wall structures (referred to as StructGAN, as depicted in Figure 2(a)) is proposed. StructGAN utilizes an image-synthesis GAN to address the challenge of mapping architectural design drawings to structural design drawings (Liao et al., 2021). Additionally, an image-text fusion GAN and its corresponding structural design methodology (referred to as StructGAN-TXT, as depicted in Figure 2(b)) are proposed, which address the issue arising from generating structural designs guided by

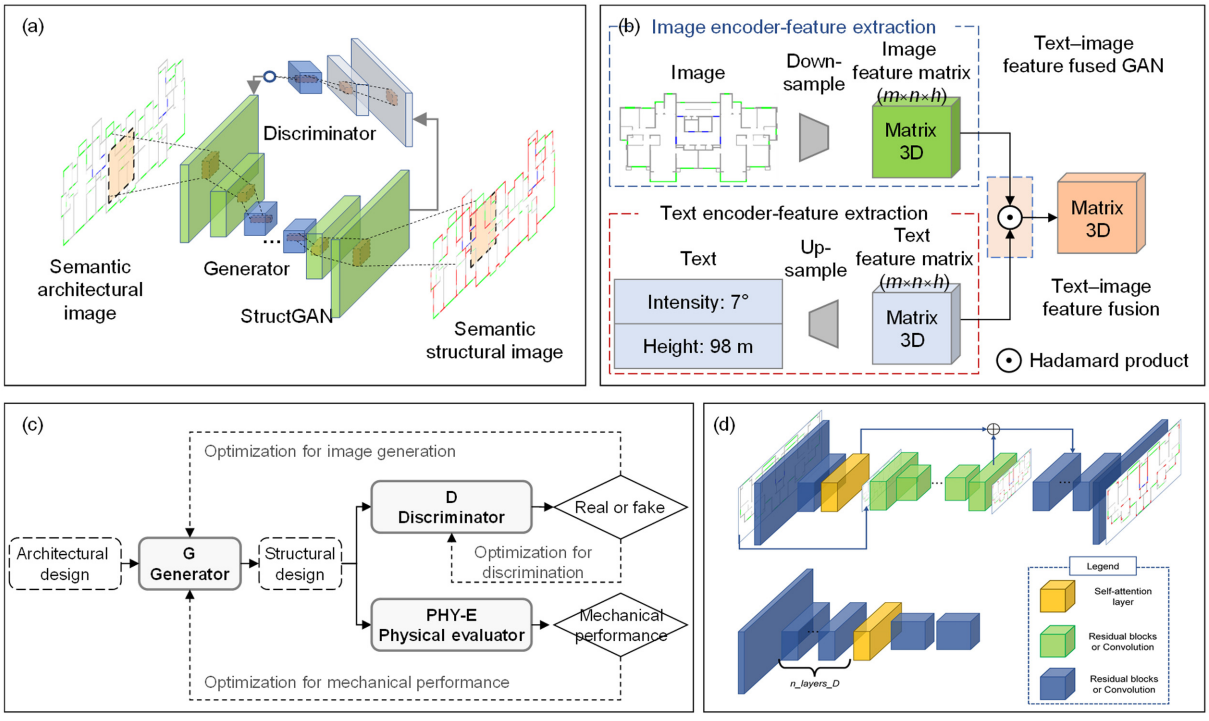


Figure 2. GAN-based intelligent scheme design for shear wall structures. (a) StructGAN; (b) StructGAN-TXT; (c) StructGAN-PHY; (d) StructGAN-AE.

design conditions (Liao et al., 2022). Furthermore, a mechanics-enhanced GAN and its mechanics-data co-training method (referred to as StructGAN-PHY, as depicted in Figure 2(c)) are proposed to address the challenge arising from structural design constraints based on mechanical properties (Lu et al., 2022). Finally, an attention-mechanism-enhanced GAN (referred to as StructGAN-AE, as depicted in Figure 2(d)) is proposed to improve the design details of key areas, such as elevators and balconies in building structures (Zhao et al., 2023a).

3.2. GNN-based shear wall structure design

The use of a graph to represent the design of a shear wall structure offers the advantages of clear topology and seamless integration with subsequent design processes. By representing the shear wall design as graph data features and utilizing a GNN for data learning, one can intelligently generate shear wall structure schemes from architectural schemes. The intelligent design approach for shear wall structures based on graph representation and GNN-based generation is illustrated in Figure 3(a) (Zhao et al., 2023c). In this method, the input graph node represents the component end, and the node features comprise x- and y-coordinates. The input graph edge represents the component, and the edge feature comprises the one-hot code of the component category, the coordinates of two nodes of the edge, and the edge length. After extracting and mapping the features using the GNNs, the output graph edge features become the length features of the shear wall components. In contrast to AI design techniques based on image learning, graph representation and GNN learning exhibit higher effectiveness, yielding results that align closely with engineers' expectations (Zhao et al., 2023c).

4. Generative AI-driven layout design of horizontal components

4.1. GAN-based design for beams of shear wall structure

When designing shear wall structures, one must focus on not only the shear wall components, but also the horizontal beam components. Unlike the design of shear walls, the design of beam layouts should consider both the spatial and structural properties of buildings. Hence, Zhao et al. (2022) proposed a GAN for the coupled learning of building components and spatial layouts, in addition to a corresponding beam component design method. To create the necessary input data, semantic architectural and structural component images, as well as building space attribute images, are generated based on the original shear wall design CAD drawings (Figure 4). Through the coupled learning of these architectural components and space attributes, the GAN can master the ability to convert architectural designs into beam structural designs. Consequently, the trained intelligent design method can generate highly consistent beam component layouts that align with the engineer's design (Figure 4).

4.2. GNN-based beam design of frame structure

The topological characteristics of beam-column components in frame structures are important, which renders the application of image representation-based AI design methods challenging in the layout design of frame beams. To overcome this issue, a novel design method for frame–beam components using a GNN is proposed. In this approach, frame columns and beams are represented as nodes and edges in a graph, respectively. Whether the corresponding features are beams can be determined by predicting the attributes of the nodes and edges (Zhao et al., 2023b). In the graph representation method, where the nodes represent frame columns, the edges denote the connection relationship between columns. The GNN model is trained using this representation method and applied to the frame beam design. The beam design results for a typical complex frame structure are shown in Figure 5. The AI design is highly consistent with the engineer's design, with a consistency rate exceeding 95%.

5. Generative AI-driven cross-sectional size design

A domain knowledge-enhanced GAN, known as Struct GAN-KNWL, and its corresponding design method for the

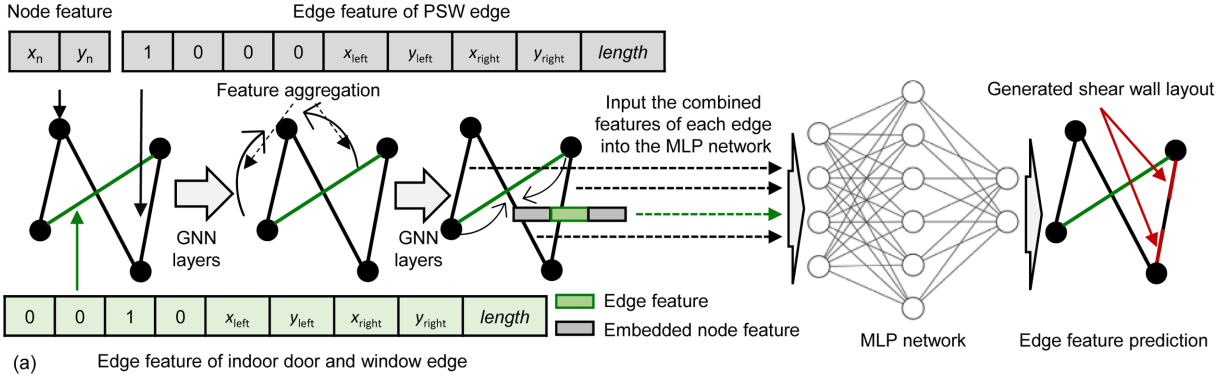


Figure 3. GNN-based intelligent scheme design for shear wall structures.

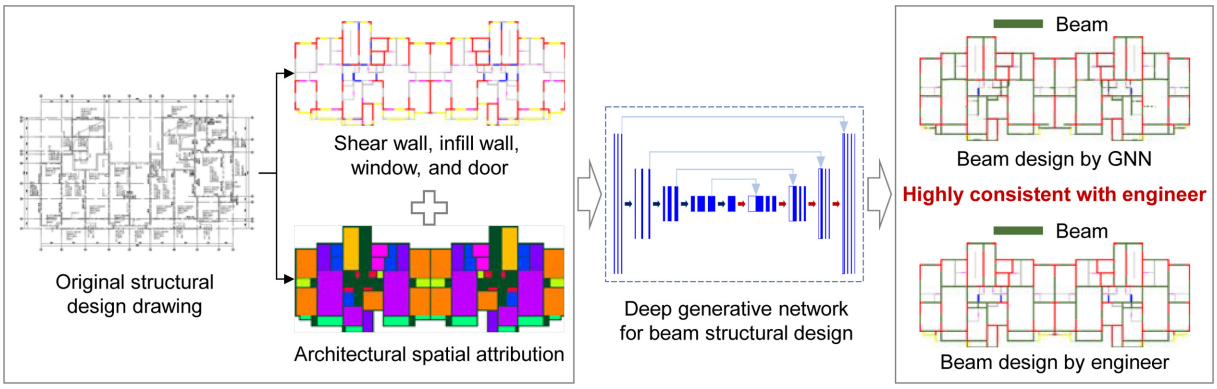


Figure 4. GAN-based beam design of shear wall structure.

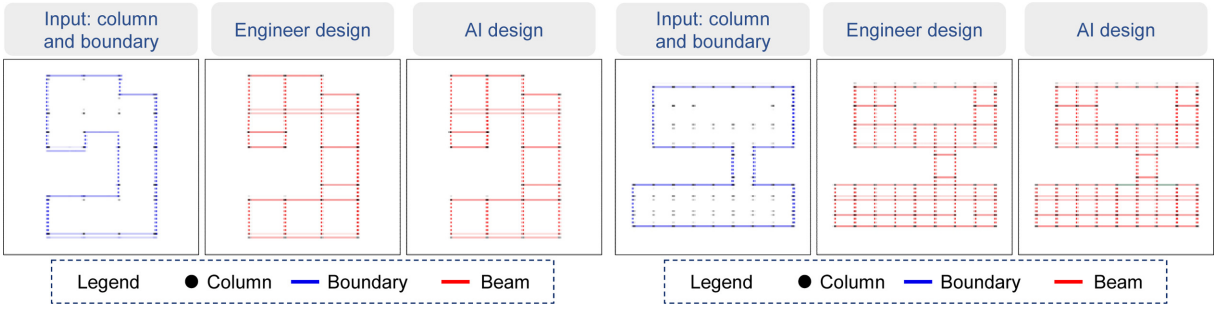


Figure 5. GNN-based intelligent design of frame beam.

cross-sectional size of the frame-core tube structural components are proposed (Fei et al., 2022a, Figure 6(a)). First, StructGAN-KNWL learns the mapping relationship among the component size, overall design conditions, specific component location, and planar size of a structure by analyzing several drawings and design conditions. Moreover, design rules such as component size symmetry, consistent sizes of collinear outer and inner walls, and section size decrease along the height are introduced in the AI learning of the frame-core tube structure design. These rules are expressed as differentiable tensor operators, which ensures the effective learning of design rules. After a comprehensive analysis of design rule-data coupling, the knowledge-enhanced AI design algorithm successfully completes the cross-sectional design of the columns and walls. The design outcomes complied with the relevant design rules (Figure 6(b)) and exhibited a high degree of consistency with the engineers' designs. Moreover, the mechanical properties of the components satisfied the specification requirements (Fei et al., 2022a).

6. Generative AI-driven parametric design of seismic isolation bearings

Acquiring seismic isolation design data is extremely difficult, which renders it challenging to develop data-driven intelligent design methods. Therefore, a self-supervised parameter design method for seismic isolation bearings co-guided by mechanical principles and empirical rules is proposed. After inputting the upper shear wall structure layout, the seismic isolation bearing layout design is automatically generates; subsequently, the trained intelligent design algorithm generates the parameters of the seismic isolation bearings (Liao et al., 2023) based on the

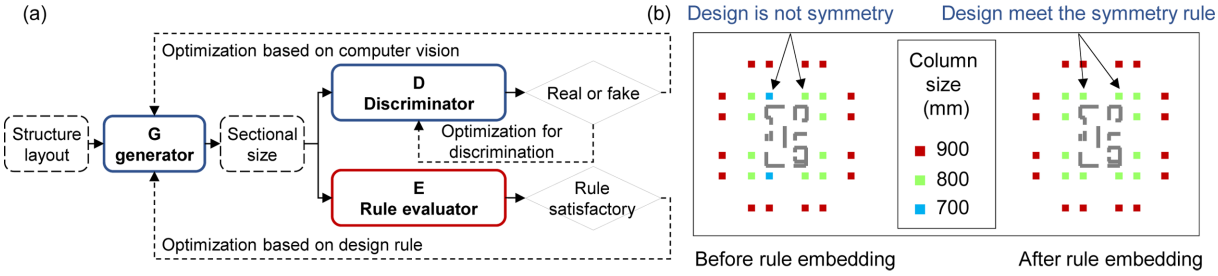
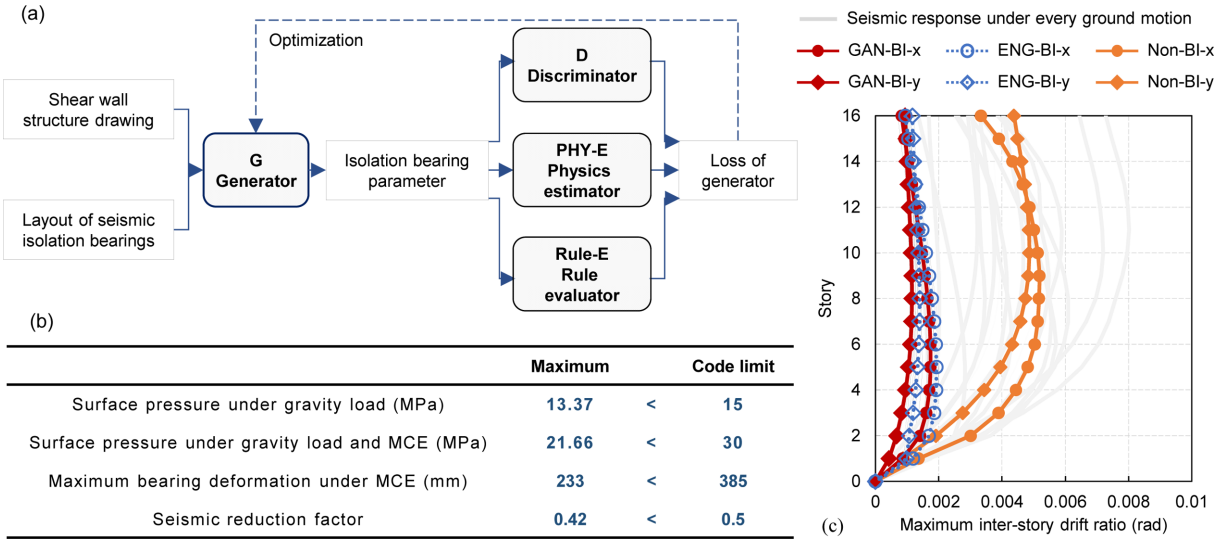


Figure 6. Empirical knowledge-enhanced GAN for cross-sectional size design of structural components. (a) Knowledge-enhanced GAN. (b) Sectional size designs of frame-core tube.



	Maximum		Code limit
Surface pressure under gravity load (MPa)	13.37	<	15
Surface pressure under gravity load and MCE (MPa)	21.66	<	30
Maximum bearing deformation under MCE (mm)	233	<	385
Seismic reduction factor	0.42	<	0.5

Figure 7. Mechanics and rules co-guided GAN for parametric design of seismic isolation bearings. (a) Mechanics and rules co-guided GAN. (b) Mechanical performance satisfying code limit. (c) Seismic response comparison among the designs of GAN, engineer, and non-isolated.

layouts of the shear walls and isolation bearings. As shown in Figure 7(a), the training of the generator is simultaneously guided by the mechanical performance evaluator (i.e., ResNet 18-based surrogate model), empirical rule evaluator (i.e., differentiable tensor operators), and discriminator, thus enabling the intelligent design of seismic isolation bearing parameters without learning from ground-truth data. The analysis of typical seismic isolation design cases shows that the structure designed using this method effectively satisfies the code limit (Figure 7(b)) and that the structural design result is similar to the engineer's design; consequently, the structural dynamic response is reduced and the structural seismic resilience is improved (Figure 7(c)).

7. Conclusions and discussion

The automation and intelligent transformation of building structure design are urgently required to enhance design efficiency and quality. The scheme design capabilities of the vertical, horizontal, and component sizes of shear walls and frame-core tube structures can be effectively learned from existing building structural design data, empirical knowledge, and mechanical principles using generative AI, thus providing favorable technical support for the intelligent transformation of building structural designs.

Whereas generative AI can design building structures, its current capabilities are relatively limited. Significant challenges in terms of data, algorithms, and evaluation methods must be addressed. The number of unconventional structural designs available for training data is limited. AI algorithms struggle to effectively learn complex domain knowledge from small sample sizes, and evaluation methods that rely significantly on domain knowledge are difficult to use for guiding AI learning. Further research is required to address these issues. Therefore, the research and development of relevant technologies must be continued to unlock their full potential.

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