

Research Article**Structural optimization and environmental response analysis of modular buildings based on BIM**Jiaming Zhang^{1,*}¹University of Pennsylvania, Philadelphia 19104, United States***Correspondence:** Jiaming Zhang, jia_m.liverpool@hotmail.com

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Abstract

Despite the benefits of efficiency and fast construction associated with modular steel structures, the structural design of modular buildings is faced with unique challenges concerning the connection properties between modules during different loads. This paper proposes a comprehensive BIM-driven approach integrating multi-objective optimization of the structure and assessment of the multi-physics environmental response to the building, namely a six-story modular steel building in Changsha, China. The parametric design carried out by using Autodesk Revit software, incorporating the attributes of wind, earthquake, and temperature effects, was utilized for analysis purposes. When combined with the finite element analysis via automatic IFC exchange, the NSGA-II algorithm provides a Pareto front consisting of 22 non-dominated solutions between steel usage and lateral stiffness; the adopted balanced solution demonstrates a reduction in the steel mass by 8.2%, compared to the un-optimized one, as well as the improved drift behavior. The environmental impact analysis for the optimized solution under wind loads, seismic excitations, and thermal conditions indicates that although the connection region of modules complies with all international standards, there is an increased wind stress concentration by 20.7%, seismic dynamic magnification of 2.16 at the horizontal module junction, and condensation potential in winter due to the temperature lower than the dew point at the inner surface of the connection junction. These vulnerabilities at the level of the connections, which cannot be detected using standard optimization strategies based on global performance indicators, prove the need to combine optimization with a multiphysics environmental evaluation strategy using a BIM model. Supplementary connection, stiffness-transition, thermo-mechanical, and thermal-bridge checks were added to clarify the robustness and limitations of the reported results.

Keywords

Modular steel building, Building information modeling (BIM), Multi-objective structural optimization, Environmental response analysis, Inter-module connection

1. Introduction

Modular construction, where 3D volumetric modules are constructed in factory settings reducing construction timelines by 25-50% and installed on-site, has been widely studied as an efficient alternative to traditional construction. In modular buildings, the reliability and efficiency of inter-module joints play a critical role because their mechanical properties under lateral loading conditions have yet to be fully investigated; for instance, The moment transfer capability of a new type of self-locking joint has been studied, concluding that joint ductility is dependent on localized deformations(Chen et al.,2021). To solve such problems in connection-dependent systems, design optimization tools that work effectively must be implemented. Parametric design in BIM systems has made it possible to automatically perform optimization of structural designs based on a trade-off analysis of material usage versus global stiffness (Kang et al., 2023). In seismic design research, it has been found that rotational stiffness plays a crucial role in drift distribution and the formation of soft storeys; however, most such research optimizes structural parameters including inter-storey drift ratio and axial compression ratio while neglecting the impact of external loads outside the structure (Wang & Chan, 2023). The wind-induced dynamics of modular steel structures, including stress redistribution at connections in response to changing pressures, have been analyzed using computational fluid dynamics combined with finite element analysis, identifying weaknesses in design criteria focused solely on optimization under static loads (Elsayed et al., 2022). Another issue is associated with the heat resistance of joints between modules, whereby steel fasteners, serving as thermal bridges, can raise local values of the U-factor by 28% to 42%, which will increase condensation probabilities on the internal surfaces during heating periods (Milovanović et al., 2022). Although advancements have been made within all three areas, an integrated approach for conducting structural optimizations and multi-physics evaluations for environmental response in one model based on BIM is still yet to be considered, which leads to missing connection performance issues during final testing phases. In order to fill this research gap, a parametric BIM model for a six-storey modular steel structure for residential use is created in this study followed by an application of a multi-objective optimization algorithm (NSGA-II) coupled with finite element analysis. In addition, performance of the optimized design under wind, earthquake, and thermal loadings is examined in detail.

2. BIM-Based Parametric Modeling of Modular Buildings

2.1. Case description and parametric modeling framework

The present case focuses on analyzing the design of a 6-story, steel frame structure residential building situated in Changsha, Hunan province, China. Each story has eight modular units arranged in a 4×2 grid configuration. These units are of the size 3.0m (width) x 6.0m (length) x 3.0m (height). Hence, each story would cover an area of 144 m² while the whole building has a total area of 864 m². Here, it is noteworthy to point out that the width of 3.0m of the modules falls within the 3.5m transport limit in Chinese freight regulations. Primary structural columns and beams are made from Q355B hot-rolled H sections complying with GB/T 1591-2018 specifications. Their minimum yield strength is 355 MPa, while their minimum tensile strength varies between 470 and 630 MPa. The secondary structural frames are constructed using Q235B grade steel. Composite flooring consists of C30 concrete having thickness of 120 mm applied to profiled steel deck flooring. This construction provides for in-plane action as diaphragms in each module. Connections between modules are established with M20 Grade 10.9 high-strength friction-grip bolts forming semi-rigid joints with a rotational stiffness of 8,500 kNm/rad. All structural and environmental design data are included in Table 1 below.

Table 1

Structural and environmental design parameters of the case-study building

Parameter	Value
Building	6-story modular steel residential, 8 modules/story (4×2), total 864 m ²
Module size	3.0 × 6.0 × 3.0 m (W×L×H)
Steel / slab	Columns & beams Q355B, secondary frames Q235B; C30 slab 120 mm
Inter-module connection	M20 Grade 10.9 friction-grip bolts, 8,500 kN·m/rad
Wind	0.35 kN/m ² , exposure Category B (GB 50009-2012)
Seismic	Intensity VII, PGA 0.10g, Site Class II (GB 50011-2010)
Climate	HSCW zone (GB 50176-2016)

Changsha's selection as the target location sets up the environmental loading scenario of the multi-physics assessment performed in Chapter 4. The base wind pressure on the site is 0.35kN/m² based on ground roughness category B as per GB 50009-2012. The level of seismic defense relates to Intensity VII with a base ground acceleration of 0.10g and Site Class II according to GB 50011-2010. The climatic region belongs to the Hot Summer and Cold Winter (HSCW) category, in accordance with GB 50176-2016. Such specific characteristics like wind load zone, seismic data, and climatic zones are incorporated in the BIM model as project-level shared parameters so that structural and environmental analysis will obtain their loadings from the same source and not from separately entered values into other systems.

The parametric building information modeling tool (BIM) is created using the Autodesk Revit software. All modules in the system are created as individual loadable families that have parametrically defined shapes and material attributes. The columns' sections, beams' depth, slabs' thickness, and connections are revealed as adjustable instance parameters. The modularity process follows a coordination template based on a grid system, ensuring dimensional compatibility among neighboring modules as well as keeping interface tolerance throughout the stories. The grades of materials, sectional sizes, and stiffness of connections represent the key parameters used for multi-objective optimization process as discussed in Section 3.

2.2. Inter-module connection joint modeling

The connection between modules acts as the main pathway through which loads will be transferred from the factory-produced volume modules to one another and will act in controlling the global structural response of the erected structure. Vertical unconstrained inter-modular connections display non-linear moment-rotation relationships that cannot be captured using idealized hinges or rigid assumptions (Bazarchi et al., 2023). According to the current model, the connections have been defined in two types based on their nature and load-carrying role. Vertical connection connects modules from story to story via column-to-column connections. In vertical connection, the cap plate of the lower module is connected to the base plate of the upper module through pre-tensioned M20 bolts. The horizontal connection connects the modules from the adjacent sides within the same level, which is referred to as beam-to-beam connection.

Three categories have been established for the rotational stiffness to consider the structural properties of the joints in question: 5,000 kN m/rad for a nominally pinned condition with minimal moment transfer, 8,500 kN m/rad for the baseline semi-rigid configuration, and 15,000 kN m/rad for a near-rigid condition achievable through welded stiffener plates. These stiffness constants will then be defined as common parameters in the Revit connection family, thus making sure that every joint not only has its geometrical parameters but also has certain mechanical characteristics. Parameterizing the stiffness constant is important because this would enable the optimization routine discussed in Section 3 to consider the rigidity of connections along with other design parameters such as section sizes and brace arrangements.

For the supplementary connection assessment, the reference 8,500 kN·m/rad joint was represented by a three-stage $M-\theta$ relation comprising an initial no-slip branch, a frictional-slip transition, and a post-slip bearing branch. Pretension levels of 100, 155, and 200 kN correspond to initial stiffnesses of 7,300, 8,500, and 9,300 kN·m/rad, respectively.

In order to export the completed BIM model to the FEA program, the BIM model that carries all the properties of geometries, materials, and connections is transferred from the BIM modeling

software to the analysis software by way of Industry Foundation Classes (IFC). Research on data transfer quality between architectural BIM programs and structural analysis tools has found that while IFC-based transfers preserve geometry and material properties accurately, extra property set definitions are needed for connection stiffness (Sibenik & Kovacic, 2020). The current workflow involves adding custom IFC properties to connection elements to ensure that the three-stage parameterization stiffness is not lost after importing the information in the FEM modeler, thereby preserving a seamless digital thread from the BIM modeler to the structural analysis application described in Section 3.

3. Multi-Objective Structural Optimization

3.1. Optimization problem formulation

The structure optimization of the modular building is cast as a two-objective problem aimed at minimizing the total amount of steel used while maximizing the global stiffness of the structural design. The total amount of steel used is measured as the total mass of all the structural elements used in the entire six-story system. On the other hand, the global stiffness of the system is determined from the largest elastic story drift under earthquake loadings and the goal here is to minimize this value. The design variables consist of three types: the section size of the columns and beams, which is determined from the standard H-shaped sections (HW200–HW350 for the columns and HN250–HN400 for the beams), the stiffness of connections between the modules at three distinct levels (5,000, 8,500, and 15,000 kN m/rad, as described in Chapter 2.2), and the type of lateral bracing system among four alternative systems. The constraint functions ensure adherence to Chinese building structure code standards. The elastic story drift ratio should not exceed 1/250 at a frequency earthquake level according to the GB 50011-2010 code, while the maximum value of the axial load ratio for Q355B columns is set to 0.90 in accordance with the GB 50017-2017 standard. The connection strength should meet the specifications laid out in the JGJ 1-2014 guideline for assembled structures. The conflicting considerations of economy and stiffness are optimized using the NSGA-II optimization algorithm, which uses Pareto non-domination sorting to achieve multiple optimal values.

3.2. BIM-FEA coupled optimization workflow

The design optimization process works on the principle of automatic feedback between the BIM platform and FEA software. The parametric Revit model created in Section 2 becomes the main database for generating designs. In the beginning of each cycle, the current values of the design variables are written in the Revit model using Dynamo visual scripting platform, and new section sizes, connection stiffness, and bracing systems are generated. The modified building form is exported to the structural analysis software in the form of an IFC file, wherein linear elastic finite element analysis of

the building structure is performed with respect to the defined gravity, wind, and earthquake loads. The solver will yield the maximum inter-story drift ratio, fundamental frequency, axial compression ratio, and the total mass of steel used in the structure, which in turn is fed to the constraint function evaluation process, and the objective function values are obtained. NSGA-II uses a population size of 100 for 200 generations. The non-dominated solutions are evaluated and archived in each generation to form the Pareto front. Once the process converges, the optimized set of parameters is output into the BIM model, thus closing the digital chain with complete traceability from the optimized design to the performance results.

3.3. Optimization results and comparative analysis

A converged Pareto front, shown in Fig.1 below, consists of 22 nondominated designs which define a convex curve for steel utilization and maximum inter-story drift ratio. The three selected designs were derived from the Pareto front to describe different approaches of designs. Scheme A, which is the economical design on the lower extreme of the front, utilized 40,200 kg of steel material with 1/258 drift ratio. Scheme C lies on the stiff side, with a mass of 50,800 kg and drift ratio 1/406. Scheme B lies in the knee area at the front side, with mass 43,600 kg and drift ratio 1/303. The base scheme lies at the bottom side of the Pareto front at a mass of 47,520 kg and drift ratio 1/292. It is clear that the base scheme lies under the Pareto front in Fig. 1, and therefore it is dominated by the other schemes, which offer better drift ratio for the same or lower mass value. A comparison of structural indicators of all schemes is presented in Table 2.

Figure 1

Pareto front of steel consumption versus maximum inter-story drift ratio

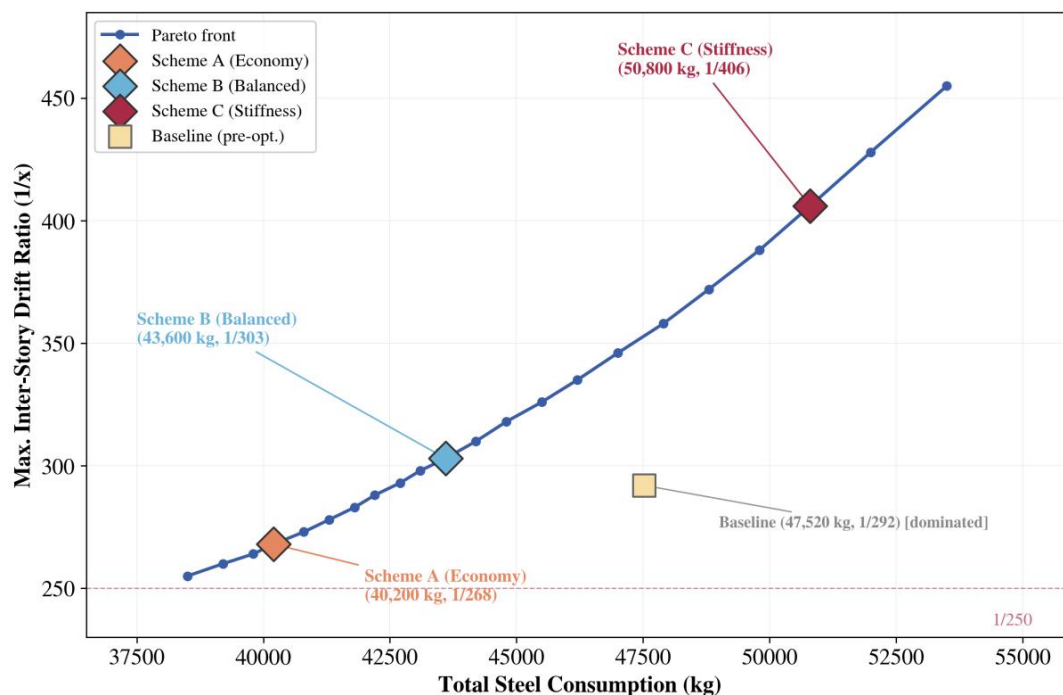


Table 2

Structural performance comparison between baseline and Pareto-optimal schemes

Indicator	Baseline	Scheme A	Scheme B	Scheme C
Total steel consumption (kg)	47,520	40,200	43,600	50,800
Steel variation (%)	-	-15.4	-8.2	+6.9
Max. seismic drift ratio	1/292	1/258	1/303	1/406
Max. wind drift ratio	1/485	1/382	1/452	1/635
Fundamental frequency (Hz)	1.62	1.45	1.78	2.15
Max. axial compression ratio	0.82	0.88	0.75	0.63

Table 2 demonstrates that Scheme B saves steel by 8.2% in comparison to the baseline solution while simultaneously improving the seismic drift ratio from 1/292 to 1/303 and raising the fundamental frequency from 1.62 Hz to 1.78 Hz, respectively. This shows that the material distribution process was optimized for structural efficiency rather than savings on material usage. Scheme A shows how savings of up to 15.4% can be attained; however, the drift factor of 1/258 is close to the code value of 1/250 by 3.2%. Scheme B is chosen as the input scheme for the analysis of environmental effects presented in Section 4, since this scheme offers enough structural margins under all constraint indices.

The stiffness-transition check shows that the drift benefit decreases progressively at higher stiffness, while the local demand indices rise slightly. Therefore, when a theoretical optimum lies between two available grades, the lower grade is selected only if its margin to the 1/250 limit is at least 10% and the connection-demand indices remain acceptable; otherwise, the stiffness is rounded upward.

Table 3

Sensitivity of drift margin and connection demand indices to inter-module rotational stiffness

k (kN·m/rad)	Drift (1/x)	Margin	SCF	DAF
5000	258	3.1%	1.75	2.1
6000	273	8.4%	1.77	2.11
7000	286	12.6%	1.79	2.13
8500	303	17.5%	1.81	2.16
10000	317	21.1%	1.83	2.18
12000	331	24.5%	1.85	2.2
15000	347	28.0%	1.88	2.23

4. Environmental Response Analysis of the Optimized Scheme

Structural optimization performed in Chapter 3 considered overall steel weight utilization and inter-story drift ratios. Scheme B conforms to all requirements specified in codes for the two objectives considered. However, the optimization model considered does not consider the effect of multi-physical environments that can affect modular construction throughout its entire service life. This chapter considers Scheme B from an environmental perspective considering three different types of environmental action – namely, wind forces, seismic forces, and thermal actions. Although these different types of effects operate in very different physical regimes, namely distinct physical domains, aerodynamic pressure, inertia forces, and heat transfer, they all focus on a single point for observation, namely the connection module area. In fact, this point acts as the path for transferring loads from one module to another as well as the thermal insulating gap that is breached by the metallic connectors. Thus, it is the point where the performance variables not considered in the optimization will probably appear.

4.1. Wind load response

The wind loads on Scheme B are calculated according to GB 50009-2012 based on a basic wind pressure of 0.35 kN/m² and wind roughness Category B. The wind pressure is considered a function of height by taking into account the change in wind velocity with respect to height via exposure and gust factors. The corresponding story-level response can be seen in Fig. 2(a). Here the inter-story drift ratio ranges from 1/1667 for the ground floor story to 1/455 for the story on the sixth floor, which suggests increasingly larger lateral deflections with height. Story shears vary inversely, from 165.2 kN at the bottom to 62.5 kN at the top. The floor drift ratios do not exceed the 1/250 code limitation at any height.

But there is another aspect to the stress distribution in the connecting regions which the drift-based optimization criterion cannot capture. Figure 3(a) shows that the SCF of standard column-beam connections increases gradually from 1.50 when subjected to static gravity load to between 1.51 and 1.62 when considering the design wind load. The inter-module horizontal connection on the fifth floor level has a higher SCF value of 1.81 under wind loads than 1.50 for static loads, i.e., an increase of 20.7%. The above-mentioned excessive amplification within the modular junction results from geometric discontinuities and stiffness differences within the bolted junction, which are significant only in cases where wind forces result in bending demands at the junction.

4.2. Seismic response

Time history analysis will be conducted on Scheme B by employing four different recorded time

histories that have been normalized to a peak ground acceleration of 0.10g, which corresponds to an earthquake intensity of VII, which occurs frequently in Changsha area. These records include three natural records of El Centro (1940 NS), Taft (1952), and Wenchuan Wolong (2008) and an artificial record of compatible spectral characteristics. Response analysis of Scheme B and Baseline Case is presented in Table 3.

Table 4

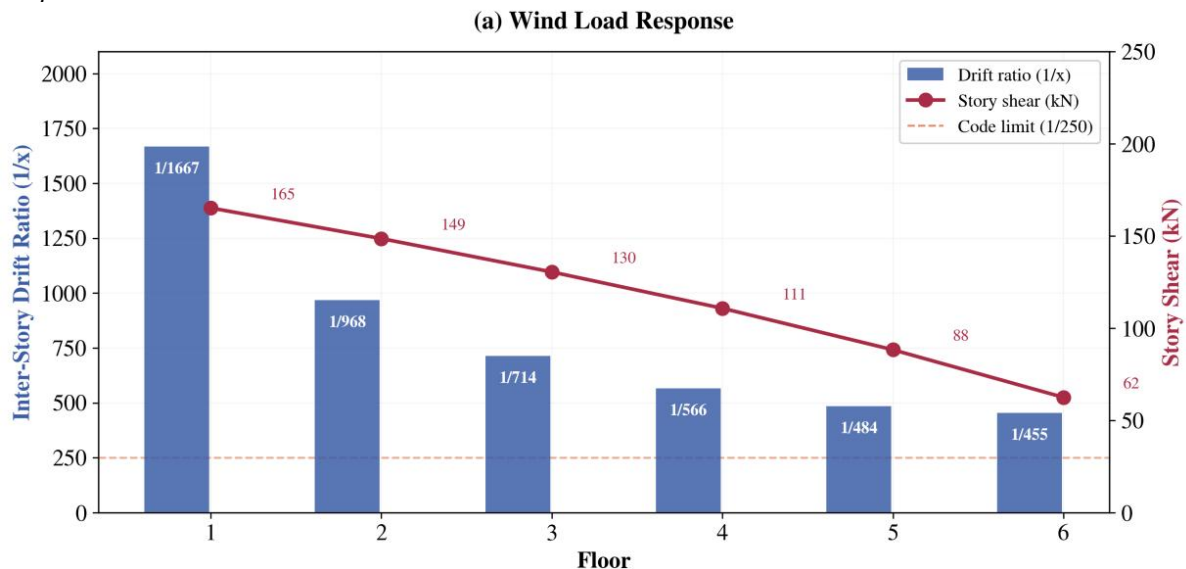
Seismic time-history response comparison between Scheme B and baseline under frequent earthquake (PGA = 0.10g)

Ground motion	Scheme B max. drift	Baseline max. drift	Scheme B max. slip (mm)	Baseline max. slip (mm)
El Centro	1/318	1/296	1.42	1.95
Taft	1/332	1/308	1.28	1.72
Wenchuan	1/305	1/285	1.68	2.35
Artificial	1/298	1/278	1.85	2.58
Average	1/313	1/292	1.56	2.15

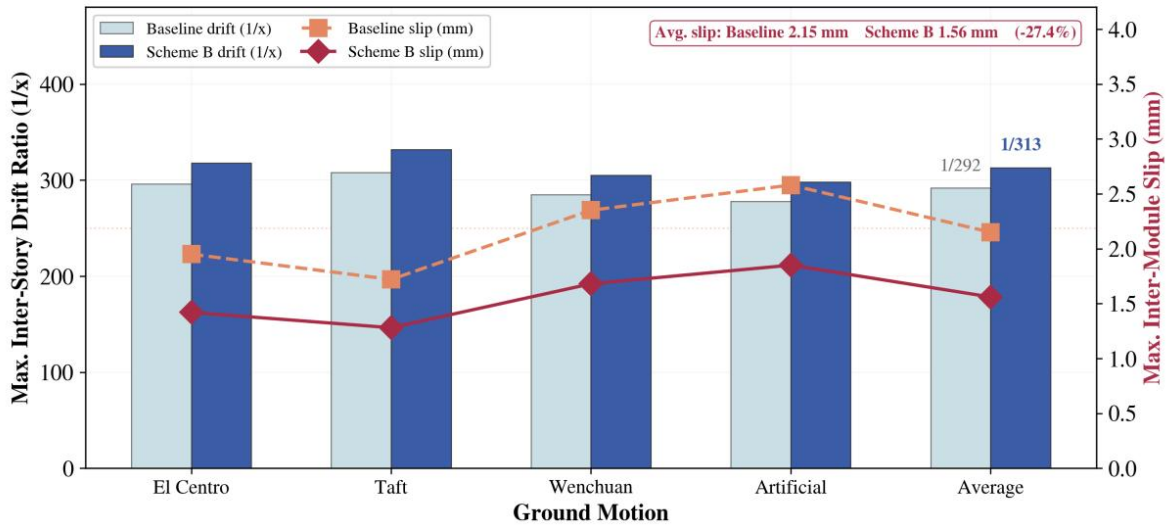
As can be seen in Table 3, the maximum inter-story drift ratio for Scheme B has an average value of 1/313, thus meeting the requirement for elastic drift being less than 1/250 with a generous buffer. Also, the maximum inter-module relative slip reduces from 2.15mm to 1.56 mm in Scheme B, representing a decrease of 27.4%. This clearly demonstrates the fact that, aside from the target variables optimized, the positive impact of optimization on structural performance is not overlooked in this case.

Figure 2

Wind load and seismic response of Scheme B: (a) story-level wind response; (b) seismic response comparison with baseline



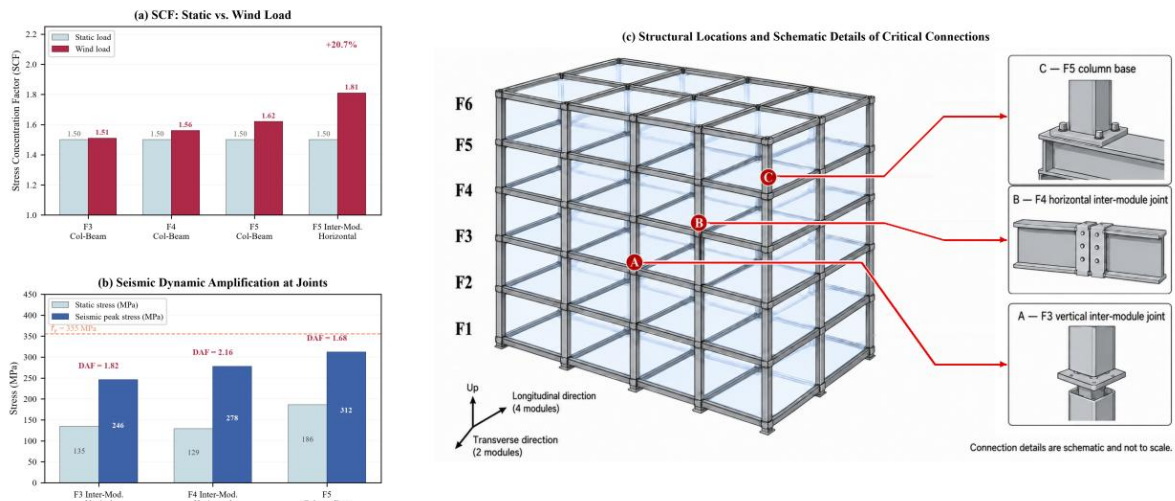
(b) Seismic Response Comparison



It can be seen from the dynamic stress behavior at the inter-module joint shown in Fig.3(b) that for the Wenchuan earthquake record, the dynamic amplification factor (DAF) of the fourth floor inter-module horizontal joint reaches up to 2.16, meaning that the peak value is amplified to greater than twice that under static loading conditions at this point. On the other hand, a relatively smaller DAF of 1.68 is obtained for the fifth floor column base under dynamic loading conditions. This proves that connection zones are prone to higher dynamic stresses than typical joints in a frame structure.

Figure 3

Stress response at connection zones under environmental loading: (a) SCF under static and wind loads; (b) seismic dynamic amplification In panel (b), A denotes the F3 vertical inter-module joint, B the F4 horizontal inter-module joint, and C the F5 column base



4.3. Thermal environmental response

The transient thermal simulations are conducted by EnergyPlus software where the envelope material property and geometry at the joint between modules are used for conducting two-dimensional

thermal conductivity simulation at the connection. Winter (January) and summer (July) design days' simulations are conducted based on meteorological information of Changsha. In the winter season, indoor air temperature is kept at 20°C with 60% relative humidity which corresponds to dew point temperature of 12.0 °C.

The thermal transmittance of the wall panel in the central area is 0.45 W/(m².K). However, the thermal transmittance of the module joint becomes higher by 51.1% and reaches 0.68 W/(m².K) because the steel bolt-and-plate connection causes the module joint to behave as a thermal bridge. Different thermal responses can be observed in the temperature variations of the central area of the panel and the module joint throughout the season. In the winter design day, the outdoor temperature drops to its lowest value of -2.3°C at 06:00. For the present moment, the inner surface temperature for the center region of the panel is 15.2°C, still being much higher than the dew point. As for the inner surface temperature for the region around the module connection, it equals 10.8°C, thus being 1.2°C lower than the dew point. The temperature difference of 4.4°C indicates that the greatest heat losses occur at the region of the connection. During the summer design day, the thermal bridge operates in reverse. The outdoor temperature peaks at 38.5°C at 14:00, and the module joint inner surface reaches 31.6°C compared with 28.2°C at the panel center, yielding a temperature differential of 3.4°C. The elevated joint surface temperature during cooling seasons represents an additional thermal load absent from the panel center region and entirely outside the scope of the structural optimization conducted in Section 3.

A temperature–pretension–stiffness parametric study was performed to evaluate the influence of ambient temperature variations on the connection properties. The results show that the pretension change remains below 0.7 kN across the temperature range from -10°C to 60°C, and the corresponding stiffness variation is less than 0.2% of the nominal 8,500 kN·m/rad. A mesh refinement check for the thermal bridge model shows that the joint U-value changes from 0.691 to 0.680 W/(m².K), i.e. a difference of 1.6%, which is within the adopted 5% engineering tolerance. The thermal-bridge solution is therefore considered mesh-converged.

Table 5

Effect of ambient temperature on bolt pretension, connection stiffness, and dynamic response

T (°C)	ΔP (kN)	k (kN·m/rad)	DAF	Drift (1/x)
-10	-0.455	8490	2.158	303.3
0	-0.303	8493	2.159	303.2
20	0	8500	2.16	303.0
40	0.303	8507	2.161	302.8
60	0.606	8513	2.162	302.6

4.4. Connection nonlinearity verification

The equivalent-linear connection results were compared systematically with the supplementary nonlinear models. For the fifth-floor horizontal connection under wind loading, SCF changes from 1.81 to 1.74, corresponding to a relative difference of 3.9%. For the fourth-floor horizontal connection under the Wenchuan record, DAF changes from 2.16 to 2.03, corresponding to a difference of 6.0%. Both differences are below a conservative 10% engineering screening bound adopted from the range commonly reported for simplified semi-rigid connection idealizations in the cited experimental and numerical literature (Chen et al., 2021; Bazarchi et al., 2023). The linear spring model is therefore retained for global critical-location screening, while bolt slip, contact redistribution, and local plasticity require a detailed nonlinear connection model for final design verification.

5. Discussion

The 8.2% savings in steel, as well as improvement in drift, realized through Scheme B can be evaluated in light of current BIM-optimized research. Material cost savings of up to 15% have been reported for reinforced concrete structures utilizing an automated BIM-NSGA-II optimization pipeline (Sherif et al., 2022), which indicates higher savings due to the higher degree of freedom associated with concrete construction as opposed to steel in the present study. The multi-objective optimization approach used in this study is based on the BIM-algorithm architecture that has been proven effective in the context of energy and thermal comfort optimization research (Hosamo et al., 2022). The ability to effectively apply this approach to the context of structure optimization, resulting in the significant reduction of materials and increase in stiffness, further demonstrates the flexibility of multi-objective optimization with BIM in various applications within buildings. The additional slip reduction achieved by 27.4% without explicitly considering slip in the design optimization process shows once again that there are favorable side effects when using the Pareto-based method to optimize the structure.

These environmental load response analyses in Section 4, however, bring out three key areas of structural performance that were missed by the optimization approach. The three actions (wind, seismic, and thermal) have distinct physical bases but meet at the level of discontinuity in both geometry and material at the modular joint. The stiffening of connections has been recognized as one of the most effective approaches for enhancing the resilience of modular structures against lateral wind forces (Munmulla et al., 2023). However, the current results show that stiffness modification does not necessarily resolve stress concentration in such connections. The intersection of two weaknesses both structurally and thermally from the same interface indicates that while two-objective structural optimization may be efficient globally, it cannot ensure the overall usability of modular constructions. The inclusion of connection-level stresses and energy transmission through the building envelope as

further goals in the optimization process is a must for the future.

The BIM-driven analytical framework developed in the current research incorporates all structure- and environment-related analyses into one information model, thereby ensuring consistency in terms of parameters and avoiding any manual transfer of data between programs. This methodology can be adopted to other modular designs and settings through the adjustment of common parameters available in the Revit model. There are certain limitations of the study which have to be taken into account. Specifically, this research has been conducted on one building only, namely, a six-story modular steel residential building in Changsha. The connections between modules are modeled using simplified rotational springs; the supplementary nonlinear check in Section 4.4 bounds the resulting error below 10%, while the full experimental nonlinearity, including bolt slip and surface deterioration, is left to detailed design verification. Wind, seismic, and thermal actions are analyzed separately; the temperature–pretension–stiffness study in Section 4.3 shows the thermo-mechanical coupling is negligible over the studied range, while stronger coupling under extreme thermal cycling remains future work. The dynamic effects associated with module assembly processes have not been considered.

The framework is transferable provided that climate, height, and connection-specific inputs are re-parameterized rather than copied directly. For other climate zones, the BIM database should replace Changsha wind pressure, seismic hazard, outdoor design temperatures, and humidity conditions with local code and weather-file values. For taller buildings, higher-mode effects, $P-\Delta$ effects, vertical irregularity, and height-dependent wind exposure must be included, and the empirical six-story frequency check is no longer sufficient. For other connection types, the rotational stiffness levels, $M-\theta$ relation, slip resistance, bolt pretension, and local thermal-bridge representation must be recalibrated using connection-specific tests or detailed models. The workflow topology remains applicable, but the numerical thresholds reported for the present six-story bolted modular system should not be transferred without recalibration.

For a global order-of-magnitude check, $T \approx 0.1N$ gives $T \approx 0.60$ s and $f \approx 1.67$ Hz for six stories, differing from the baseline 1.62 Hz by 3.1% and from Scheme B 1.78 Hz by 6.2%. This supports the scale of the modal response, although it is not experimental validation.

6. Conclusion

A novel BIM-based integrated approach was developed and implemented to optimize the structure design and analyze its multi-physics environmental responses for a six-story modular steel residential building. The generated BIM model using Revit, with all of its information, formed the sole data source, wherein all of the environment-specific data such as wind, earthquake, and thermal were stored in it as shared parameters. The NSGA-II-based multi-objective optimization algorithm along

with finite element modeling using IFC based automated data exchange was found to yield 22 Pareto optimal solutions in terms of trade-off between steel utilization and structural lateral stiffness. Scheme B, which is a well-balanced scheme, yielded a 8.2% saving in the amount of steel utilized without compromising on other parameters like maximum seismic drift ratio, which improved from 1/292 to 1/303, and increased fundamental frequency from 1.62 Hz to 1.78 Hz.

An evaluation of the environmental response of the optimized system to wind, earthquake, and thermal loads showed that although the inter-module coupling area was functioning well on a global structural scale, there were certain local weaknesses that could not be addressed by the optimization criterion. The stress concentration coefficient for the wind load acting on the horizontal joint at the fifth floor was 1.81, or 20.7% higher than its static counterpart. Seismic dynamic amplification for the horizontal connection of the fourth floor had a value of 2.16 in case of the Wenchuan ground motion. As far as winter internal surface temperature in the module joint is concerned, it went down to 10.8°C being lower than 12.0°C, the condensation critical point. Taken together, all the above results show that optimization of buildings' structure based on overall performance criteria only is not enough to achieve overall operability of modular buildings.

The supplementary working checks further illustrate the intended design rule: retain at least a 10% drift margin when selecting between discrete stiffness grades, and verify global optimization results using connection-level nonlinear and two-dimensional thermal-bridge models.

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No data availability statement is required.

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