

Risk-informed embodied-carbon compliance of new construction buildings: A probabilistic framework integrating seismic risk and dynamic decarbonization-consistent limits

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ABSTRACT

As the building sector transitions toward deep decarbonization, embodied carbon (EC) is becoming the dominant contributor to life-cycle emissions. Conventional life cycle assessment (LCA), however, typically assumes structural integrity throughout service life, neglecting the additional EC induced by low-probability but high-consequence seismic events. This study proposes a probabilistic framework to evaluate embodied-carbon compliance of new buildings by integrating seismic risk with national decarbonization pathways. Dynamic, planning-period-dependent EC limits are derived by reconciling top-down carbon budgets with bottom-up construction demand. A seismic-risk-informed LCA is then conducted using hazard-consistent nonstationary stochastic ground motions and time-dependent emission factors to ensure temporal consistency with evolving industrial trajectories. The framework is demonstrated through a comparative case study of multi-story steel moment frames (SMF) and steel braced frames (SBF) in China. Results show that although SBF exhibit an increase in initial EC, they reduce extreme post-earthquake reconstruction emissions. By introducing probabilistic compliance metrics, including compliance probability, expected exceedance, and Conditional Value-at-Risk, the study highlights structural resilience as a critical lever for mitigating embodied-carbon exceedance risk. The proposed approach provides a robust decision-support tool for balancing average carbon performance against extreme seismic-driven outcomes in seismically active regions.

1. Introduction

Climate change poses a critical threat to both ecological integrity and human civilization, driven primarily by anthropogenic greenhouse gas emissions [1]. Despite international commitments to limit global warming to well below 2 °C under the Paris Agreement, current mitigation efforts remain insufficient, with projected temperature increases of 2.6–3.1 °C by the end of the century [2,3]. In this context, the building and construction sector has emerged as a key target for mitigation, accounting for approximately 34% of global CO₂ emissions [4]. The sector faces a dual challenge: it must rapidly decarbonize while simultaneously addressing the retrofit of aging infrastructure and meeting new construction demand driven by ongoing urbanization [5].

To operationalize decarbonization, life cycle assessment (LCA) has

become the principal framework for quantifying building-related carbon emissions [6,7]. Within LCA, emissions are commonly divided into operational carbon (OC), arising from energy use during operation, and embodied carbon (EC), associated with material production, construction, maintenance, and end-of-life processes. While policy and regulatory efforts have historically targeted OC, rapid decarbonization of energy systems and the adoption of high-performance building technologies have substantially reduced operational emissions in many regions [8,9]. As a result, embodied carbon—currently limited to mandatory calculation requirements rather than actual restrictions—has emerged as the dominant contributor to life-cycle emissions and a critical bottleneck in the transition toward deep decarbonization [10].

In response, extensive research has explored strategies to quantify and reduce embodied carbon, including sustainable material selection

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[11–14], green construction techniques [15,16], efficient structural systems [17–20], and circular economy principles [21–24]. However, most of these studies rely on a critical yet often implicit assumption: that the structural system remains undamaged and fully functional throughout the building's service life. This assumption neglects the impact of low-probability, high-consequence events, particularly seismic hazards, as noted by Bocchini et al. [25]. Major earthquakes can necessitate extensive repair or complete reconstruction, generating substantial additional embodied carbon from material replacement and construction activities, as observed following the 2011 Great East Japan Earthquake [26] and the 2010/2011 Canterbury Earthquake Sequence [27]. These emissions are typically excluded from conventional LCA, despite their potential to significantly alter life-cycle carbon outcomes in seismically active regions [28,29].

The second-generation performance-based earthquake engineering (PBEE–2) framework provides a probabilistic structure linking seismic hazard, structural response, damage, and consequences, enabling risk-informed decision-making [30]. Widely adopted guidelines, such as FEMA P–58 [31], facilitate the translation of engineering demand parameters into decision-relevant metrics. This framework has been increasingly extended to assess environmental consequences, including earthquake-induced carbon emissions. Recent studies have quantified seismic-related embodied carbon [32–36], incorporated seismic risk into life-cycle carbon assessment [28,37–40], and further expanded these analyses to broader sustainability dimensions [29,41–53]. However, most existing frameworks adopt static material emission factors and rarely account for future decarbonization trajectories, limiting their ability to evaluate long-term carbon performance under evolving policy constraints.

Despite these advances, most existing studies focus on quantifying seismic-related emissions without providing a consistent benchmark against policy-driven decarbonization targets. The absence of explicit embodied carbon limits at the building level creates a fundamental design challenge: minimizing carbon emissions in isolation may conflict with other essential objectives, such as structural safety and resilience [54,55]. While recent studies have begun translating national carbon budgets into building-scale limits—most notably through the dual-bound methodology proposed by Xia et al. [56]—these approaches have not yet been integrated with seismic-risk-informed life-cycle assessment within a probabilistic and decision-oriented framework.

Moreover, seismic-risk-informed life-cycle assessment is subject to substantial uncertainties, arising from both life-cycle parameters (e.g., carbon emission factors) and seismic modeling choices (e.g., ground motion representation) [14,57]. While reliability-based methods have advanced uncertainty treatment in structural engineering [24,58,59], most existing seismic-risk-informed LCA studies address uncertainty primarily within seismic components, treating other life-cycle parameters deterministically. In addition, reliance on limited sets of recorded ground motions may inadequately capture demand variability and introduce selection bias [31]. Nonstationary stochastic ground motion simulation offers a promising alternative for representing realistic temporal-spectral variability [57,60–62], yet its application within seismic-risk-informed embodied carbon assessment remains limited.

Collectively, these limitations indicate that current seismic-risk-informed embodied carbon assessments remain largely descriptive rather than decision-enabling. Without explicit planning-period-dependent carbon limits, probabilistic treatment of both seismic and life-cycle uncertainties, and unbiased characterization of earthquake demand variability, it is difficult to determine whether a structural design can reliably comply with decarbonization pathways under rare but high-consequence seismic events. This gap highlights the need for a unified probabilistic and policy-consistent framework that can support risk-informed embodied carbon compliance evaluation at the building scale.

Motivated by these gaps, this study proposes a comprehensive probabilistic framework for evaluating the life-cycle embodied carbon

performance of new construction buildings under seismic uncertainty. The framework explicitly integrates seismic risk with national decarbonization pathways by establishing dynamic, planning-period-dependent embodied carbon limits that reconcile top-down carbon budgets with bottom-up sectoral demand. A seismic-risk-informed life-cycle assessment is then conducted, in which earthquake-induced repair and reconstruction emissions are evaluated probabilistically and consistently aligned with time-dependent, material-specific emission factors along the decarbonization trajectory. To support risk-informed decision-making, the framework introduces multiple performance-consistent compliance metrics, including compliance probability, expected exceedance, and Conditional Value-at-Risk (CVaR), enabling explicit characterization of both average embodied carbon performance and extreme tail risks driven by rare seismic events. The proposed approach is demonstrated through a comparative case study of alternative steel structural systems, illustrating how structural resilience can serve as a critical lever for mitigating extreme embodied carbon exceedance risk in seismically active regions.

2. Proposed probabilistic framework

The proposed framework evaluates the life-cycle embodied carbon of newly constructed buildings under seismic uncertainty and assesses compliance with planning-period-dependent carbon limits (Fig. 1). It comprises two integrated components.

- The first component (Section 2.1) derives dynamic building-level embodied carbon limits by reconciling top-down national decarbonization targets with bottom-up construction-demand projections. New construction, renovation, and maintenance are treated as concurrent segments of annual construction activities. Then, the embodied carbon limit adopted herein corresponds to the portion of the national decarbonization pathway allocated to new construction.
- The second component (Sections 2.2–2.3) performs a probabilistic, time-dependent LCA that quantifies both conventional embodied carbon and earthquake-induced repair or reconstruction emissions, explicitly incorporating time-dependent, material-specific emission factors aligned with national decarbonization pathways. Uncertainties in life-cycle parameters (e.g., emission factors) and seismic demand are propagated using hazard-consistent ground-motion ensembles generated via nonstationary stochastic simulation (see *Supplementary Note 1*). The resulting distribution of total embodied carbon enables probabilistic compliance evaluation against dynamic carbon limits.

Based on the probabilistic representation of life-cycle embodied carbon emissions, decision-oriented indicators are subsequently defined to evaluate carbon compliance and tail risk under prescribed limits (Section 2.4).

2.1. Derivation of embodied carbon limits for building structures

To ensure consistency with both national decarbonization targets and sector-specific development dynamics, embodied carbon limits for building structures should reflect not only top-down carbon-budget constraints but also bottom-up technological improvement pathways. In rapidly developing contexts such as China, where construction demand, renovation activity, and building-stock evolution vary substantially over time, a purely top-down allocation of the national carbon budget may yield limits that fluctuate with sectoral shares rather than capture genuine decarbonization progress. To address this, Xia et al. [56] introduced a dual-bound formulation that combines a top-down upper bound derived from a grandfathering-based allocation of the national carbon budget with a bottom-up lower bound reflecting projected reductions in embodied carbon intensity. This dual-bound structure is adopted in this study, while the framework remains adaptable to

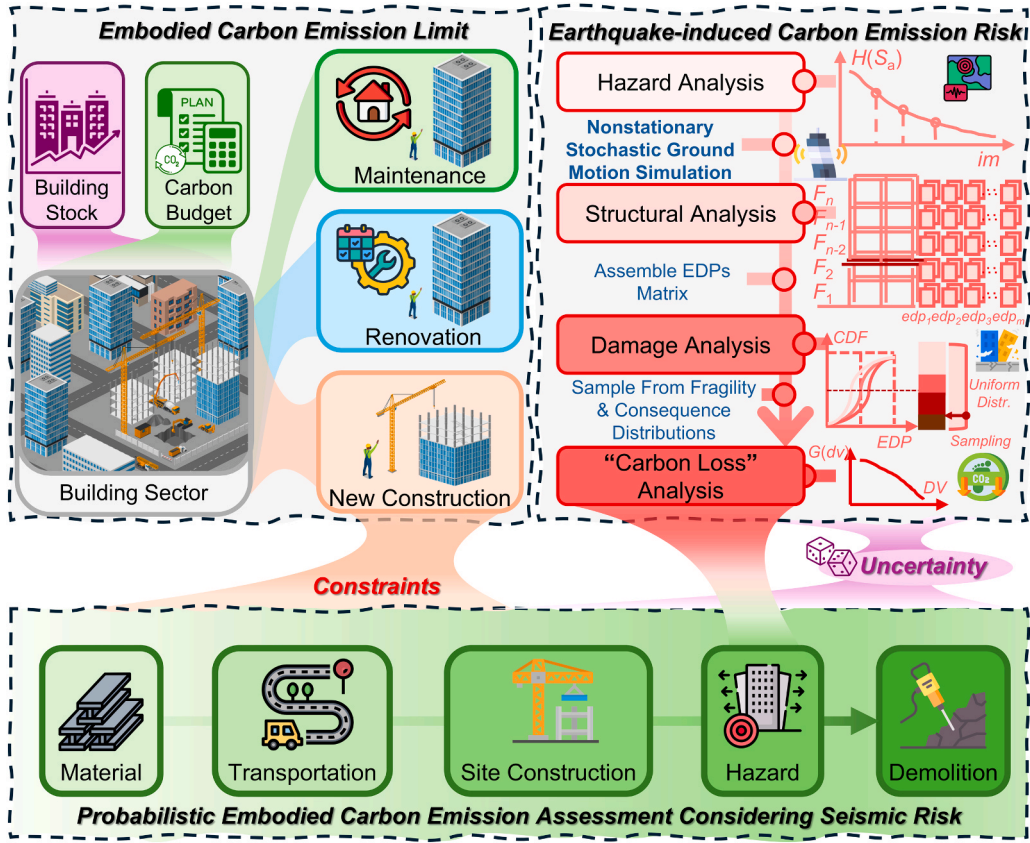


Fig. 1. Schematic of the overall framework.

alternative limit-setting approaches when applied to other regions.

Based on this conceptual structure, the embodied carbon limit for new construction in a given future period i is determined in three steps. The top-down upper bound is obtained by first converting the national carbon budget $C_{N,i}$ into a collective budget for building structures using the status-quo emission share β_b , and then distributing this budget over the required floor-space supply:

$$L_{c,i}^U = \frac{C_{c,i}}{A_i[(1-r_{r,i})r_{n,i} + r_{r,i}r_{n,i}\alpha_{r,i} + \alpha_{m,i}]} \quad (1)$$

where A_i is the cumulative occupied floor area; $r_{r,i}$ is the ratio of planned building floor area of renovation ($\Delta A_{r,i}$) to the incremental space demand (ΔA_i); $r_{n,i}$ then denotes the proportion of ΔA_i of A_i ; $\alpha_{r,i}$, $\alpha_{m,i}$ are the ratios of carbon intensities of renovation and maintenance to new construction. The bottom-up lower bound scales the benchmark carbon intensity for construction $B_{c,i}$, according to the target reduction in national emissions:

$$L_{c,i}^L = \bar{B}_{c,i} \frac{C_{N,i}/N_{y,i}}{C_{NB,i}} \quad (2)$$

where $C_{NB,i}$ is the benchmark year national emissions; $N_{y,i}$ is the number of years for the time interval i . Finally, the regulation-adjusted limit is obtained by interpolating between the two bounds:

$$L_{c,i} = \gamma_L L_{c,i}^U + (1 - \gamma_L) L_{c,i}^L \quad (3)$$

where $\gamma_L \in [0, 1]$ specifies the desired level of regulatory stringency.

2.2. Probabilistic embodied carbon emission assessment considering seismic risk

To account for both conventional construction activities and seismic

risks, the total embodied carbon of a newly constructed building, denoted as E_{LC} , is quantified as the sum of emissions from five distinct stages: material production (E_{mat} , EN 15978 [63] Modules A1-A3), transportation (E_{trans} , A4), on-site construction (E_{cons} , A5), earthquake-induced damage (E_{haz}), and demolition (E_{dem} , C1-C4). The system boundary follows the Chinese standard GB/T 51366-2019 [64] and is consistent with the modular structure of EN 15978. Use and routine maintenance stages (Modules B1-B5) are intentionally excluded under an activity-based carbon-budget accounting setup, in which building-sector carbon allowances are separated between new construction and future maintenance/renovation activities; accordingly, B1-B5 emissions are accounted for in the latter budget pool rather than attributed to the embodied-carbon allocation for new construction.

Accordingly, the governing equation for total embodied carbon is expressed as:

$$E_{LC} = E_{mat} + E_{trans} + E_{cons} + E_{haz} + E_{dem} \quad (4)$$

The initial embodied carbon E_{mat} represents baseline emissions associated with the production of building components, covering structural and nonstructural systems. It is calculated by aggregating material quantities extracted from the bill of materials with their corresponding carbon emission factors:

$$E_{mat}(t) = \sum_{i=1}^n Q_i \cdot EF_i(t) \quad (5)$$

where Q_i represents the quantity of material type i , and $EF_i(t)$ is its time-dependent emission factor evaluated at calendar year t . To simultaneously represent product-level variability and long-term decarbonization, emission factors are modeled as the product of a stochastic baseline component and a deterministic, material-specific decarbonization pathway:

$$EF_i(t) = EF_{i,0}\phi_i(t) \quad (6)$$

where $EF_{i,0}$ denotes the baseline emission factor at the reference year, treated as a random variable to capture supply-chain and manufacturing uncertainty, and $\phi_i(t)$ represents the decarbonization trajectory normalized to unity at the baseline year. This formulation ensures temporal consistency between embodied carbon accounting and national decarbonization pathways.

While transportation (E_{trans}), construction (E_{cons}), and demolition (E_{dem}) emissions theoretically derive from specific logistics and machinery energy profiles, the preliminary design phase implies inevitable data sparsity. To bridge this gap, these non-material components are modeled as probabilistic coefficients calibrated against historical benchmarks, leveraging the dominance of material production in total emissions. Furthermore, the framework incorporates E_{haz} to quantify the conditional embodied carbon associated with post-seismic repair and replacement actions, which occur at uncertain future times during the service life and are therefore evaluated using the time-dependent formulation described above, as further detailed in Section 2.3. The resulting distribution serves as the basis for defining compliance- and risk-oriented carbon performance indicators, as introduced in Section 2.4.

2.3. Earthquake-induced carbon emission risk

Earthquake-induced embodied carbon arises from repair, replacement, or demolition actions triggered by seismic damage and therefore represents a probabilistic, consequence-level extension of life-cycle carbon accounting. Within the PBEE framework [30], seismic risk is propagated sequentially from hazard to structural response, damage, and carbon-emission consequences. This cascading process can be expressed in the following integral form:

$$\lambda(CE) = \iiint G(CE|DM)dG(DM|EDP)dG(EDP|IM)d\lambda(IM) \quad (7)$$

where IM denotes the ground motion intensity measure; EDP the engineering demand parameter, DM the damage state, and CE the corresponding carbon-emission consequences. The integral is evaluated numerically using Monte Carlo simulation, with each PBEE stage supplying the conditional distribution required by the subsequent stage.

Importantly, earthquake-induced repair or reconstruction occurs at uncertain times during the building's service life. As national decarbonization progresses, the embodied-carbon intensity of materials and construction activities is expected to decrease over time. To maintain temporal consistency between the decarbonization-informed carbon limits (Section 2.1) and the carbon accounting for future seismic recovery actions, the consequence model $G(CE|DM)$ is formulated to be time-dependent through material-specific emission factors (Section 2.2). This time dependence is incorporated using a piecewise temporal discretization of the service life, as described after the PBEE stages below.

The four PBEE stages applied in this study are summarized below:

- 1) **Hazard analysis [$\lambda(IM)$]**: Site-specific seismic hazard is characterized using probabilistic seismic hazard analysis (PSHA). Hazard-consistent ground-motion ensembles are generated to adequately represent demand variability; nonstationary stochastic simulation is adopted to avoid record-selection bias (see *Supplementary Note 1*).
- 2) **Structural analysis [$G(EDP|IM)$]**: Hazard uncertainty is propagated to structural response using nonlinear dynamic analysis. Key response metrics include peak inter-story drift ratio (PIDR), peak floor acceleration (PFA), and component-level deformation measures, following GB/T 38591–2020 [65]. Maximum residual inter-story drift ratio (RIDR) is additionally evaluated to assess post-earthquake reparability [66].

- 3) **Damage analysis [$G(DM|EDP)$]**: Each realization is classified into collapse, irreparable, or repairable states based on global performance thresholds defined by PIDR and RIDR. Collapse or irreparable cases are directly assigned to full replacement, whereas repairable cases are evaluated using component-level fragility functions conditioned on the corresponding EDPs.
- 4) **Carbon-emission consequence analysis [$G(CE|DM)$]**: Damage states are mapped to repair, replacement, or demolition actions to quantify embodied carbon consequences. Monte Carlo sampling across hazard levels and damage realizations yields a probabilistic distribution of earthquake-induced embodied carbon, capturing both expected losses and low-probability, high-consequence tail risks.

Temporal consistency via service-life discretization and Poisson aggregation. The Monte Carlo procedure yields an annual exceedance-rate relationship between carbon-loss thresholds and their occurrence frequencies. To ensure temporal consistency with evolving emission factors, the 50-year building service life T is discretized into k consecutive 5-year segments, consistent with the planning-period intervals used for the dynamic embodied-carbon limits. For each segment i , the midpoint year is defined as the representative year t_i , and time-dependent emission factors $EF_m(t_i)$ are used to recalibrate the damage-to-carbon mapping, resulting in a segment-specific consequence model $G_i(CE|DM)$ and snapshot risk curve $\lambda_i(X)$. Under a piecewise-stationary approximation, exceedance events within each segment are modeled as a Poisson process with a rate $\lambda_i(X)$. The expected number of exceedance events over the service life is given by:

$$\Lambda(X, T) = \sum_{i=1}^k \lambda_i(X) \Delta T_i \quad (8)$$

where ΔT_i is the duration of segment i . The probability that a carbon loss threshold X is exceeded at least once during the service life follows directly from Poisson theory:

$$\Pr(CE > X, T) = 1 - \exp(-\Lambda(X, T)) \quad (9)$$

This life-cycle aggregation provides a transparent and computationally tractable link between time-dependent seismic carbon risk and compliance assessment.

2.4. Compliance- and tail-risk-oriented carbon performance indicators

Once the probabilistic distribution of the total life-cycle embodied carbon emissions EC is obtained by integrating conventional and seismic-induced components, a set of performance indicators is required to evaluate carbon compliance and associated risk under a prescribed carbon limit L . To this end, three complementary indicators are introduced, targeting probability of compliance, expected exceedance severity, and tail-risk behavior, respectively.

(1) **Probability of compliance (P_{comp})**: The probability of compliance quantifies the likelihood that the total embodied carbon emissions do not exceed the prescribed limit L , and is defined as:

$$P_{comp} = \mathbb{P}(EC \leq L) = \int_{-\infty}^L f_{EC}(x) dx \quad (10)$$

where $f_{EC}(\cdot)$ denotes the probability density function of total embodied carbon emissions. This indicator provides a direct measure of the feasibility of meeting carbon constraints.

(2) **Expected exceedance (EE)**: While P_{comp} captures the likelihood of compliance, it does not reflect the magnitude of violation when exceedance occurs. To characterize the overall severity of carbon limit exceedance, the expected exceedance EE is defined as

$$EE = \int_L^{+\infty} (x - L) f_{EC}(x) dx \quad (11)$$

The expected exceedance assigns zero contribution to compliant realizations and aggregates the mean magnitude of exceedance over non-compliant outcomes, thereby capturing the average extent of carbon overrun across the entire distribution.

(3) **Conditional Value-at-Risk (CVaR) of exceedance** [67]: Low-probability, high-consequence events generally dominate extreme carbon exceedance. To explicitly capture such tail behavior, the conditional value-at-risk (CVaR) of carbon exceedance is introduced.

First, the value-at-risk (VaR) at confidence level α is defined as

$$\text{VaR}_\alpha = \inf\{x \in \mathbb{R} : P(EC \leq x) \geq \alpha\} \quad (12)$$

The corresponding CVaR of exceedance is then defined as the conditional expectation of exceedance beyond VaR_α :

$$\text{CVaR}_\alpha = \mathbb{E}[EC - L|EC \geq \text{VaR}_\alpha] \quad (13)$$

This indicator represents the average severity of carbon exceedance within the worst $(1-\alpha)$ fraction of outcomes, and is particularly suited for assessing tail-risk-dominated carbon impacts induced by rare but severe seismic events.

While these metrics are individually informative, decision-making across multiple indicators is inherently nontrivial, particularly when different metrics favor different design options. To facilitate a unified and transparent decision framework, this study further introduces a **Mean-CVaR trade-off** formulation [67,68], which balances average embodied carbon performance against tail risk. The composite objective function is defined as

$$J(\lambda) = (1 - \lambda)\mathbb{E}[EC] + \lambda\text{CVaR}_\alpha(EC), \quad \lambda \in [0, 1] \quad (14)$$

where λ represents a risk-aversion parameter. Specifically, $\lambda = 0$ corresponds to a purely mean-oriented perspective, focusing exclusively on average carbon performance, while $\lambda = 1$ represents an extremely conservative stance that prioritizes against extreme tail outcomes. In engineering decision-making, λ should be interpreted as a stakeholder preference parameter rather than a physical model parameter. Lower values represent a mean-oriented design attitude focused on expected carbon performance, higher values represent a risk-averse attitude prioritizing protection against rare but severe carbon exceedance, and intermediate values reflect a balanced trade-off between the two objectives.

3. Application of the framework

To demonstrate the implementation and effectiveness of the proposed framework, this section presents a case study of typical multi-story steel residential buildings in China. Although the application is contextualized within the Chinese construction and seismic environment, the underlying methodology is general and can be readily adapted to other regions by calibrating region-specific inputs, such as decarbonization pathways, carbon emission databases, and seismic hazard models.

3.1. Embodied carbon limit for urban residential buildings in China

This section derives time-dependent embodied carbon limits $L_{c,i}$ for urban residential buildings (URBs) in China, following the dual-bound methodology introduced in Section 2.1. The derivation relies on projections of the national carbon budget and the evolution of the building stock.

The national carbon budget ($C_{N,i}$) serves as the macro-level constraint for the top-down allocation. Referring to the global carbon budget allocation principles compatible with the 2°C climate target, China's remaining carbon budget C_N for the period 2023–2060 is estimated as 165.112 billion t CO₂ based on its population share [1,56]. To reflect the gradual tightening of emission allowances, the annual national carbon budget is modeled using a cubic decay function, starting

from the present status and decreasing to near-zero by the carbon neutrality target year of 2060. Fig. 2 illustrates this assumed pathway, where the continuous curve is discretized into five-year intervals (e.g., 2026–2030, 2031–2035) to align with China's Five-Year Plan (FYP) policy cycles. These period-averaged budgets serve as the foundational input ($C_{N,i}$) for calculating the collective budget for the building sector.

Complementing the macro-level constraint, the derivation is anchored to the current status of the construction sector using 2022 as the benchmarking year. This involves determining two fundamental bottom-up parameters: the carbon intensity benchmark (B_c) and the status-quo emission share (β_b). Leveraging statistical data from the China Association of Building Energy Efficiency [69] and the dynamic URB stock modeling results from Xia et al. [70], the baseline characteristics are identified. Specifically, in 2022, the newly completed floor space of URBs in China reached 1873 million m², with associated embodied carbon emissions amounting to 756 million tCO₂. This yields a national average embodied carbon intensity benchmark ($\bar{B}_c$) of 403.6 kg CO₂/m². Furthermore, the status-quo emission share (β_b)—defined as the proportion of national emissions attributable to the embodied carbon of URBs—is calculated to be 6.32% [56]. This value is derived by aggregating the emissions from new construction and the maintenance of the existing building stock (estimated with a maintenance carbon intensity coefficient of approximately 0.3% year⁻¹ [56]), and comparing this aggregate against China's total national carbon emissions in 2022 (12,527 million tCO₂) [71].

Using these baseline parameters, time-dependent embodied carbon limits for the period 2026–2060 are projected. Future floor-area demand and renovation ratios are obtained from the dynamic building stock model of Xia et al. [70], which accounts for demographic change and urbanization. Two construction management scenarios are considered to bound potential outcomes: (i) a Business-as-Usual (BAU) scenario, in which historical construction and demolition trends persist, and (ii) a Renovation and Demolition Restriction (RND) scenario, which limits demolition and promotes renovation to substitute new construction demand [56].

Substituting scenario-specific stock parameters into Eqs. (1)–(3) yields the upper and lower bounds of embodied carbon limits for new construction. In the case study, the regulatory stringency parameter was set to $\gamma_L = 0.5$, representing an intermediate regulatory scenario in which the adopted embodied-carbon limit is obtained by equally interpolating between the top-down upper bound and the bottom-up lower bound. This value was adopted as a neutral baseline scenario for demonstrating the proposed framework. Fig. 3 illustrates the resulting trajectories under both scenarios. While the lower bounds are identical, as they are governed solely by national decarbonization rates and are independent of construction volume, the upper bound differs due to differences in building stock dynamics. Under the BAU scenario, sustained high demand for new construction necessitates more stringent per-unit embodied carbon limits to satisfy the fixed national carbon budget. In contrast, the RND scenario reduces overall new construction demand, allowing relatively less restrictive limits for the remaining new projects.

3.2. Investigated buildings

A typical six-story steel residential building is selected as the case study. The hypothetical building is located in Beijing and is classified as Site Class II, corresponding to a shear-wave velocity $v_{s,30}$ ranging from approximately 260–510 m/s. The building represents an ordinary mid-rise residential structure designed in accordance with Chinese seismic provisions for common buildings (Category C with a seismic grade of III). The seismic fortification intensity is 8, with a design basic acceleration of ground motion of 0.20 g, and the design earthquake is assigned to Group 2, corresponding to a characteristic site period (T_g) of 0.40 s [72].

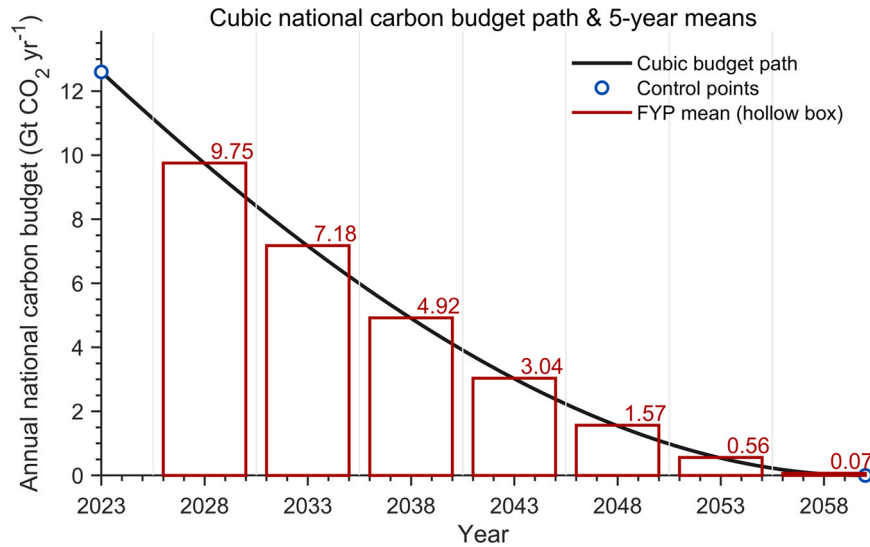


Fig. 2. National carbon budget pathway used to derive building-scale embodied carbon limits.

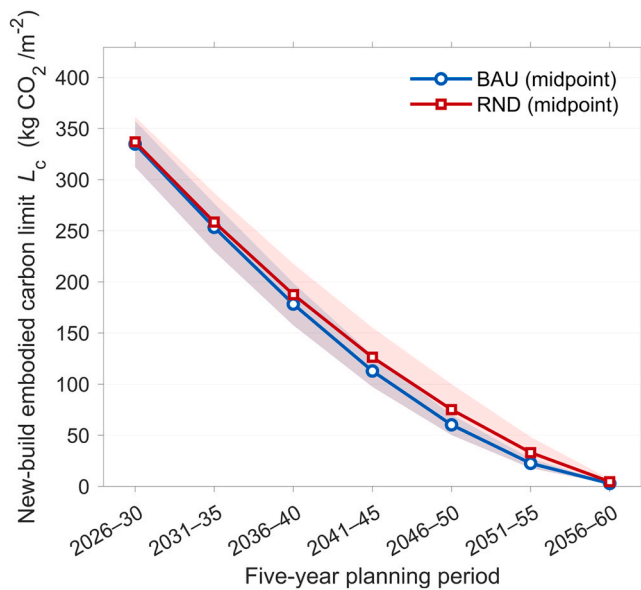


Fig. 3. Embodied carbon limits for new construction.

The building has a regular rectangular plan measuring 27 m × 13.5 m, with uniform column spans of 4.5 m in both directions.

The total structural height is 18 m, with a consistent story height of 3.0 m. The representative dead and live loads are taken as 6.0 kN/m² and 2.0 kN/m², respectively, and all load combinations follow the Chinese code [73]. The primary structural material is Q355 steel with a nominal yield strength of 355 MPa.

Two alternative lateral load-resisting systems are designed and compared using the structural design software YJK [74]: a conventional steel moment frame (SMF) and a steel braced frame (SBF). The SMF system resists lateral forces through rigid beam-column connections, whereas the SBF system is derived by introducing bracing elements at the four corners of the plan layout (Fig. 4), with corresponding reductions in beam and column cross-sections to account for the contribution of the braces. Although the two systems were designed to achieve comparable code-level seismic performance under the same design conditions, identical inter-story drift ratios could not be fully achieved due to the inherently higher lateral stiffness of the SBF system and code-mandated ductility constraints on braced members, such as width-to-thickness ratio limits. As a result, the SBF exhibits inherently higher stiffness than the SMF even when minimum feasible member sizes are adopted. The detailed member sizes for both systems are summarized in Table 1. The fundamental periods of the first three modes are 1.84, 1.74, 1.57 s for the SMF, and 0.93, 0.92, 0.56 s for the SBF, respectively. The building includes no basement levels, and the foundation system consists of isolated trapezoidal footings beneath each column.

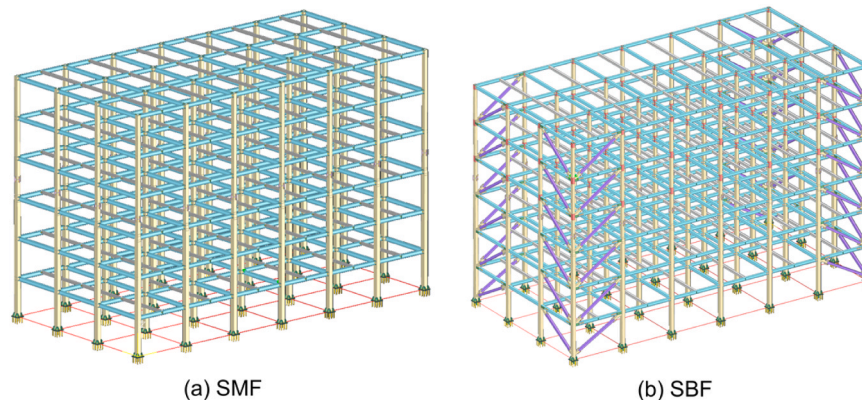


Fig. 4. Illustration of SMF and SBF.

Table 1
Section dimensions of the SMF and SBF models.

Models	Beam	Column	Brace
SMF	H250 × 150 × 6 × 9	Floors 1–3: □300 × 300 × 10 Floors 4–6: □250 × 250 × 10	---
SBF	H250 × 125 × 6 × 9	Floors 1–3: □250 × 250 × 10 Floors 4–6: □200 × 200 × 10	□150 × 150 × 6

Note: H denotes H-shaped section; □ denotes hollow square section.

3.3. Assessment of conventional embodied carbon

In this framework, material-production embodied carbon refers to E_{mat} from Modules A1–A3 only, while conventional embodied carbon (E_{conv}) denotes the baseline embodied carbon excluding earthquake-induced emissions, including material production, transportation, construction, and demolition. Total life-cycle embodied carbon refers to the sum of conventional embodied carbon and earthquake-induced embodied carbon (E_{haz}). Among these, material production (E_{mat}) is the dominant contributor and provides the basis for estimating emissions in subsequent stages.

Following the GB/T 51366–2019 [64], the calculation of E_{mat} covers the structural and nonstructural components. Quantities of structural materials were extracted directly from the bill of quantities generated by the YJK design model. Quantities of nonstructural components (e.g., partition walls, ceilings, and piping systems) were determined based on typical configurations specified in GB/T 38591–2020 [65], ensuring consistency with the subsequent seismic damage analysis. To represent variability in nonstructural component density, three inventory levels corresponding to the 10th, 50th, and 90th percentiles (P10, P50, and P90) were adopted from the supporting data tables associated with GB/T 38591–2020, representing sparse, median, and dense configurations, respectively.

Carbon emission factors for all materials were obtained from national standards [64,75,76], relevant literature [48], and open-access databases [77] (Table 2). As the study investigates a hypothetical building without project-specific supply-chain data (e.g., EPDs from specific manufacturers), emission factors are assumed to vary within a range of $\pm 20\%$ around their respective mean values collected from the literature. This approach enables uncertainty in material-related emissions to be propagated into the baseline assessment results [14]. In practical engineering applications, these parameters should ideally be calibrated using specific data provided by material suppliers to reduce dispersion.

The probabilistic results for embodied carbon from material production are summarized in Fig. 5. Differences between the SMF and SBF systems are observed in the distribution of emissions across structural subsystems. On average, the introduction of bracing in the SBF reduces embodied carbon in the superstructure relative to the SMF, while increasing embodied carbon in the foundation due to higher stiffness demands. The combined effect leads to a slightly higher total conventional embodied carbon for the SBF system than for the SMF system, with a relative increase of 3.58 kg CO₂e/m².

For nonstructural components (NSCs), Fig. 5 indicates pronounced sensitivity of total embodied carbon to component quantity assumptions. As the inventory scenario shifts from the sparse (P10) to the dense (P90) level, the embodied carbon exhibits a marked escalation. This increase is primarily driven by component-intensive elements such as MEP systems. This observation underscores the necessity for decision-makers to explicitly account for the variability in nonstructural quantities during life-cycle assessments. Neglecting this variability could lead to an underestimation of the baseline carbon footprint and, more critically, misinform the subsequent assessment of seismic risks, as a higher

Table 2
The carbon emission factor of considered components.

Type	Component	Amount (SMF)	Amount (SBF)	Carbon factor (kg CO ₂ e per unit)
Steel Structure	Beam	37.07 ton	31.96 ton	2350
	Column	40.53 ton	30.72 ton	2350
	Brace	-	4.93 ton	2350
	Secondary beam	14.71 ton	14.74 ton	2350
	Bolt	2.52 ton	2.91 ton	9470
Slab	Plate	10.92 ton	13.90 ton	2400
	Concrete	218.70 m ³	218.70 m ³	295
	Steel bar	15.80 ton	15.80 ton	2340
Foundation	Concrete	49.50 m ³	106.00 m ³	295
	Steel bar	1.44 ton	3.01 ton	2340
Nonstructural (Amount: P10/P50/P90)	Glass curtain wall	262.44/656.10/1312.20 m ²		254
	Internal partition wall	306.18/524.88/699.84 m ²		87.38
	Partition wall finishes	85.03/166.91/267.69 m ²		9.63
	Suspended lamps	0/0/8.75 EA		7.92
	Hot water pipe	301.81/583.93/1006.02 m		0.71
	Dirty water pipe	87.48/139.97/264.63 m		141.14
	Galvanized steel pipes for HVAC	0/32.81/109.35 EA		19.24
	Branch pipes and air vents	0.17/8.75/17.50 m		72.14
	VAV box	0/0/29.52 EA		384.76
	Fire sprinkler water pipe	437.40/481.14/546.75 m		23.19
	Nozzle Riser	21.87/26.24/30.62 EA		9.56
	Traction elevator	1/1/9 EA		17044
	Water Chillers	0/0/1 EA		16893.9
	Cooling Tower	0/0/1 EA		7433.32
	Air handler	0/0/1 EA		5896.92
	Motor control box	0/0/1 EA		721.98

density of NSCs implies a greater potential for earthquake-induced damage and carbon losses.

To reflect long-term decarbonization targets, material-specific emission factors are modeled as time-dependent rather than static inputs. Steel-based materials follow industry roadmaps distinguishing business-as-usual and Net Zero scenarios [78]; cement-based materials adopt Net Zero-aligned sectoral pathways [79]; and, in the absence of product-specific decarbonization pathways, emission factors for non-structural building components are assumed to evolve in line with the national electricity grid decarbonization pathway as a practical approximation [78,80]. This assumption is mainly intended for electricity-intensive nonstructural components, such as MEP equipment, lighting fixtures, elevators, HVAC components, ducts, pipes, and control boxes, and should be refined in future applications using component- or manufacturer-specific data. The resulting decarbonization pathways for major construction materials and the electricity grid adopted in this study are illustrated in Fig. 6.

Emissions associated with transportation, construction, and demolition are estimated using simplified ratios recommended in the *Building Carbon Emission Calculation Guidelines of Jiangsu Province* [76], reflecting the limited availability of detailed logistics data at the preliminary design stage. Transportation and construction emissions are taken as 2%–6% and 5%–10% of E_{mat} , respectively, while demolition emissions are estimated as 85%–95% of construction emissions. These ratios are treated probabilistically within the specified ranges. Fig. 7 presents the resulting conventional embodied carbon of the two structural systems under different decarbonization scenarios and nonstructural inventory

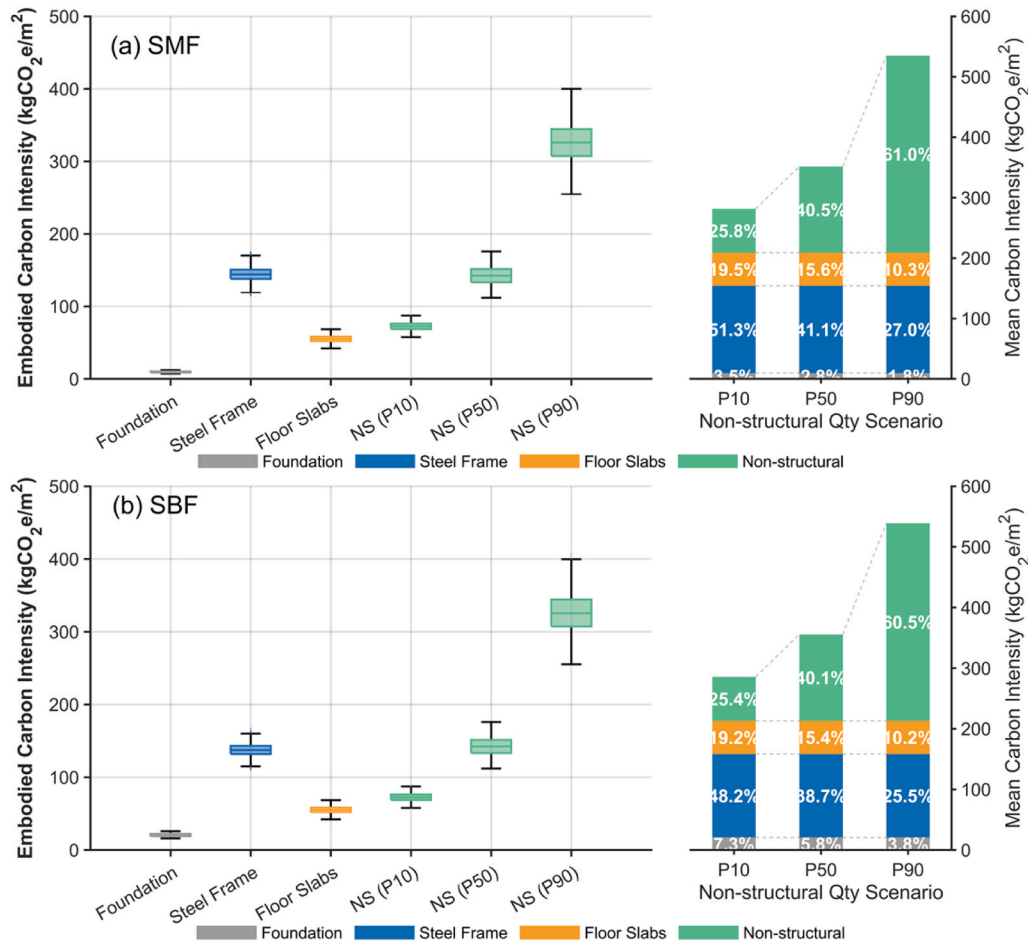


Fig. 5. Probabilistic assessment of material-production embodied carbon (A1-A3) for (a) SMF and (b) SBF systems considering nonstructural component variability.

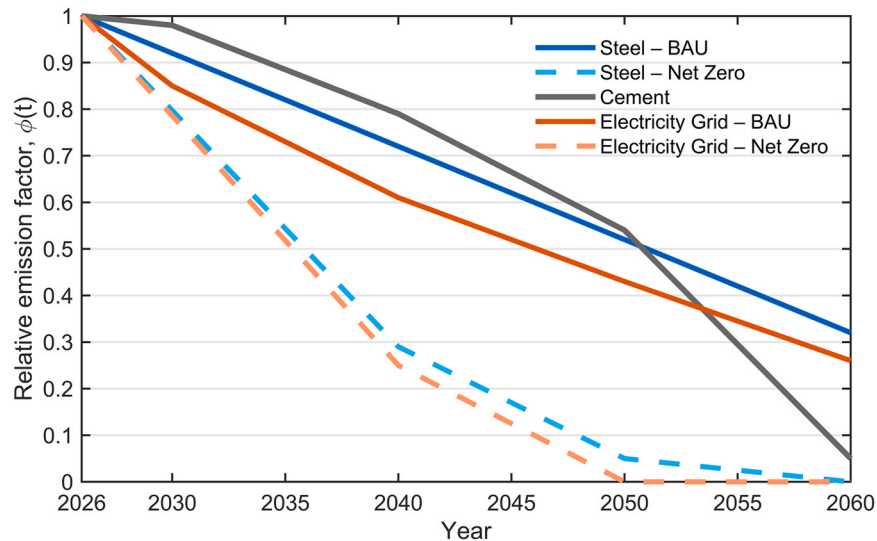


Fig. 6. Decarbonization pathways of construction materials and electricity grid.

levels, excluding earthquake-induced emissions.

3.4. Seismic risk-related carbon emissions

3.4.1. Hazard analysis and stochastic ground motion generation

In accordance with the *Seismic ground motion parameters zonation map*

of China [81], the seismic hazard at the selected site is characterized by four intensity levels: Frequent, Basis, Rare, and Very Rare earthquakes. These levels correspond to 50-year exceedance probabilities of 63%, 10%, 2%, and 0.5%, respectively. Fig. 8 illustrates the target specification spectra associated with these hazard levels. For each level, a suite of 233 ground motions was generated using the nonstationary stochastic

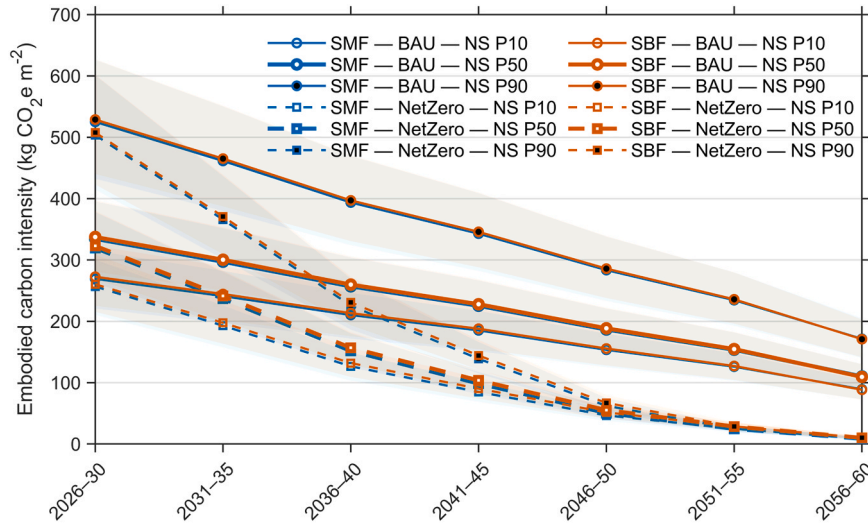


Fig. 7. Conventional embodied carbon excluding earthquake-induced emissions over planning periods.

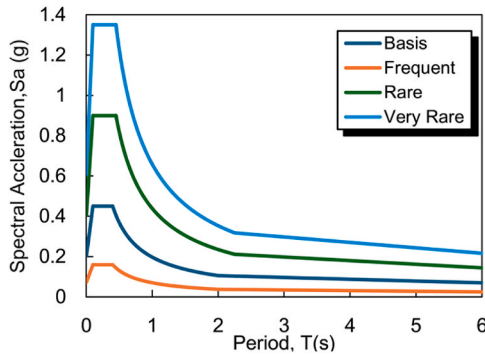


Fig. 8. Specification spectra related to four hazard levels.

simulation procedure described in *Supplementary Note 1*, with model parameters summarized in *Supplementary Table S1*.

The statistical validity of the generated ground motions is demonstrated in Figs. 9 and 10. Fig. 9 presents the statistical characteristics of the generated ensemble, comparing the mean and variance of the synthetic records against the theoretical targets. The close agreement indicates that the simulation algorithm effectively captures the non-stationary features of the design earthquake. Furthermore, Fig. 10 specifically compares the acceleration response spectra of the generated sample set with the target specification spectrum for the Basis earthquake level. As shown in the figure, after three iterations of spectral matching correction, the mean spectrum of the 233 simulated records aligns well with the target code spectrum, ensuring that the input motions are hazard-consistent and suitable for the probabilistic seismic performance assessment.

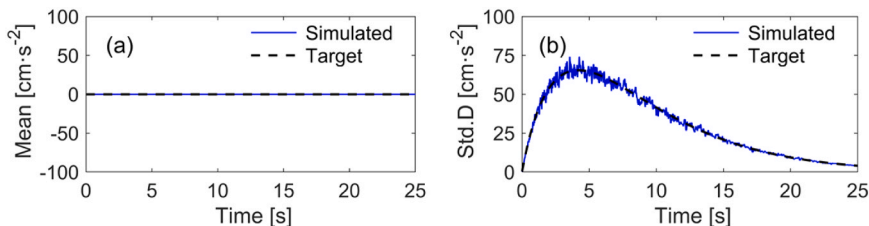


Fig. 9. Comparison of the (a) mean and (b) standard deviation of sample set and target.

3.4.2. Structural analysis

Three-dimensional nonlinear numerical models were developed for both the SMF and SBF systems using the OpenSees platform, following the modeling strategy illustrated in Fig. 11. A hybrid modeling approach was adopted for the frame elements. Beams were simulated using a concentrated plasticity model, consisting of a linear elastic element (*ModElasticBeam3d* [82]) with zero-length rotational springs at both ends, whose hysteretic behavior was represented by the Modified Ibarra-Medina-Krawinkler (IMK) deterioration model [83]. The composite effect of the floor slab on beam behavior was considered by modifying the IMK backbone parameters following Elkady and Lignos [83], including the increased flexural stiffness/strength and asymmetric hysteretic response of composite beams. Columns were modeled using force-based beam-column elements with fiber-discretized cross sections. For the SBF system, steel braces were modeled following Karamanci & Lignos [84], with sufficient member discretization sufficient to capture global buckling behavior. All brace connections were modeled as pinned, and the structure was fixed at the base. Energy dissipation was represented using Rayleigh damping. In accordance with the GB/T 38591-2020 [65], a damping ratio of 4% was assigned to the Frequent and Basis earthquake levels, while a ratio of 5% was adopted for the Rare and Very Rare levels. This distinction reflects the expected increase in equivalent energy dissipation under stronger shaking, where the structure is more likely to experience nonlinear response. Ground motions were applied bi-directionally, with a peak acceleration ratio of 1:0.85 between the principal and orthogonal horizontal directions.

Key EDPs were recorded during the nonlinear dynamic analyses for subsequent damage assessment. At the component level, maximum chord rotations of beams and columns and maximum axial deformations of steel braces were extracted. At the story levels, the PFA and PIDR were monitored to evaluate the state of acceleration-sensitive and drift-sensitive nonstructural components, respectively. Furthermore, to capture the maximum RIDR, a 20 s zero-amplitude extension was appended

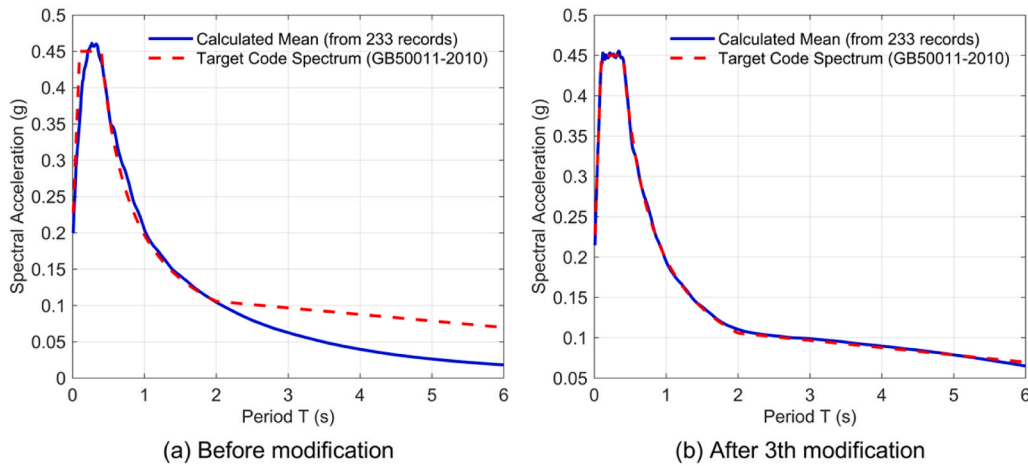


Fig. 10. Acceleration spectra of target and sample sets under basis earthquake level.

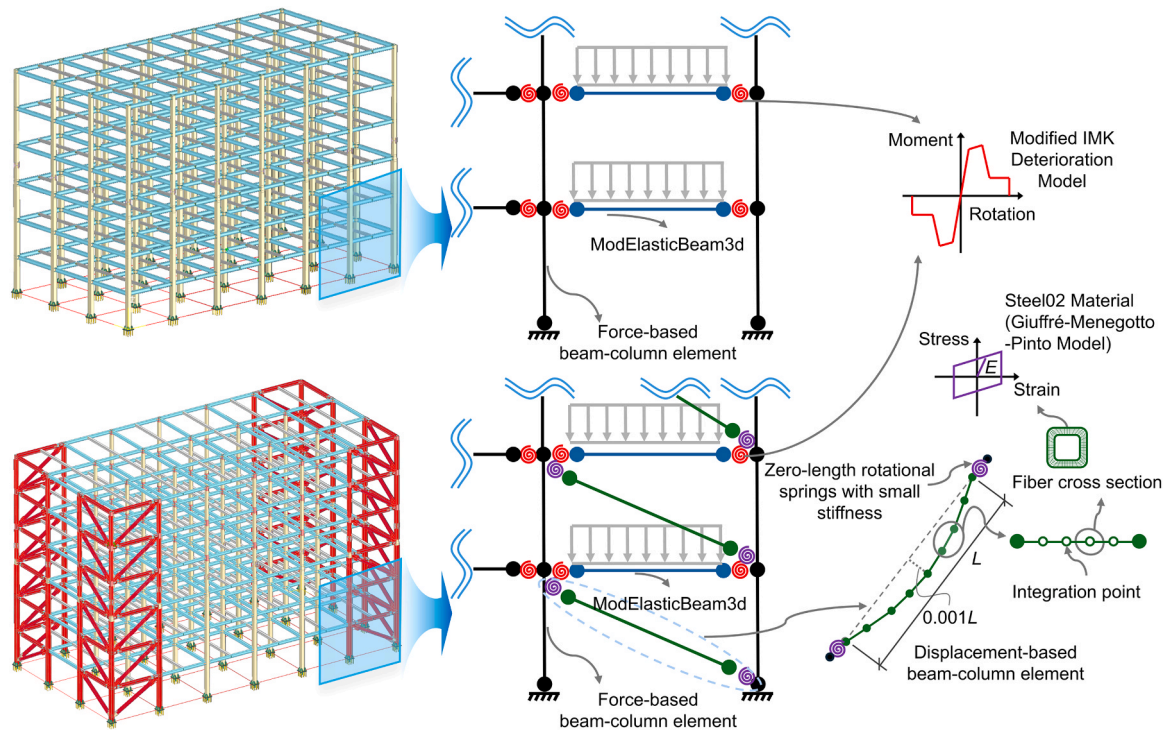


Fig. 11. Schematic illustration of the OpenSees modeling strategy.

to the end of each ground motion record, allowing free vibration decay and stabilization of permanent drifts.

Global failure states were defined based on prevailing performance-based design standards. Structural collapse was identified when PIDR exceeded 4.5%, following the *Standard for Performance-based Seismic Design of Building Structures* [85]. A residual inter-story drift ratio (RIDR) threshold of 0.5% was adopted to delineate irreparability, consistent with GB/T 38591–2020 [65]. It should be noted that these PIDR and RIDR thresholds directly affect the classification of collapse, irreparable, and repairable states, and therefore may influence the estimated seismic-induced carbon emissions and associated tail-risk metrics. Although code-recommended values are adopted here for consistency and reproducibility, the sensitivity of carbon-risk outcomes to alternative damage-state thresholds warrants further investigation.

The statistical results of seismic responses for both systems are visualized in Fig. 12, which compares maximum PIDR values for the

SMF and SBF systems across four seismic intensity levels. For clarity, only repairable realizations are shown explicitly, while collapse and irreparable cases are annotated. The results indicate that the inclusion of steel braces substantially enhances lateral stiffness and stability, leading to reduced collapse and irreparability rates under high-intensity ground motions and, consequently, lower potential for post-earthquake reconstruction-related carbon emissions.

3.4.3. Damage and post-earthquake recovery-related carbon emissions analysis

The probabilistic mapping from EDPs to physical damage states is governed by component-specific fragility functions. Fragility models for primary structural members and typical nonstructural components are adopted from GB/T 38591–2020 [65]. The nonlinear behavior of steel members is represented through simplified backbone relationships defining moment-rotation responses for flexural components and axial

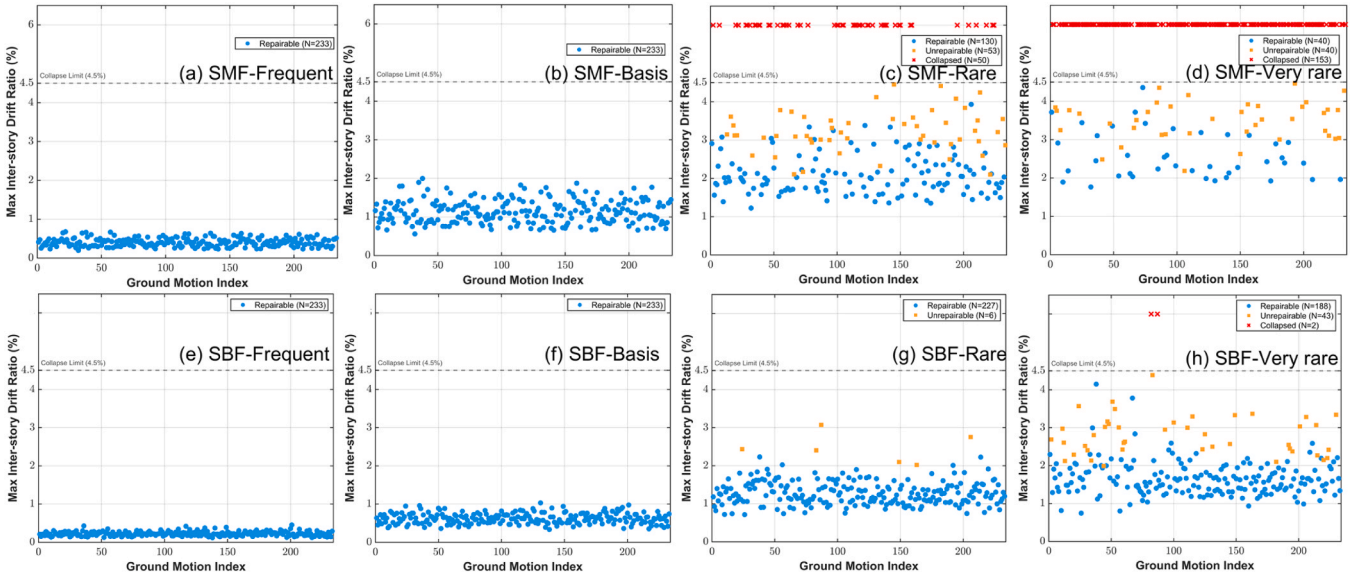


Fig. 12. Scatter statistics of maximum PIDR under different earthquake levels.

force-deformation behavior for braces. Performance thresholds corresponding to yield, peak, and ultimate capacities, as well as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) limit states, are consistently defined. Detailed parameters for fragility and consequence models are provided in [Supplementary Table S2 and S3](#).

In addition to structural and nonstructural components, this study explicitly accounts for building contents, defined as furniture, electronics, and equipment not integral to the structure. Although contents are often excluded from conventional embodied carbon assessments, their replacement following seismic damage represents a direct consequence of structural performance, particularly the ability to limit acceleration demands. Since such site- and structure-specific risks cannot be reasonably internalized in product-level life-cycle assessments, the associated carbon emissions are included within the building-level seismic risk boundary. Owing to limited data on detailed content inventories and damage, the assessment follows the HAZUS [86]. Based on the building attributes, the structure is mapped to the S1M and S2M types [87], and content damage and loss are modeled using the corresponding lognormal distributions. Carbon losses associated with contents are estimated by assuming that the ratio of content embodied carbon to initial building embodied carbon is equivalent to the ratio of content value to building replacement cost in HAZUS, with the maximum content-related carbon loss capped at 50% to account for partial damage, reuse, and post-disaster salvage. This value-based mapping is adopted as a practical approximation because China-specific data linking contents inventory, seismic damage, replacement value, and embodied carbon are currently limited; localized contents inventory and carbon-consequence data should be incorporated in future work.

Carbon emissions associated with repair activities for structural and nonstructural components are quantified using a simplified repair-cost ratio approach [36,48], consistent with GB/T 38591–2020. Repair-related carbon emissions are calculated as the product of initial material production emissions and factors representing damage severity and repair complexity. For collapse or irreparable cases, carbon consequences are assigned as the sum of full building replacement emissions and the maximum content-related carbon loss.

Based on this methodology, probability-of-exceedance curves for earthquake-induced embodied carbon over a 50-year period, assuming no future material decarbonization, are shown in [Fig. 13](#), comparing the SBF and SMF systems across three nonstructural inventory levels (P10, P50, and P90). The results indicate that nonstructural inventory density

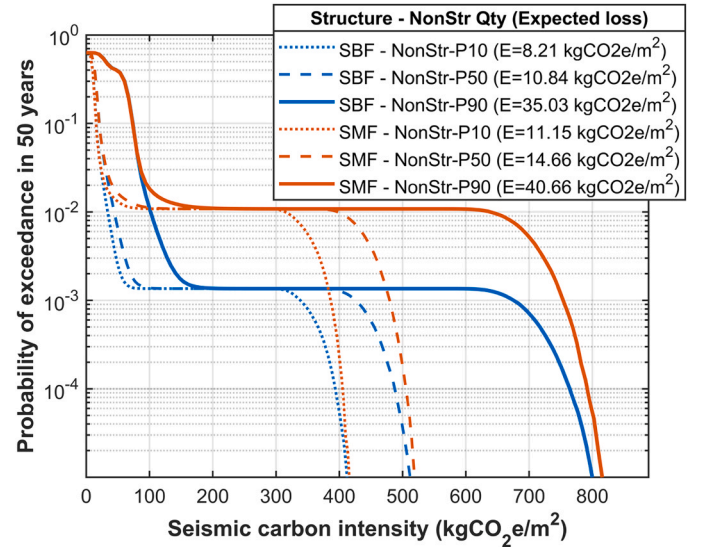


Fig. 13. Exceedance probability curves for seismic-induced carbon without future decarbonization.

strongly influences seismic carbon outcomes, with substantially higher expected losses observed for the P90 scenario. Across all probability levels, the SBF system consistently exhibits lower exceedance probabilities than the SMF system, particularly in the tail region corresponding to low-probability, high-consequence events. This reflects the enhanced seismic performance of braced systems and their effectiveness in reducing extreme carbon losses.

To ensure temporal consistency with national decarbonization pathways, [Fig. 14](#) extends the seismic carbon risk assessment by incorporating time-dependent decarbonization pathways for construction materials and the electricity grid, as described in [Sections 2.2–2.3](#). Relative to the baseline assumption of static emission factors, accounting for future decarbonization results in a substantial reduction in seismic-related carbon risk over service life. Across all nonstructural inventory scenarios, the Net Zero pathway consistently yields lower seismic carbon risk than the BAU pathway. Although the SBF system outperforms the SMF system under both assumptions, the performance gap narrows when future decarbonization is considered, indicating that

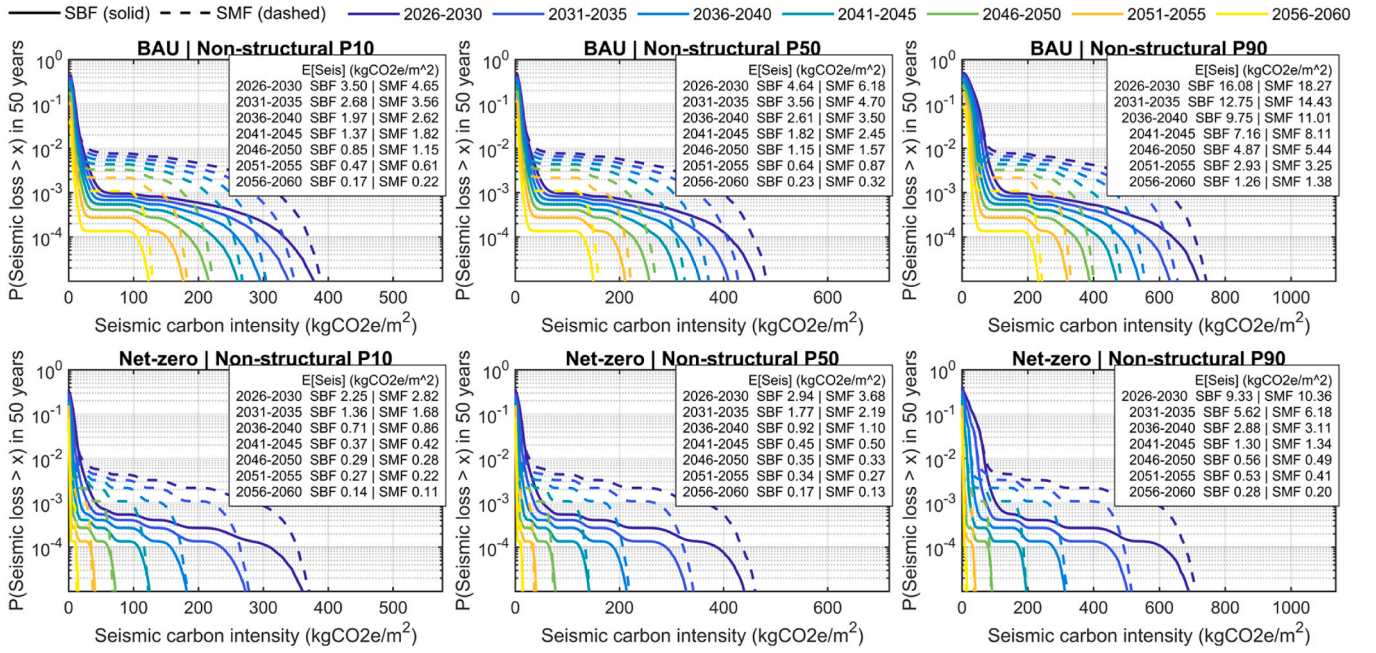


Fig. 14. Exceedance probability curves for seismic carbon emissions across construction periods under time-dependent decarbonization.

the marginal carbon benefit of enhanced structural resilience diminishes as upstream material production and energy systems decarbonize. Fig. 14 further reveals a strong dependence of seismic carbon risk on construction timing: buildings completed in later planning periods experience a shorter exposure to high-carbon seismic recovery, leading to a markedly reduced life-cycle probability of carbon-intensive post-earthquake recovery. These results highlight the importance of coordinating structural design, construction timing, and national decarbonization trajectories.

4. Results and discussion

By probabilistically convolving conventional embodied carbon emissions with hazard-consistent seismic carbon losses, the total life-cycle embodied carbon distributions of the SMF and SBF systems were obtained, as shown in Figs. 15 and 16. When future material decarbonization is not considered (Fig. 15), the SMF system exhibits a slightly lower central tendency than the SBF system, consistent with its lower initial embodied carbon. However, the upper tail of the distribution reveals an opposite trend: the SMF system shows a higher probability of extreme high-carbon outcomes. This behavior is primarily driven by low-probability, high-consequence seismic events, which disproportionately affect systems with lower lateral stiffness and higher collapse

or irreparability risk.

When future decarbonization is incorporated (Fig. 16), seismic risk has limited influence on the mean embodied carbon but substantially expands the upper tail, highlighting its dominant role in extreme carbon outcomes. Using the compliance- and tail-risk-oriented indicators defined in Section 2.4, the probabilistic carbon-limit performance of the two systems is evaluated.

Fig. 17 presents the compliance probability and expected exceedance under the BAU and RND carbon limits. While differences between the two limit scenarios are modest due to their similar magnitudes, compliance probability clearly distinguishes the relative performance of the two systems, favoring the SMF system due to its lower conventional embodied carbon. Future material decarbonization substantially improves compliance probability, whereas high non-structural component-related carbon realizations significantly undermine compliance across all scenarios. In such unfavorable cases, the expected exceedance results suggest that supplementary mitigation measures, such as carbon off-setting or sinks, may be required to compensate for budget overruns.

Fig. 18 isolates the influence of seismic risk on these two indicators. For the present case studies, incorporating seismic risk alters compliance probability by less than approximately 5% and expected exceedance by less than about 20 kg CO₂e/m². In contrast, Fig. 19 demonstrates that tail-risk-sensitive metrics reveal a markedly different performance

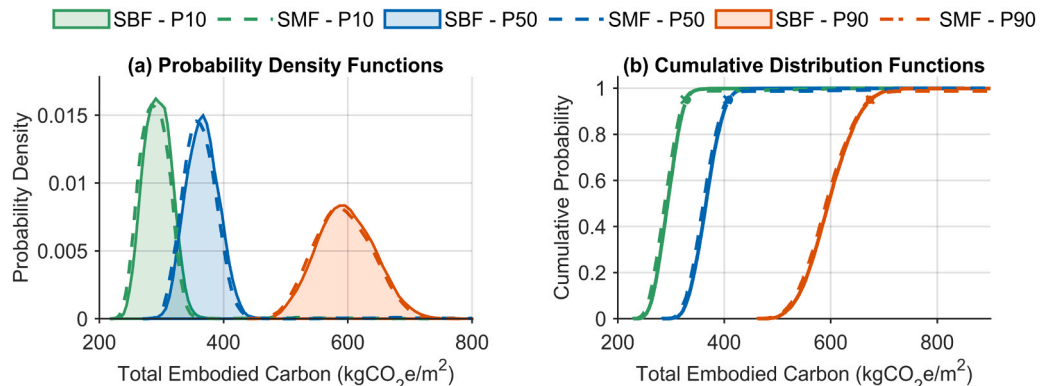


Fig. 15. Comparison of total life-cycle embodied carbon emission probability distributions for two structural systems without future material decarbonization.

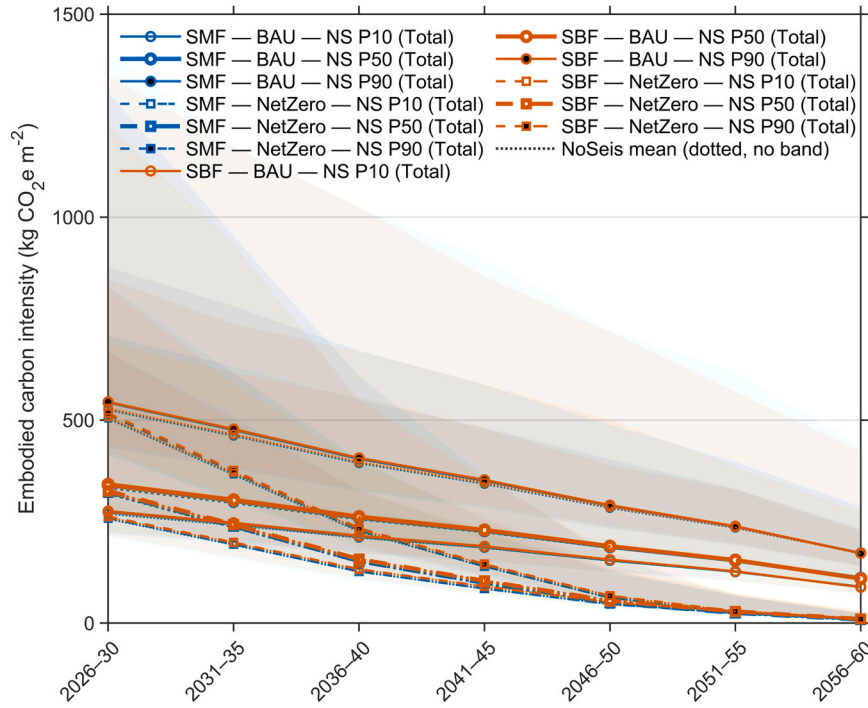


Fig. 16. Evolution of total life-cycle embodied carbon intensity under seismic risk and decarbonization scenarios.

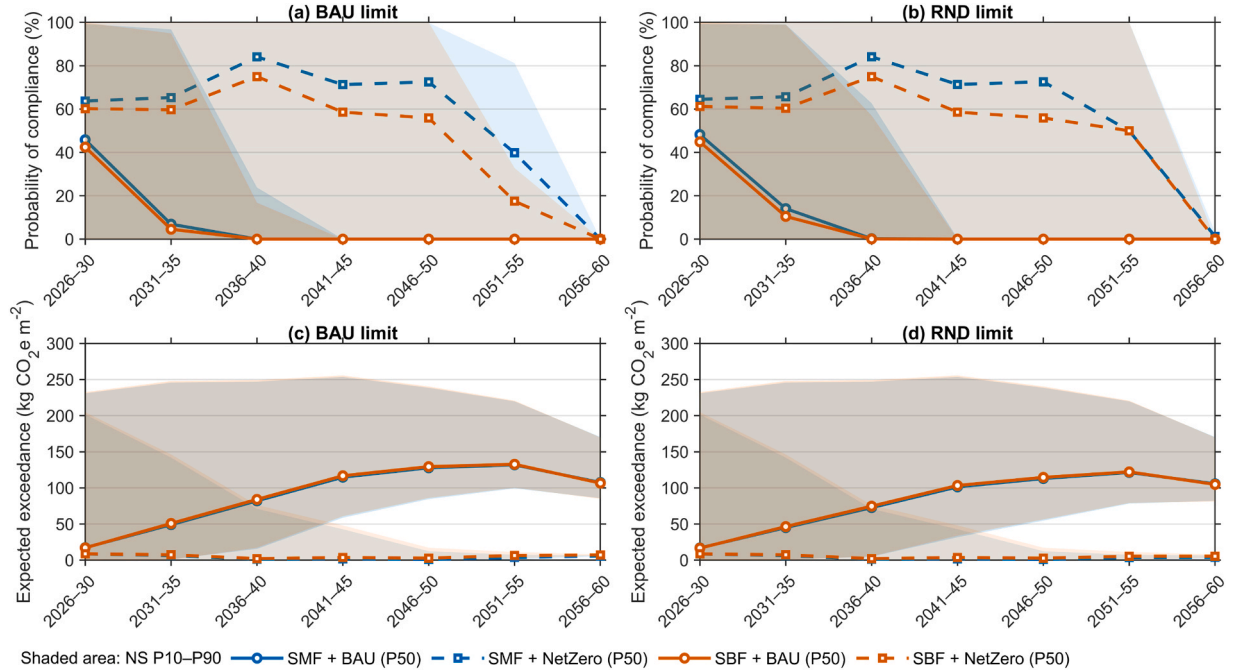


Fig. 17. Compliance probability and expected exceedance under BAU and RND carbon limits.

ranking. Under both $CVaR_{95\%}$ and $CVaR_{99\%}$, the SMF system consistently exhibits inferior performance, with larger dispersion and more severe extreme exceedance outcomes. The amplified performance gap under $CVaR_{99\%}$ further confirms that seismic risk dominates the extreme tail behavior of embodied carbon emissions, particularly for systems with higher vulnerability to rare but severe events.

Finally, Fig. 20 illustrates the implications of these findings for risk-informed decision-making using the Mean-CVaR trade-off method. Under the BAU decarbonization pathway, the SMF system is preferred only when decision-making is primarily driven by mean performance,

whereas increasing emphasis on tail risk progressively favors the SBF system. Under the Net Zero pathway, substantial anticipated reduction in carbon factors diminishes the relative importance of future seismic-related carbon losses, leading to a preference for the SBF system primarily in the earlier planning periods. These results highlight that optimal structural selection depends not only on average carbon performance but also on the decision-maker's tolerance for extreme carbon risks.

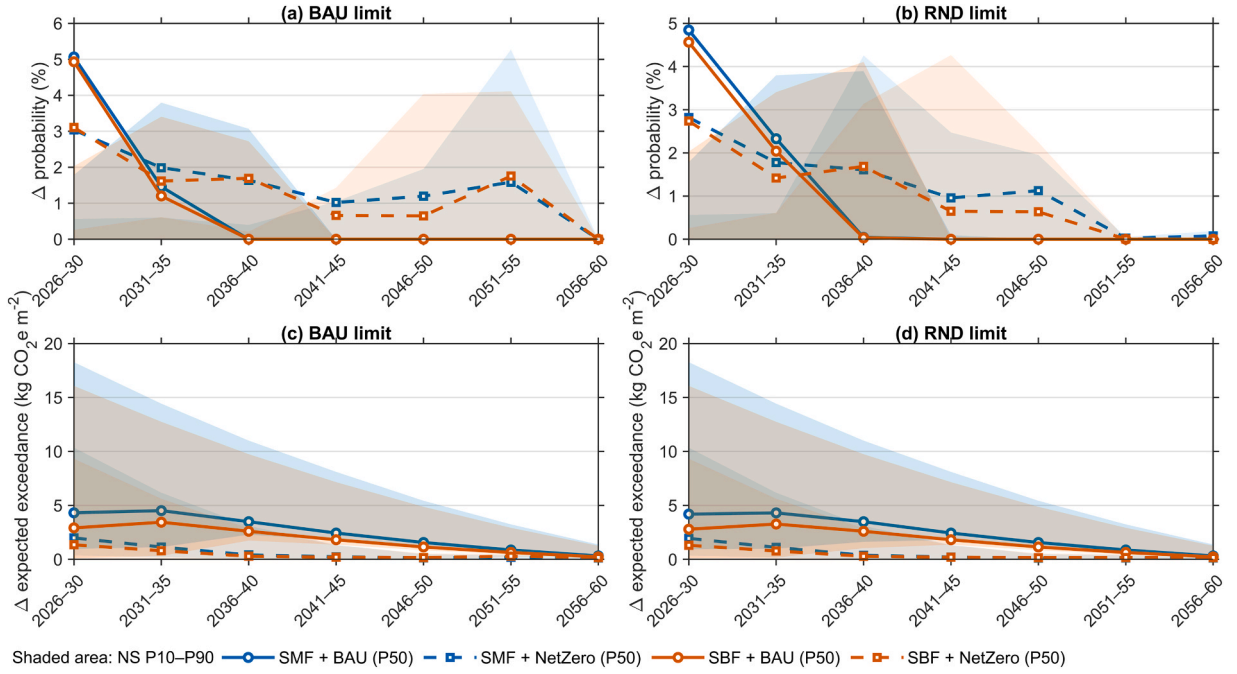


Fig. 18. Impact of seismic risk on compliance probability and expected exceedance.

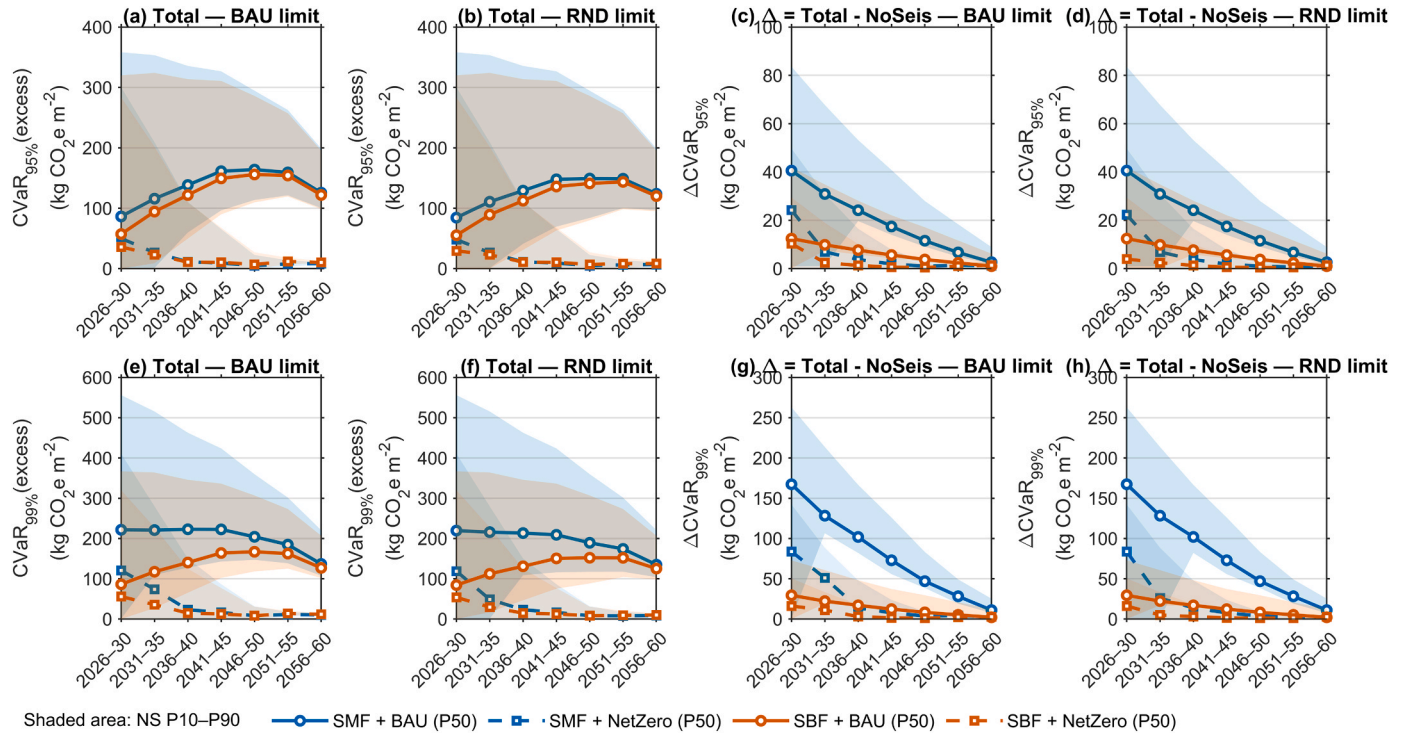


Fig. 19. Tail risk of embodied carbon exceedance quantified by CVaR_{95%} and CVaR_{99%}.

5. Summary and conclusions

This study proposes a probabilistic, seismic-risk-informed framework for auditing the embodied-carbon performance of new construction buildings under national decarbonization constraints. A key contribution is the introduction of dynamic, planning-period-dependent embodied carbon limits at the building level, which translate national decarbonization targets into actionable constraints for structural design and provide a policy-consistent benchmark for evaluating alternative

design solutions.

Building on these limits, a probabilistic embodied-carbon audit framework is developed by integrating life-cycle embodied carbon assessment with the PBEE methodology. Earthquake-induced repair and replacement emissions are quantified probabilistically and combined with conventional embodied carbon sources using time-dependent, material-specific emission factors aligned with national decarbonization pathways. This formulation enables consistent propagation of uncertainties across life-cycle parameters and seismic performance,

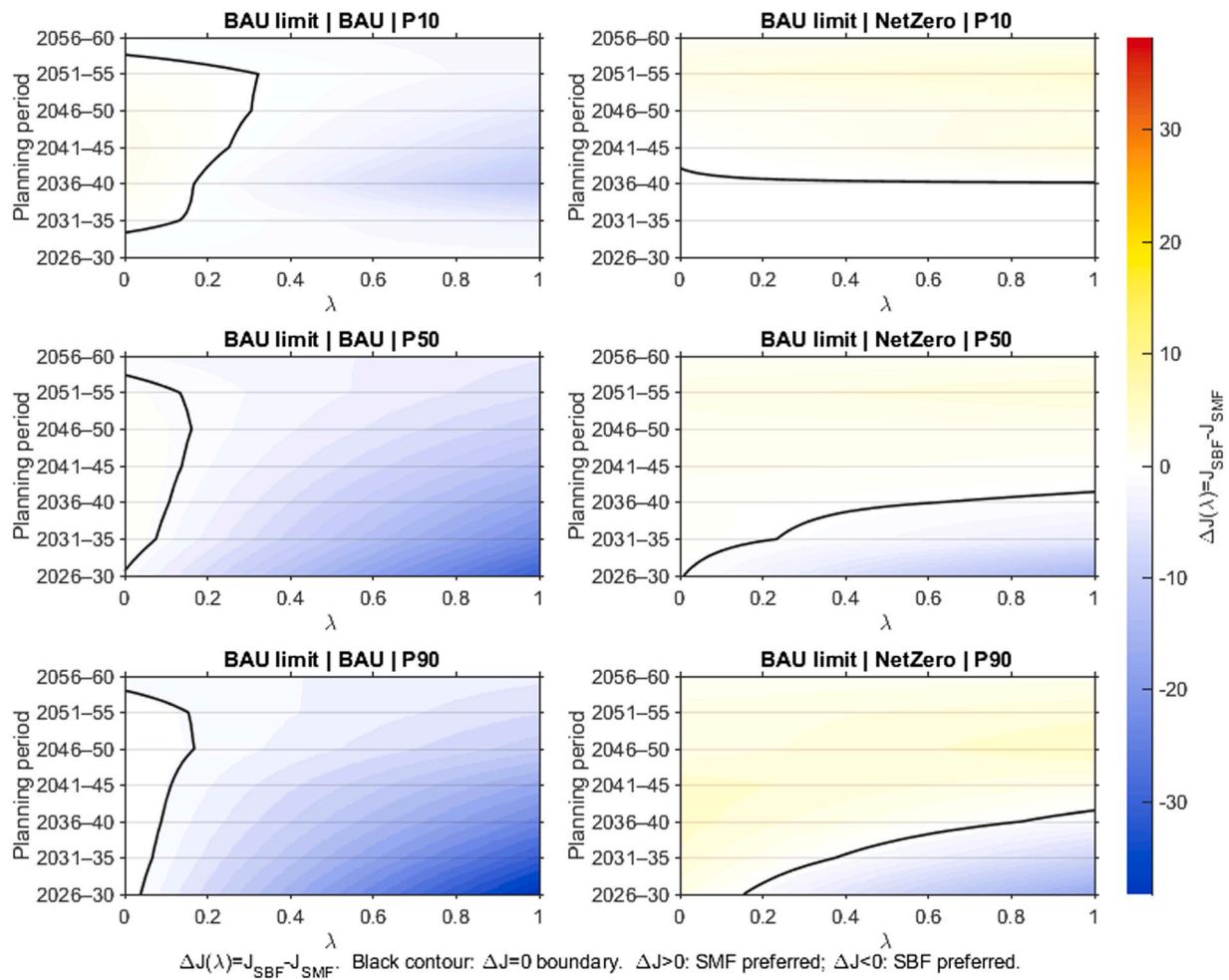


Fig. 20. Mean-CVaR trade-off under BAU carbon limits and seismic risk.

yielding full probability distributions of life-cycle embodied carbon outcomes.

To support risk-informed decision-making, the framework introduces complementary probabilistic performance metrics, including compliance probability, expected exceedance, and tail-sensitive indicators such as Conditional Value-at-Risk. Application to steel moment frame and steel braced frame systems demonstrates that while seismic risk has a limited influence on mean embodied carbon, it can substantially amplify tail risk, and that structural systems with lower initial embodied carbon may perform unfavorably when evaluated from a risk-informed perspective. The findings further indicate that nonstructural component quantities and building contents are important contributors to seismic risk-informed embodied carbon outcomes. In particular, uncertainty in nonstructural inventories can strongly affect both conventional and earthquake-induced emissions, while content replacement may represent a non-negligible post-earthquake carbon consequence that is often omitted in conventional LCA. Future work should therefore improve the inventory, fragility, and carbon consequence modeling of nonstructural components and contents.

Several limitations should be acknowledged. The case study focuses on a representative six-story steel residential building in Beijing, China, and the quantitative results depend on the selected building height, layout, structural design, nonstructural inventory assumptions, seismic hazard context, and decarbonization pathways. Therefore, the observed preference shift from SMF to SBF under tail-risk-oriented metrics should be interpreted as case-specific rather than a universal ranking between these structural systems. Nevertheless, the underlying decision mechanism is more general: structural systems with slightly higher initial

embodied carbon may be favored when they substantially reduce low-probability, high-consequence seismic carbon losses. Future work should examine whether this trade-off persists across different building heights, layouts, structural systems, hazard contexts, and decarbonization pathways, while also refining key input information that affects decision robustness, including product-specific decarbonization pathways for nonstructural components, project-specific nonstructural component inventories, and more detailed fragility and carbon consequence models for nonstructural components and building contents. Improving these data would reduce uncertainty in both conventional and seismic-induced embodied-carbon estimates and support more reliable risk-informed decision-making. The proposed probabilistic compliance metrics may further support the development of performance-based embodied carbon codes as regulatory frameworks evolve.

CRedit authorship contribution statement

Charlotte Toma: Writing – review & editing, Supervision, Methodology, Conceptualization. **Jiajun Du:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ting Lou:** Writing – review & editing, Methodology, Conceptualization. **Wei Wang:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wei Wang reports financial support was provided by National Natural Science Foundation of China. Jiajun Du reports financial support was provided by China Scholarship Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.engstruct.2026.123066](https://doi.org/10.1016/j.engstruct.2026.123066).

Data availability

Data will be made available on request.

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