Moving Towards the 3D Seismic Design of Structures: A Review

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ABSTRACT

There is a common simplification in seismic design codes that independently computes the seismic force in the two orthogonal directions. Then, individual frames are designed based on the distributed lateral forces. The 3D effects, including the interaction of adjacent and orthogonal frames, are omitted in this process, while research shows that the design results differ between 2D and 3D methods. Although most seismic assessment procedures and philosophies have been developed for 2D frames, there is no standard prescription for adopting them to assess 3D structures. The progress in the computational capability of computers makes the 2D design philosophy not acceptable anymore, and the engineering community needs to move toward a 3D point of view in assessing and designing structures. Many works have investigated the 3D behavior of structures or proposed 3D design strategies for different issues. There is a need to clarify the importance of the problem as an independent research field. This paper reviews the research in which the 3D structural design or behavior is addressed and shows weaknesses and future research paths. The study includes four main parts: modeling, assessment, design, and optimization of 3D structures. Finally, the main results and recommendations are presented.

KEYWORDS

3D structures, 3D modeling, seismic design, seismic assessment, nonlinear behavior

1. Introduction

Simplification is an inextricable part of preparing a structural design code; however, the simplification level must be adjusted to consider advances in computer technology and the increasing understanding of structural behavior. Future groundbreaking computational progress necessitates further improvement of the code provisions. For example, quantum computers and computing [1] can revolutionize the computing pace, and complex problems would be solved quickly. Or, GPU-accelerated computing can analyze structures faster than traditional CPU-based analyses [2]. The following are the significant common simplifications in seismic design codes:

Using the semi-probabilistic method in loading: There is an uncertainty in code-prescribed loads and their combinations. Most codes adopt a semi-probabilistic perspective [3, 4], like the Load and Resistance Factor Design (LRFD) [5] method for combining loads and the partial safety factors for amplifying the effects of loads [6]. The semi-probabilistic approach is the lowest level of considering uncertainties [3, 7].

Amplification factor: Nonlinear behavior of structures is not directly considered in the design process. Elastic responses are multiplied by an amplification factor depending on the structural system. However, nonlinear analyses might be mentioned as alternative and more accurate methods. For example, ASCE 7-22 [8] and Eurocode 8-1 [9] employ deflection amplification (C_d) and displacement amplification factors (q_d), respectively. Both codes use a behavior factor to reduce the seismic force. The code-prescribed behavior factors are lower than the actual behavior factors obtained through nonlinear analysis [10]. So, codes are conservative in this case.

Distributing the seismic load in two independent directions: First, the seismic loads are calculated for the X and Y directions. Then, the force in each direction is distributed between the frames of that direction, usually proportional to the lateral stiffness. In the last step, the base shear of each frame is vertically distributed. In summary, building codes assume that nonlinearity does not alter the force distribution [11-13]. The well-known 100-30 combination rule is applied in assessing the element forces. The performance criteria, like drift, are compared to the allowable value for each direction independently. However, in the draft of the newest edition (fifth) of the Iranian seismic design code, Standard No. 2800 [14], the inter-story drifts in both directions should be combined using the 100-30 rule. The 100-30 rule is not an accurate combination for all structural systems, demands, irregular structures, and analysis methods [15].

Seismic design codes recommend 3D analysis in certain cases, such as for irregular structures in the plan. However, as explained later, research has shown that 3D effects are considerable even in regular systems. Moreover, this permission is applicable after design, which means the structure is designed based on conventional methods, and the performance assessment is carried out using the 3D model.

Structural reliability analysis can be used to mitigate the consequences of the first simplification. It calculates or predicts the probability of violating a performance measure, like the ultimate state [7]. For the second and third simplifications, Nonlinear Time-History Analysis (NTHA) can be used to obtain the nonlinear response of the structure. An uncertainty in using NTHA arises from the selection and scaling of earthquakes, known as 'Record-to-Record Variability' (RRV). RRV can be addressed by analyzing the structure under a vast number of records and employing record selection strategies, such as the Conditional Mean Spectrum (CMS) [16, 17], Conditional Spectrum (CS) [18], and Generalized Conditional Intensity Measures (GCIM) [19, 20].

Record selection methods involve seismic hazard disaggregation [21] and utilize Intensity Measures (IM) to indicate the earthquake severity [22]. However, most IMs and record selection methods have been initially developed for 2D planar frames. Also, record scaling with two orthogonal components is another controversial research field [23].

The shaking table test experiment is the most straightforward way to understand 3D behavior. However, shaking table test facilities are not widely accessible, and the required funds are substantial. Software helps researchers and engineers investigate 3D structures. Modeling 3D systems in software requires suitable material and element models. A behavioral model for material should consider the 3D force interactions, whether in the force-displacement or stress-strain curve. In addition to the material model, an element model should be formulated to account for the same interactions. Such models are developed based on experimental works and under different loading protocols that come at a significant cost, including test facilities and specimens.

Earthquakes damage building structures more than before [24]. One cause of this increase in damage is that buildings are becoming more complex. However, the design process remains rooted in the 2D philosophy, and any code improvements are still tied to this outdated strategy. The necessity of research on 3D structures has been effectively recognized since the 2000s, but the works in this area are sparse. The question is, where does this field of study lead, or can we expect any integrated conclusion to be reflected in codes?

The 3D design philosophy should be developed in three main branches: 3D models, 3D assessment processes, and 3D design methods. This paper focuses on these three topics. First, the weaknesses of modeling are briefly highlighted. In the second step, seismic analysis approaches are reviewed, as they form the basis of seismic assessment. Next, a review of research on 3D design methods is conducted. Finally, the optimal design of 3D structures is reviewed since it also encompasses seismic design. The Web of Science database [25] was used to find related papers. Existing gaps are highlighted to give prospects for future research. The primary objective of this paper is to demonstrate the necessity of transitioning from 2D design to 3D design of structures and to establish this topic as an independent research area.

2. Modeling

Modeling has two levels: micro and macro modeling. Micro modeling is a research approach that examines the behavior of individual elements, such as beams, columns, shear panel zones, or connections. Assembling individual parts to create an integrated structure is known as macro modeling. Accurate micro modeling is a prerequisite for accurate macro modeling and is reviewed in Section 2.1. While many behavioral models exist for the 2D state, the scarcity of 3D behavioral models limits the scope of 3D numerical studies. Using 2D models can cause overestimation or underestimation of structural responses [26, 27]. Moreover, it can cause a profound misunderstanding of the collapse mechanisms of structures [28].

Hybrid FEM modeling, also known as multi-scale modeling, combines micro- and macro-level modeling to capture structural responses. The concept involves inducing the stress and strain distribution of an element into a larger element or structure through common nodes. Despite its high accuracy, hybrid modelling requires significant time and is not suitable for structures with many elements. Hybrid Modeling (HM) is frequently used in RC structures, especially in shear walls, due to the presence of rebars [29-35]. Additionally, the HM of masonry structures is crucial due to the mortar, masonry blocks, and interfaces [36-38]. The advantages and shortcomings of hybrid modelling of 3D structures have not been investigated or compared with other methods. Liu et al. [39] have reviewed the pros and cons of multi-scale modeling of engineering structures.

2.1. Micro modeling

Some accepted elements and approaches are available for beams and columns in the 3D state, like fiber sections and plastic hinge models [40]. Fig. 1 shows modeling methods for beam-column elements. Figures 1-(b) to (d) primarily show macro elements (beam-columns), but micro simulation and formulae are needed to capture the plastic hinge behavior. The micro features of hinges should be addressed to be able to define a macro element. The hinge location [41-43], hinge length [44-53], and force interactions are research subjects for the concentrated and finite length models on which there is no consensus (Fig. 1-(b) and (c)). As some examples of force interactions, ASCE 41 [54] proposes formulae to consider the interaction between axial load and one-way bending (P-M) for steel and Reinforced Concrete (RC) structures. NIST GCR 17-917-46v2 [55] introduces formulae for the P-M interaction in steel structures. Since the P-M interaction in RC members is more complex than in steel, NIST GCR 17-917-46v3 [56] does not provide any specific relationship for RC structures. The interaction among axial load and bending about two axes (P-M-M) can also be modeled using fiber sections (Fig. 1-(d)) [54, 56]. P-M-M interaction may be defined using two zero-length elements to represent two-way bending. The question is still how to reflect the three-component simultaneous interaction.

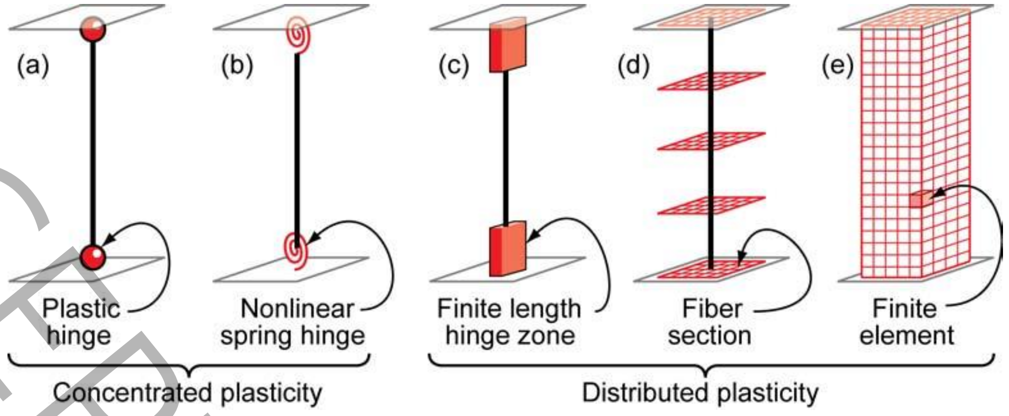

Fig. 1. beam-column element models [40]

Fig. 1-(e) shows the continuum finite element model. 3D continuum models capture complex behavior and geometries but have the highest computational cost [57]. So, they are not suitable for studying the whole structure.

For beam-column elements, as illustrated, numerous studies have been conducted to derive their behavioral models, and existing models are being refined to capture various behaviors. For example, Maity et al. [58] developed a new nonlinear fiber-based beam-column element to model the interaction between local and global buckling in steel members. Wayghan and Sadeghian [59] presented an accurate plastic hinge model for deep RC members suitable for macro modeling of structures. Alghossoon and Varma [60] introduced a 3D behavioral model to simulate the stiffness and strength deterioration of high-strength steel beams. Kassab et al. [61] provided a new 3D kinematic formulation and model for thin-wall rods that includes cross-sectional wrapping and plasticity.

2.2. Macro modeling

Many efforts have been made to develop independent 3D macro elements for masonry structures [62-67]. However, research on developing new macro elements for steel and RC structures is limited. One reason for this scarcity can be the adequacy of existing beam-column macro elements for modeling common structures. Despite significant work on beam-column elements, modeling Shear Panel Zones (SPZs) and shear walls requires more research, as described in the following subsections. SPZs are present in all buildings, and shear walls are frequently used as a lateral load-resisting system in RC structures. So, these two topics are considered for further expansion. Other structural components like slabs, foundations and non-structural elements are modeled in specific cases, or their behavior is induced in the model indirectly (like rigid diaphragms for floors and springs for soil-structure interaction rather than modeling the whole foundation). Therefore, they are not discussed in this review.

A few papers develop new macro elements or methods for RC and steel structures. Tistel and Grimstad [68] proposed a macro model for shallow foundations in 2D and 3D states. The model uses an elasto-plastic formulation and a yield surface in the horizontal, vertical and moment loading space to capture soil-structure interaction. It is suitable for both force and displacement-control actions. Pantò et al. [69] developed a 3D macro approach to model the effect of masonry infills in structural frames. The model is able to capture the out-of-plane and in-plane behavior. Silva et al. [70] introduced 3D joint model for steel structures. The model considers beam-column deformability. Sistla et al. [71] captured out-of-plane buckling of gusset plates in buckling-restrained frames using a new 3D macro element. Analyzing a structure under bidirectional earthquakes showed that considering gusset plate buckling decreases the structure’s deformation capacity and increases its mean annual frequency of collapse. The mentioned papers indicate that developing new 3D macro elements and including them in seismic analysis improves accuracy and prevents overestimation.

2.2.1. Modeling shear panel zones and joints

SPZs are critical elements in macro modeling. Numerous test results on 2D SPZs [72], and several behavioral models have been developed in finite element software like OpenSees [73]. The current models suffer some shortcomings, and research on the 2D state continues to derive more reliable behavioral models [74, 75]. While extensive research has been conducted on 3D connections [76-82], behavioral models for 3D SPZs are very few (related works: [83-87]). Another obstacle is that different joint configurations and sections have specific behaviors, and the study results might not be generalizable.

Connections in composite structures are an ongoing research topic. Connections in composite structures, whether concrete-filled steel columns [88, 89] or composite roofs, exhibit different behavior from bare connections. Also, modeling mixed actions affects global structural responses, as Jeyarajan and Liew [90] stated that modeling concrete slabs in analyzing 3D steel structures overcomes the response overestimation problem. The composite effects on the behavioral models have been investigated using cruciform configurations and 3D continuum finite element models [91-98]. Further research on two-way cruciform configurations or corner connections is needed, as demonstrated by Gil et al. [99], Fan et al. [100], Xu et al. [101], and Tonidis et al. [102].

2.2.2. Modeling shear walls

Shear walls (SWs) resist lateral forces and can be constructed using in-situ RC, precast RC [103], steel plates [104], composite steel-concrete [105], and wooden shear walls [106]. Only the modeling trends of RC shear walls are discussed here.

Modeling SWs is divided into two main categories [107]: i) microscopic: these models are like continuum FEMs and can model complex force interactions and responses. However, microscopic models need high computational efforts. ii) macroscopic: These models are computationally efficient and more practical than microscopic models. They are suitable for analyzing the whole structure and comprise some sub-elements like plates or truss elements. Comprehensive descriptions of the most common 2D microscopic and macroscopic models and their shortcomings are available in Kolozvari et al. [107, 108]. The main gaps in studying and modeling the behavior of shear walls are related to [109]: the 3D force interactions (and out-of-plane behavior), multi-directional loading, the structural behavior in association with the other structural components (most studies are on the isolated walls), different wall geometries (non-rectangular), post-critical near-collapse mechanisms (like bar buckling), and validation against a vast range of parameters.

Developing 3D models for shear walls has gained attention in recent years. However, a few studies have developed 3D models that address the out-of-plane or 3D behavior of shear walls. Studies by Fischinger et al. [110], Lu and Panagiotou [111], Lu et al. [112], Kolozvari et al. [113], and Kolozavari et al. [114] are pioneers in modeling 3D SWs. Also, To et al. [115] compared the precision of different concrete material models in predicting the response of 3D shear walls. Nevertheless, some shortcomings remain, such as the bar buckling. It is interesting that, unlike 3D shear walls, the 3D behavior of masonry walls has been extensively investigated [36, 62, 116-119].

A behavioral model or a new element should be defined for the commercial software to be helpful. Otherwise, they do not solve any practical problem. To this end, some people should focus on the interdisciplinary topics of structural and computer engineering.

3. Assessment of 3D structures

Pushover and time-history analyses are the most widely used and well-known analyses in the literature. Also, the severity of a seismic loading scenario is indexed by an IM. This section contains the research on these three topics since they are the foundations of assessment approaches (e.g., fragility curves, Performance-Based Design (PBD)).

3.1.1. Pushover analysis

Pushover Analysis (PA) is a static method that pushes the structure to reach the target drift or displacement. PA is more suitable for 2D frames since a lateral load pattern is needed to model the drift pattern over the structural height. Most studies on 3D structures try to investigate the effect of plan irregularity in using PA [120-127].

PA can be used for 3D systems by assuming two identical or independent vertical load distributions in the two orthogonal directions. However, this assumption is invalid, as demonstrated by Ghamari and Shooshtari [128] and Ghamari et al. [129] showed. Alternatively, the analysis can be performed using combination rules, typically the 100-

30% principle (e.g., [130]), that is, combining the target displacement in a direction by a fraction of the target displacement in the other direction. Choosing a combination rule is controversial, and there is no consensus on it [15, 131].

The other main challenges (even in the 2D state) are determining the target point (e.g., [132-136]), the effects of higher modes (e.g., [137-139]), and variable load patterns during an earthquake [140-145]. The nature of earthquakes and structural height play significant roles in determining which PAs to use [146]. These issues, along with the 3D load pattern problem, should be investigated for 3D systems.

3.1.2. Time-History analysis

Time-History Analysis (THA) calculates structural responses at discrete time steps by applying time histories of accelerograms to the structure. Record selection and scaling are the pillars of THA that depend on an intensity measure. Suitable intensity measure for 3D structures is discussed in section 4.2. NIST GCR 11-917-15[23] and Sextos[147] illustrate the fundamentals of record selection and scaling.

Another problem related to THA for 3D structures is the generation of artificial records. Artificial accelerograms are used where there are insufficient historical records compatible with the desired hazard or the site conditions. A seed motion is selected, and new accelerograms are generated by altering it using signal-processing techniques such as wavelet or Fourier transforms [148]. The remaining problem is modifying a seed motion to produce multi-dimensional (2D or 3D) records. Some papers have tried to generate multi-dimensional ground motions [148-151].

3.2. Intensity Measures

The analysis methods depend on IMs. IMs indicate the potential destructiveness of an earthquake and are utilized in record selection, scaling, and performance assessment methods (e.g., fragility curves). A limited number of works address the use of IMs in the 3D state [152-158]. These works employ a combination rule to unify IMs in both directions into a single IM. Moreover, most papers ignore the vertical seismic component. There is no IM that encompasses the two or three directions without using a combination rule. Only Ayabakan et al. [159] used the three-dimensional elastic energy spectrum as IM. They extracted the elastic response spectrum by analyzing an SDOF system and did not assess the IM according to the available criteria mentioned in the next paragraph.

There are several suitability criteria for selecting an IM, including efficiency, sufficiency, practicality, proficiency, and hazard computability. An Engineering Demand Parameter (EDP) is needed to calculate the suitability criteria. Assessing these criteria remains an open research field, even within 2D frames. In 3D structures, the responses are bi- or three-dimensional, which doubles the problem: i) IM should integrate the severity of all components, and ii) a unified EDP parameter should be defined.

4. 3D design

The phrase '3D design' indicates that the design problem is not decomposed into designing individual frames. However, some research considers 3D force states in the design of individual structural elements [160-166]. Nevertheless, the obstacle is that the 3D global behavior must determine the magnitude of these element-level forces. Research on the 3D design of structures, which considers global seismic behavior, is very scarce.

One approach is to perform THA according to a pre-specified design and then evaluate global and local performance (e.g., PBD). In addition to the time required for repetitive analyses and the RRV problem, this approach entails developing performance assessment concepts for the 3D state, as mentioned in sections 4.1.2 and 4.2. THA needs expertise and knowledge in record selection and scaling. Therefore, THA is not suitable for real design problems.

The other alternative is to utilize the seismic energy concept, which has recently garnered attention. Seismic input energy and the ability of the structure to dissipate it determine the severity of the damage [167-169]. Seismic energy, or more generally, energy, is a scalar quantity, and the structure is subjected to it as an integrated body. So, it does not seem reasonable to design structures by assuming that the lateral load-resisting systems in the considered directions act solely. In addition, buildings have different geometries, materials, and constraints that make codifying the 3D design more complex. The seismic energy concept can be a solution to this issue.

Energy-based design methods balance the seismic input and dissipated energies [170]. Housner [171] used the concept to design a 2D SDOF structure for the first time. The Performance-Based Plastic Design (PBPD) [172] method is the most popular energy-based method among researchers since it has been developed for various structural systems and conditions [173]. Ghamari and Shooshtari [128] introduced the PBPD-3D design method by relating the base shears in the two orthogonal directions and adjacent frames. In this way, the interaction between adjacent and orthogonal frames is considered. Ghamari et al. [129] developed a new design method in which the base shear is determined from the expected seismic energy demand and distributed as a vector. The distribution is unique for each earthquake, and the decomposition angle of the story force vector varies among the stories. The base shear vector distribution and the decomposition angles are calculated using earthquake characteristics. So, the structure is not decomposed into two independent orthogonal directions and individual frames. The mentioned studies indicated that reflecting 3D effects in determining seismic force and its distribution leads to safer structures. However, energy-based design methods rely on estimating seismic input energy using THA, which makes these approaches impractical.

There are several efforts to develop a 3D design method that does not rely on the energy concept. Kappos and Stefanidou [174] proposed a design method for 3D RC buildings. The methodology uses linear analysis at the first step to identify the basic strength level. Then, a partially nonlinear model is created that allows plastic hinges to form at predetermined locations. Finally, THA is performed to determine the design forces and conduct the serviceability check. The advantage of this method is that the nonlinear deformation of the members can be predefined, allowing the structure to exhibit the desired performance level. Tzimas et al. [175] extended the Hybrid Force/Displacement (HFD) design method [176] to 3D steel structures. The HFD design method combines the force-based design and the direct displacement-based design method [177]. This methodology controls structural and non-structural damage levels with fewer iterations. Farokhnia and Hooks [178] proposed a seismic design framework for 3D-printed structures. They validated the design results with the continuous finite-element and experimental methods. A formula was derived to determine the minimum wall length in the orthogonal directions.

Considering the reviewed papers, it can be stated that the inclusion of 3D effects in the design process entails nonlinear modeling and analysis. Nonlinear modeling and analysis are complex and are not commonly used by practical engineers, except for special structures. There are two options for making 3D design a practical and popular method for engineers: i) deriving empirical and simplified formulae to estimate nonlinear response of structures (like stored plastic energy, base shear, vertical and horizontal base shear distribution) and codifying the procedures, and ii) developing linear approaches to consider 3D effects explicitly. Several papers have tried to estimate seismic stored energy in 2D frames [179-181]. However, no paper was found in the database regarding the estimation of stored seismic energy in 3D structures. Also, the literature lacks studies on developing linear analysis and design methods that accurately account for 3D effects. Of course, attempts have been made to predict nonlinear responses using machine learning [182-185]. Further development is required to effectively utilize these tools in the 3D design of structures.

5. Optimization

Optimal design of structures is a research field that has been expanded to 3D systems. Structural seismic design optimization has three main branches: sizing optimization, shape optimization, and topology optimization [186, 187]. Sizing optimization refers to optimizing the size of elements (i.e., cross-sectional area), whereas shape optimization involves optimizing the overall shape of the structure. For 3D structures and like shape optimization, topology optimization has gained less attention. The optimal material distribution throughout the entire structure is the goal of topology optimization.

Optimizing the design of 3D structures has been common recently. For example, Kaveh et al. [188] used the cuckoo algorithm [189] to optimize the self-weight of 3D steel structures. The cross-sectional area of elements was the optimization variable. Other code limitations, like displacement range, were defined as constraints. Martin and

Deierlein [190] optimized the topology of 2D and 3D tall buildings using modal decomposition. They minimized the seismic vibration. Kaveh and Rezazadeh Ardebili [191] used the improved plasma generation algorithm to minimize the material cost of 3D RC structures. Section geometry and rebars were the optimization variables. Mergos [192] optimized the material cost of 3D RC structures using the flower pollination algorithm [193]. In another research, Mergos [194] used a surrogate-based optimization method to minimize the material cost of 3D RC structures. The cross-sectional areas of the beams and columns were treated as variables in the two later papers. Haji Mazdarani et al. [195] investigated the optimal layout of concentric braces in 3D steel structures. The objective function was to minimize the total weight. A reliability-based optimization algorithm was employed, in which the reliability index is calculated using the Monte Carlo method. The probabilistic variables were the intensity of the distributed load and the cross-sectional area of the braces and columns. The distance between the center of mass and the center of rigidity was considered as the probabilistic constraint. Comparing the reliability-based and deterministic design optimization procedures revealed that the former results in a heavier structure. Xing et al. [196] proposed an optimization procedure for high-rise buildings with outrigger systems. Structural weight and reliability were the objectives. The structural responses were derived using NTHAs. The proposed methods consider both shape and sizing optimization.

As can be inferred from the mentioned papers, most studies on 3D design optimization focus on sizing optimization. Shape optimization is more challenging for a 3D structure, as the geometry must be optimized in a 3D Cartesian space. Also, architectural constraints make the procedure more complex. No paper was found on the shape optimization of 3D structures. Therefore, shape and topology optimization of 3D structures should be considered in future research.

Another drawback is the objective function, which typically represents the total cost or weight of the materials. An optimal design should simultaneously satisfy performance (reliability) and minimize construction costs, as demonstrated by Haji Mazdarani et al. [195] and Xing et al [196]. Single-objective optimization can be used when performance limitations (e.g., drift) are defined as constraints (as in Kaveh et al. [188]). But, satisfying the constraints does not lead to the best performance, which is the ultimate goal of structural design. Also, a probabilistic approach in defining constraints or objective functions reduces uncertainties in design. A comparative study is needed to clearly demonstrate the advantages and disadvantages of deterministic and reliability-based optimization procedures.

One important issue in optimizing the design of 3D structures is the analysis method. The analysis should reflect the real behavior of the structure. For example, Xing et al. [196] used a reliability-based optimization procedure with NTHAs. Due to the limited research in this field, the optimal design of other structural systems should also be investigated. Similar to steel structures with shear walls or various types of braces and dual systems.

6. Summary and Conclusion

This paper reviewed the tendency to study structures in the 3D state under seismic loading, from modeling to design. The most significant portion of the papers is modeling and studying the behavior of elements under different loading protocols. Assessment of 3D structures is the second favorite field of research. Assessing a 3D model cannot be considered related work unless seismic assessment concepts have been expanded to the 3D state (e.g., bi-directional IDA).

Some studies have attempted to design structural elements under complex three-dimensional loading states. But 3D designing in this paper refers to a design method that considers the 3D structural behavior and interactions in determining the seismic force and its distribution. Only a few papers discuss this aspect, so more attention is needed to design structures based on their near-reality behavior. Optimization has gained more attention than other research topics related to 3D structures. Like the design phase, some optimization algorithms should be developed based on the 3D behavior of structures (not just using 3D models). Table 1 summarizes the reviewed topics, their main contributions, and their limitations. Table 2 shows the main research gaps identified in this review.

Table 1. The summary of the reviewed topics

Category	**Reviewed Topics**	**Key Contributions**	**Limitations**
modeling: micro	beam-column behavior hinge models P–M–M interaction 3D continuum FE	captures detailed 3D response at the element level	high computational cost lack of generalized 3D hinge models
modeling: macro	3D macro elements for shear walls, joints, SPZs	efficient for whole structure analyses	A few 3D macro elements for RC/steel structures limited generality
assessment: pushover analysis	Multimode, torsional, bidirectional pushover	a simple method extended to 3D irregularity	not accurate for 3D drift patterns no agreed 3D load pattern
assessment: time-history analysis	record selection/scaling multidirectional ground motions	the most accurate method for 3D seismic response	record-to-record variability limited multidirectional artificial motions
assessment: intensity measures	IMs for 3D structures combination rules	progress toward 3D severity quantification	no unified 3D IM lack of 3D EDP definition
3D design	energy-based hybrid force/displacement PBPD-3D	considers global 3D behavior and frame interactions	requires NTHA impractical for routine design
optimization	sizing, shape, topology, and reliability-based	reduces weight/cost includes uncertainty	almost no shape optimization

			limited 3D-dependent objective functions

Table 2. Main research gaps in the reviewed fields

Research field	Main gap
3D element models	generalized, validated 3D macro and micro models (joints, SPZs, walls and etc.) with practical formulations
3D pushover analysis	accurate 3D load patterns and unified drift/EDP measures
multidirectional ground motions	reliable generation of artificial 3D motions and consistent scaling/selection procedures
3D intensity measures	unified IMs incorporating all components and a 3D EDP definition
3D design methods	linear or semi-empirical design formulae to avoid full NTHA energy-based approximations
optimization	topology and shape optimization for 3D structures multi-objective performance-cost formulations methods based on real behavior of structures inclusion of various structural systems
software integration	implementation of new 3D elements into commercial software consistent documentation and dissemination

According to the reviewed papers, variety in element types (e.g., panel zone, floors, beam-columns, connections) and their integrated performance in a 3D structure, variety in the types of a specific element (e.g., different types of floors are available), the internal features of an element (e.g., concrete strength, rebar percentage, bolt size) and different loading protocols make direct test and understanding of 3D structural behavior difficult. Additionally, the mentioned complexity limits the applicability of the available research in all cases (lack of generality). However, there is a tendency in the research community to assess the real 3D behavior of structures.

Despite extensive research on testing and formulating elements that capture 3D behavior, few papers have attempted to develop a 3D design concept. There are elements formulated for 6 degrees of freedom. But inducing seismic force in a 3D building and then distributing it among the individual elements without directional separation requires more attention. Energy-based design methods may be a suitable candidate, but they introduce additional challenges: estimating input and stored plastic energy due to an earthquake with three components, as well as the effects of material and structural features.

Some measures are also needed to quantify earthquake power, structural damage, and structural performance in 3D. These measures are the essential tools for understanding the 3D behavior of structures. Seismic intensity measures have been generalized to 3D structures in a few papers. More research is needed about structural damage and performance measures. For example, inter-story drift is calculated for each direction independently; A combination method is needed to combine the inter-story drifts of the two directions, reflecting the structural damage in a meaningful way.

Two main causes for simplifying the assessment and design of 3D structures using 2D concepts are practicality and computational constraints. An engineer requires a clear and straightforward description of the assessment methods and criteria. Moreover, the methods and criteria should not entail higher education skills that the majority of engineers do not have. To make the findings practical, a clear formulation is needed, which can be challenging in some cases, such as seismic energy. One solution to overcome challenging formulation cases may be connecting analyses. A connecting analysis is a low-level and straightforward analysis whose results are used to predict the outcomes of a more complex analysis. For example, estimating input seismic energy to a 3D structure using the results of linear static analysis and some formulae. Of course, there are numerous papers proposing machine learning procedures for predicting nonlinear structural behavior (e.g., He et al. [183], Choi et al. [184] and Zhang et al. [185]). It is not practical to use machine learning algorithms in real-world building projects, as they are often trained on limited data and require specialized knowledge in machine learning and its applications.

Another problem is the computational cost of complex analyses. Time limitation is important for employers. A complex analysis can be time-consuming, especially when the structure is big and there are many elements. Fast computers are expensive, and it is not efficient to purchase one for a few projects. As mentioned before, a connecting analysis and its suitable formulation seems to be the best solution. Nevertheless, it is possible to analyze complex structures with several variables considering the available computational facilities. Therefore, researchers should utilize advances in computation to understand the three-dimensional behavior of various structures.

Another obstacle in 3D assessment of structures is the inclusion and formulation of elements in the software packages. The reviewed papers provided valuable insights into the 3D behavior of elements. But their result is not usable. Element definition in commercial software packages is the final step in facilitating the 3D assessment and design of structures. Even after extensive testing and refinement of the formulation, the element remains unusable unless a known software library includes it. Formulation refinement is necessary to minimize the analysis time. Adding elements to software and refining its formulation are often overlooked by researchers and software producers, or the newly added elements are not properly announced or introduced. A paper or report is needed to periodically collect and introduce newly developed and added elements.

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