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Research Article

Numerical Investigation of Seismic Demands in Floor Diaphragms and Collectors

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Abstract: This study investigates the seismic demand in diaphragms, chords, and collectors in typical floor systems used in steel structures using nonlinear Finite Element (FE) analyses. These systems include prefabricated one-way steel joist floor systems, open-web steel joists, and composite steel decks. The Lateral-Force-Resisting Systems (LFRSs) considered were Special Concentrically Braced Frames (SCBFs) and Special Moment Frames (SMFs) of varying heights. For each system, the effects of using shear connectors for collector beams, joist direction, geometric configuration, and number of stories on lateral force transfer were examined. Analyses were conducted on selected models. The study shows, in steel joist floor systems without shear connectors on collector beams, the diaphragm force transfer path is significantly influenced by joist orientation. Furthermore, using shear connectors on collectors bypasses joist participation in lateral load transfer, allowing the floor slab to transmit forces directly to the LFRS like a rigid diaphragm through the collectors. In composite steel decks, using shear connectors on collector beams was found to improve diaphragm ductility and cyclic performance. Overall, the study clarifies the true structural role of diaphragms, demonstrating that without proper analysis models, seismic load paths can become disrupted and traditional design assumptions may fail to ensure structural safety. The findings indicate that the introduction of diaphragm-specific response modification factors of one or less ($R_s \leq 1$) results in more realistic diaphragm forces. Applying the outcomes of this research will align diaphragm design practice more closely with the actual behavior.

***Keywords*:** seismic design, diaphragm, floor joist, collector, chord, composite beam, shear connector

1. Introduction

Diaphragms are fundamental components of seismic Lateral-Force-Resisting Systems (LFRSs). These horizontal elements ensure the transfer of seismic inertial forces to vertical LFRS elements through collectors. The diaphragm itself bends in its own plane, creating tensile and compressive forces in the chords at its boundaries. Figure 1 illustrates the primary diaphragm components involved in a typical building subjected to earthquake loading.

O'Brien et al. [1] indicated that within a diaphragm, shear forces are transmitted through slab action and discrete collectors, while axial forces due to bending are resisted by chords along the diaphragm boundaries, analogous to the flanges of deep beams under bending (Figure 2). Continuity of this load path requires effective shear transfer through shear connectors and/or embedded steel reinforcement in concrete.

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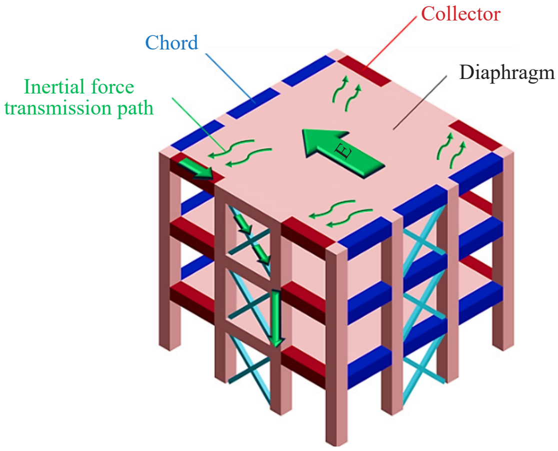


Figure 1. Diaphragm elements in a building with bracings

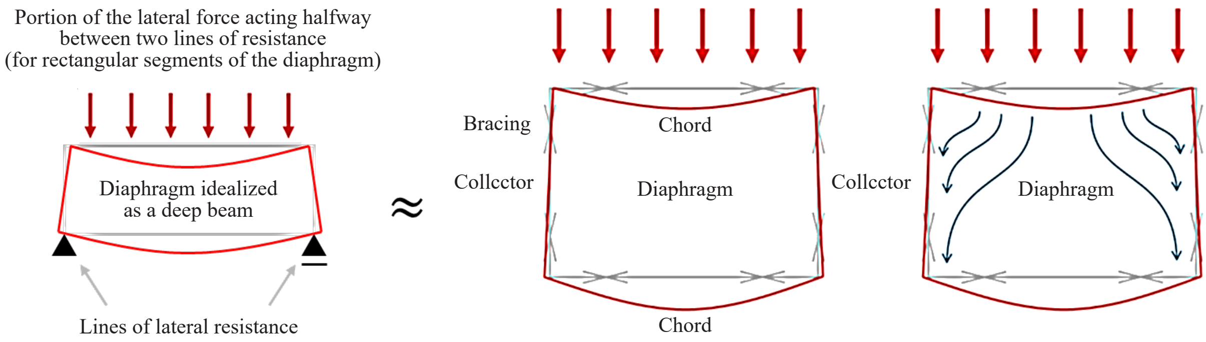


Figure 2. Similarity of diaphragm behavior to a deep beam after applying a lateral load

In obtaining the design forces for diaphragms, seismic design provisions such as ASCE-7 [2] apply the same response modification factor (R) to horizontal diaphragms and vertical LFRSs, implicitly assuming comparable ductility and energy dissipation. However, analytical studies and post-earthquake investigations have demonstrated that diaphragms exhibit distinct stiffness and deformation characteristics. Recent experimental and analytical investigations have further demonstrated that steel diaphragms may exhibit complex nonlinear force-transfer mechanisms that differ from conventional rigid diaphragm assumptions. These studies indicate that diaphragm stiffness, connection detailing, and interaction between the deck and surrounding framing members significantly influence seismic force distribution and deformation demands [3]. Higher-mode effects and floor-specific acceleration spectra can generate diaphragm demands substantially greater than those implied by story shear distributions. The 1994 Northridge earthquake highlighted this vulnerability, where diaphragm deficiencies—rather than failures of the vertical LFRS—were responsible for several progressive collapses, particularly in parking structures. Subsequent research, including Rodriguez et al. [4], showed that elastic diaphragm forces may exceed ASCE-7 predictions by a factor of two to three. These findings motivated the introduction of diaphragm-specific response modification factors (R_s), calibrated according to material type, configuration, and nonlinear response characteristics (ASCE-7 Section 12.3.2). While values for precast concrete diaphragms are codified, calibration for steel diaphragms remains incomplete.

Recent work by Eatherton et al. [5] under the Steel Diaphragm Innovation Initiative (SDII) extended this calibration to steel roof diaphragms using FEMA-P695 [6] procedures. Results confirmed that the traditional ASCE-7 approach systematically underestimates seismic demand, particularly in joist-supported systems. Experimental data further demonstrated that diaphragm ductility is highly sensitive to deck-to-beam connection type: spot arc welds exhibit brittle behavior (R_s = 1), whereas mechanical screw fasteners provide enhanced ductility (R_s = 2.5). Table 1 summarizes the ASCE-7 requirements and the suggested changes based on recent research. The applicability of the diaphragm design force-reduction factor (R_s) for steel deck diaphragms has also been questioned in recent studies. Eatherton et al. analyzed an extensive database of more than 750 diaphragm tests and concluded that the available experimental evidence was insufficient to justify a single R_s value for steel deck diaphragms. Their study highlighted the need for a more rational determination of R_s based on diaphragm ductility, overstrength, and validated system-level behavior [7]. Complementary experimental studies have shown that diaphragm ductility and energy dissipation capacity are strongly governed by connection details, including fastener type, weld configuration, and boundary attachment conditions. Therefore, diaphragm performance cannot be evaluated independently from the surrounding framing connections [8].

Despite these advances, current codes insufficiently address the interaction between diaphragms and vertical LFRSs, especially in joist-supported systems, where neglecting this interaction can lead to stress concentrations and premature failure. Furthermore, the influence of diaphragm-to-collector connectivity on the actual seismic force-transfer mechanism remains insufficiently understood. In many practical floor systems, positive in-plane shear transfer between the slab and perimeter collector beams is not explicitly provided, and the resulting load path may differ significantly from the assumptions commonly adopted in structural analysis software. Collectors, which play a critical role in force transfer, remain comparatively under-researched, and their design is often governed by simplified overstrength factors (Ω_o = 2-3), resulting in oversized members and uneconomical connections under major seismic demands. Recent full-scale cyclic experiments on deep steel roof deck diaphragms have further demonstrated that the in-plane seismic performance of steel diaphragms is strongly influenced by deck geometry, stiffening details, and connection configuration. The experimental results also showed that current design equations may overestimate diaphragm stiffness because they do not fully capture distortional deformation mechanisms, emphasizing the need for more refined numerical modeling of diaphragm behavior [9]. Another recent shake-table testing of steel buildings has shown that seismic collectors experience not only axial forces but also significant bending moments during earthquake loading. The study further demonstrated that the rigidity of collector-to-column connections and the participation of adjacent gravity framing modify the diaphragm load path, indicating that conventional analysis procedures may overestimate collector axial force demands and underestimate connection demands when these interaction effects are neglected [10].

Table 1. Comparison of traditional and new methods for estimating diaphragm seismic demand

Seismic demand	Related formulas	
The portion of the seismic base shear induced at level *i* for SFRS.	$C_{vi}=\dfrac{w_i h_i^k}{\sum_{j=1}^{n} w_i h_i^k} \rightarrow F_i = C_{vi} V_b$	(1)
Diaphragm seismic design force at level *i* (Traditional method in ASCE-7).	$F_{pi}=\dfrac{\sum_{x=i}^{n} F_X}{\sum_{x=i}^{n} w_x} w_{pi} \rightarrow \begin{cases} (F_{pi})_{\min} = \overbrace{0.2S_{DS}}^{0.5PGA} I_e w_{pi} \\ (F_{pi})_{\max} = \underbrace{0.4S_{DS}}_{PGA} I_e w_{pi} \end{cases}$	(2)
Diaphragm seismic design force at level *i* (New method in ASCE-7).	$F_{pi}=\dfrac{C_{pi}}{R_s} w_{pi} \geq (F_{pi})_{\min} = \overbrace{0.2S_{DS}}^{PGA/2} I_e w_{pi}$	(3)

This study investigates numerically the seismic demand in diaphragms, chords, and collectors in typical floor systems used in steel structures. These systems include prefabricated one-way steel joist floor systems, open-web steel joists, and composite steel decks. All floor systems include a reinforced concrete slab topping. The collector beams deliver the inertial forces from the diaphragms to the LFRS. Two types of LFRSs were considered: Special Concentrically Braced Frames (SCBFs) and Special Moment Frames (SMFs) of varying heights. For each system, the effects of using shear connectors for collector beams, joist direction, geometric configuration, and number of stories on lateral force transfer were examined. Linear elastic analyses were conducted on structural models in SAP2000 [11], while detailed nonlinear finite-element simulations were performed in ABAQUS (see Wang et al. [12]) to investigate local force-transfer mechanisms and potential failure modes. Results obtained from the simplified SAP2000 models were compared with the refined ABAQUS simulations, showing good agreement in the elastic range. The connection details between diaphragms and surrounding beams were explicitly modeled and discussed. Based on the numerical observations, recommendations regarding diaphragm force-transfer mechanisms and the applicability of diaphragm response modification factors are also presented.

2. Floor and roof diaphragm systems in steel construction

This study focuses on three representative diaphragm systems commonly employed in steel buildings. Each incorporates a reinforced concrete topping slab but differs in its supporting substructure and load-transfer mechanism:

• Prefabricated Steel Joist System (PJS): In this system, prefabricated joists, spaced at 0.5-1.0 m, support a reinforced concrete slab with a thickness of 50-100 mm. The construction stages are shown in Figure 3. Both reinforced concrete joists and prefabricated steel joists are commonly used in floor systems, with their cross-sections as shown in Figure 4. The joists are evenly spaced and separated by filler blocks (typically clay tile or polystyrene foam), which act as formwork for the concrete slab. The concrete topping is poured and finished on site. There are no shear connectors on the steel joists, but the top flange is embedded in concrete and composite action in bending is generally achieved. Similarly, in concrete joists, the top reinforcement is embedded in the slab. Joists may be arranged unidirectionally or in a checkered pattern, alternating joist orientation in adjacent spans. The seismic performance of this system is highly dependent on diaphragm-to-collector connectivity, particularly when positive in-plane shear transfer between the slab and collector beams is not provided.

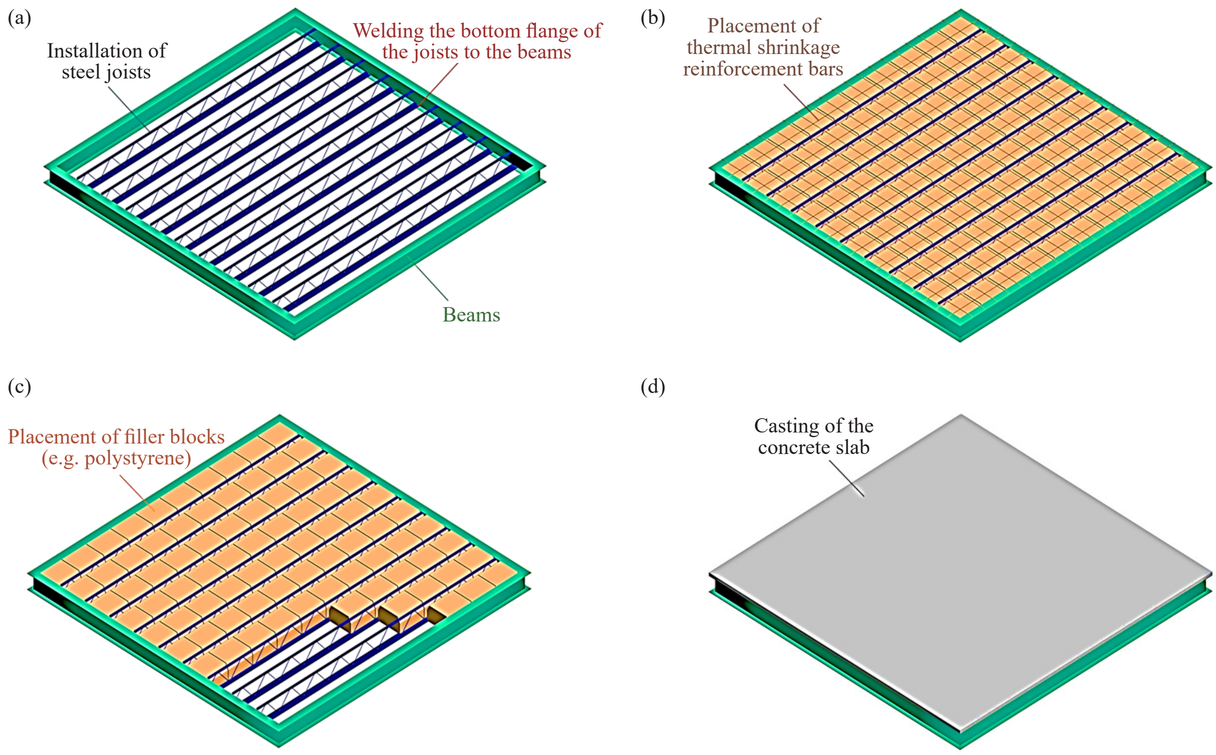


Figure 3. Construction stages of the PJS system

• Open-Web Steel Joist (OWSJ) System: Open-web steel (truss) joists, typically spaced at 2-3 m, support a thicker concrete slab (≈ 90 mm). Their open-web configuration facilitates the integration of mechanical and electrical services (see Figure 5). Design and fabrication are standardized by the Steel Joist Institute (SJI) [13], with series such as K-Series, LH-Series, and CJ-Series. Shear connectors are commonly used on the joists to engage the slab in bending and ensure composite action. As will be shown later, the seismic performance of OWSJ systems is sensitive to the force-transfer mechanism between the diaphragm, joists, and supporting beams, particularly at joist-seat and collector-beam connections.

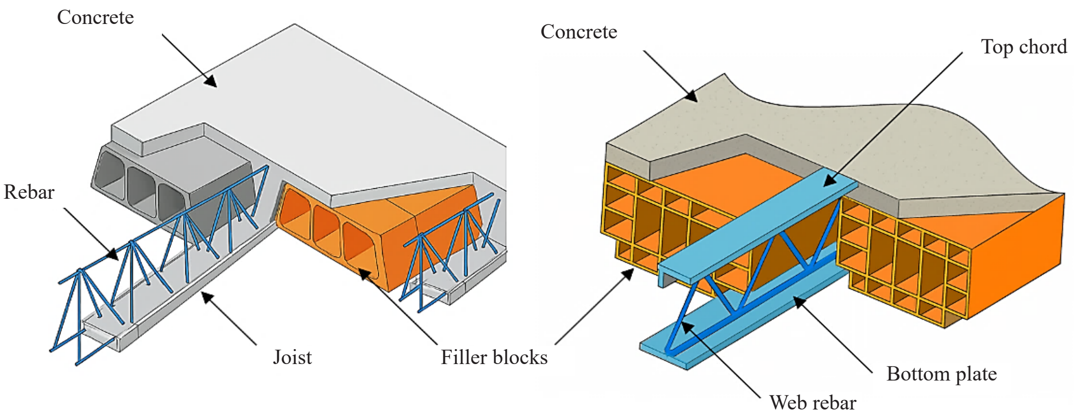


Figure 4. PJS systems with concrete and steel joists

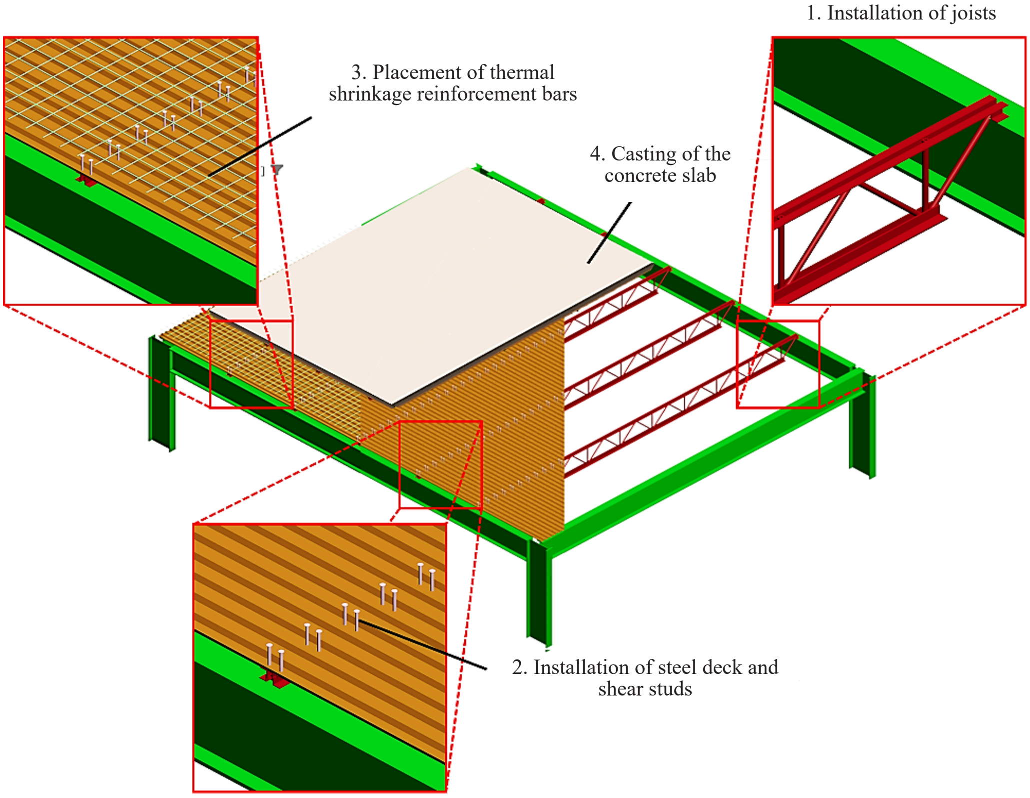


Figure 5. Construction stages of an OWSJ with steel deck

• Composite Steel Deck (CSD) Floor System: In this system, cold-formed profiled steel deck panels act as permanent formwork and tensile reinforcement for the cast-in-place slab (see Figure 6). Embossments on the deck surface ensure composite action between steel and concrete, producing a high strength-to-weight ratio. Typical slab thicknesses range from 50 mm to 127 mm, depending on deck profile depth. As will be shown later, shear transfer between the slab and collector beams plays an important role in diaphragm force-transfer behavior and overall seismic performance. Recent large-scale experimental studies have shown that the seismic performance of steel roof deck diaphragms is strongly affected by deck profile geometry, fastener arrangement, and connection details. Cyclic testing of deep stiffened steel deck diaphragms demonstrated that these systems can achieve high displacement ductility while exhibiting stiffness values lower than those predicted by current design standards, highlighting the importance of refined numerical modeling when evaluating diaphragm response.

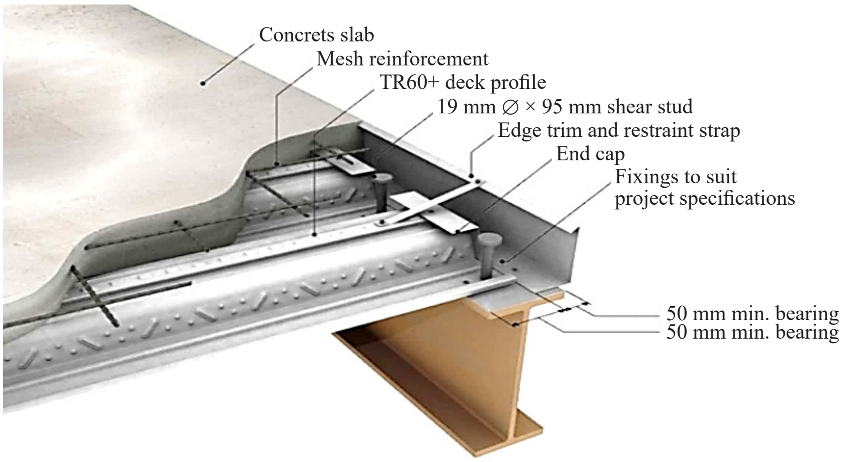


Figure 6. Composite Steel Deck (CSD) floor [14]

Table 2 summarizes the comparative characteristics of these systems, including construction details and seismic considerations.

Table 2. Comparative characteristics of common floor systems

System type	Key components	Spacing & slab	Seismic considerations
PJS	Prefabricated joists + Reinforced Concrete (RC) topping	Joists @ 0.5-1.0 m; slab ≥ 50 mm	Joist orientation governs load path; absence of shear studs forces joists into collector role
OWSJ	Truss joists with open web + RC slab	Joists @ ~ 3 m; slab ≈ 90 mm	Long spans, lightweight; sensitive to seat weld detailing
CSD	Beams + profiled steel deck + RC slab	Deck panels with 50-127 mm slab	Shear studs on collectors enhances ductility

3. Numerical modeling

Finite element models were developed in SAP2000 for SCBF and SMF building models of varying heights and dimensions. Linear elastic static analyses were performed to evaluate the global structural response. Seismic floor forces were obtained from the equivalent lateral force procedure of ASCE-7 and distributed over the building height according to code requirements. These forces were then applied to the floor diaphragms to evaluate force-transfer mechanisms and collector demands.

In all models, the floor joists and beams were connected to the slabs in all directions. However, the slab-to-collector beam connections around the perimeter of a panel were modeled both with and without horizontal shear connectivity. Note that this shear connection is intended for in-plane seismic force transfer and is different from the shear connection required for gravity-load composite action. The two modeling assumptions are referred to throughout the paper as the Design Model and the Reality Model.

The SAP2000 models were primarily used to investigate global force distribution, collector forces, joist axial demands, diaphragm deformations, and support reactions. To verify the validity of the simplified global models, selected results were compared with detailed finite-element simulations developed in ABAQUS.

To capture detailed diaphragm behavior and connection response, a single-bay, single-story building was simulated in ABAQUS using geometric and material nonlinearities. All structural components, including slabs, beams, columns, joists, and connection regions, were modeled using three-dimensional solid elements. Equivalent seismic inertial loading was applied to the slab mass, while no direct lateral loads were assigned to the supporting members. A Static General analysis procedure was adopted. Default solution controls were used, while the analysis increment size was reduced until stable convergence was achieved. A minimum increment size of 10^{-5} was found to provide reliable convergence.

The ABAQUS models were used to investigate local force-transfer mechanisms, stress concentrations, and potential failure modes that could not be captured by the global SAP2000 models. Comparisons between SAP2000 and ABAQUS results showed good agreement in the elastic range, with differences generally remaining below 5% for joist axial forces, collector forces, displacements, stresses, and support reactions. The details of the analyses for each system are described below.

3.1 *Steel joist floor system*

The seismic performance of prefabricated steel joist floor systems was investigated through analyses in SAP2000, considering both SCBF and SMF as lateral-force-resisting systems. Although the study focused on steel joists, analogous behavior is expected for concrete joist systems, where the bottom steel flange is replaced by precast reinforced concrete elements.

Joists were modeled in both unidirectional and checkered layouts. Two modeling approaches were employed regarding the collector beam-slab connection:

• Design Model: This model restrains slab (shell element) nodes to collector beam (frame element) nodes in all degrees of freedom. This modeling approach is conventionally used by design engineers and represents the default assumption in most structural software packages, including SAP2000. In this model, horizontal seismic forces are transferred directly to collectors and perimeter beams through full diaphragm-to-beam connectivity. Such force transfer requires an effective positive shear connection, typically provided by studs, channels, plates, or other mechanical connectors capable of transferring in-plane seismic shear forces.

• Reality Model: This model restrains slab (shell element) nodes to collector beam (frame element) nodes only in the vertical (Z) direction, while in-plane translations and rotational degrees of freedom remain unconstrained. This allows vertical gravity-load transfer from the slab to the surrounding beams while permitting in-plane slip under seismic loading. The approach was adopted to simulate common construction practice in prefabricated joist floor systems, where perimeter beams and collector members are often not provided with dedicated shear connectors for horizontal seismic force transfer. In such systems, the concrete slab commonly bears directly on the top flange of the supporting beam, and friction alone cannot be relied upon as a dependable seismic force-transfer mechanism. Furthermore, possible vertical separation between the slab and supporting beam during earthquake excitation may further reduce any frictional resistance. For these reasons, no in-plane force transfer through friction was assumed in the present study. It should also be noted that frictional contact cannot be represented reliably within the simplified SAP2000 diaphragm modeling framework and would prevent direct comparison with the detailed ABAQUS models used for verification. Collector beams may still act compositely under gravity loading through conventional shear studs while lacking the connectivity required for diaphragm seismic force transfer.

Twelve SCBF structures (see Figure 7) with 5 m spans (widths = 3, 4, and 5 m; story height = 3 m) were analyzed using S235 steel, C25 concrete, and reinforcement with a yield strength of 300 MPa. The analytical results obtained from the two modeling approaches are presented in the following sections.

3.1.1 *Design model results for PJS*

In the Design Models, analyses showed that the seismic inertial forces bypassed the joists entirely. In other words, the floor acted as a rigid diaphragm. No significant axial forces developed in the joists. The seismic forces were transferred through the collectors and perimeter beams to the LFRS, consistent with conventional design assumptions and as illustrated in Figure 7.

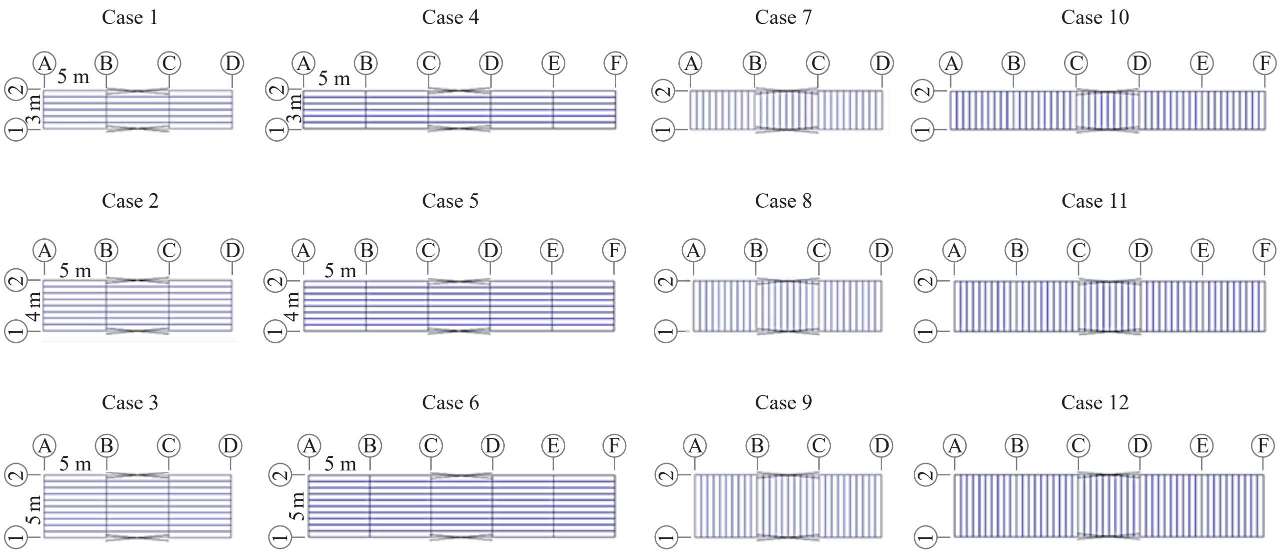


Figure 7. Base structures plan with steel joist floor

3.1.2 *Reality model results for PJS*

In the Reality Models, analyses revealed a joist-orientation-dependent load-transfer mechanism as follows:

• Parallel Excitation: When the applied seismic force (E_x) was parallel to the joists, exterior joists (Joists 1 and 5 in Figure 8) developed significant axial forces and acted as collectors, transferring inertial loads from the slab to the chords and main beams and subsequently to the LFRSs. In other words, the collector beams in the *X* direction were less effective in force transfer than the exterior joists. Figure 9 shows the typical internal force distribution for this condition.

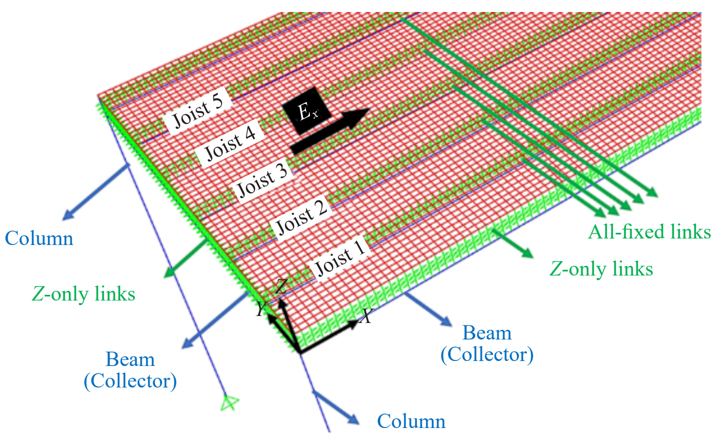


Figure 8. Elements and links in steel joist roof modeling

The axial compressive force remained nearly constant along the collector beams. Peak axial forces occurred in the exterior joists, while the force changed from compression to tension near the joist midspan. The middle joists exhibited lower axial demand. This behavior highlights the concept of the diaphragm core (see Section 4), in which only a portion of the diaphragm effectively participates in transferring seismic forces to the LFRS. Since joists in typical construction are generally designed for gravity loads only, the induced axial demands may become significant even when the slab remains within its elastic range. Increasing diaphragm width from 3 m to 4 m and 5 m (Cases 1-3 of Figure 7) did not significantly affect the exterior joist forces.

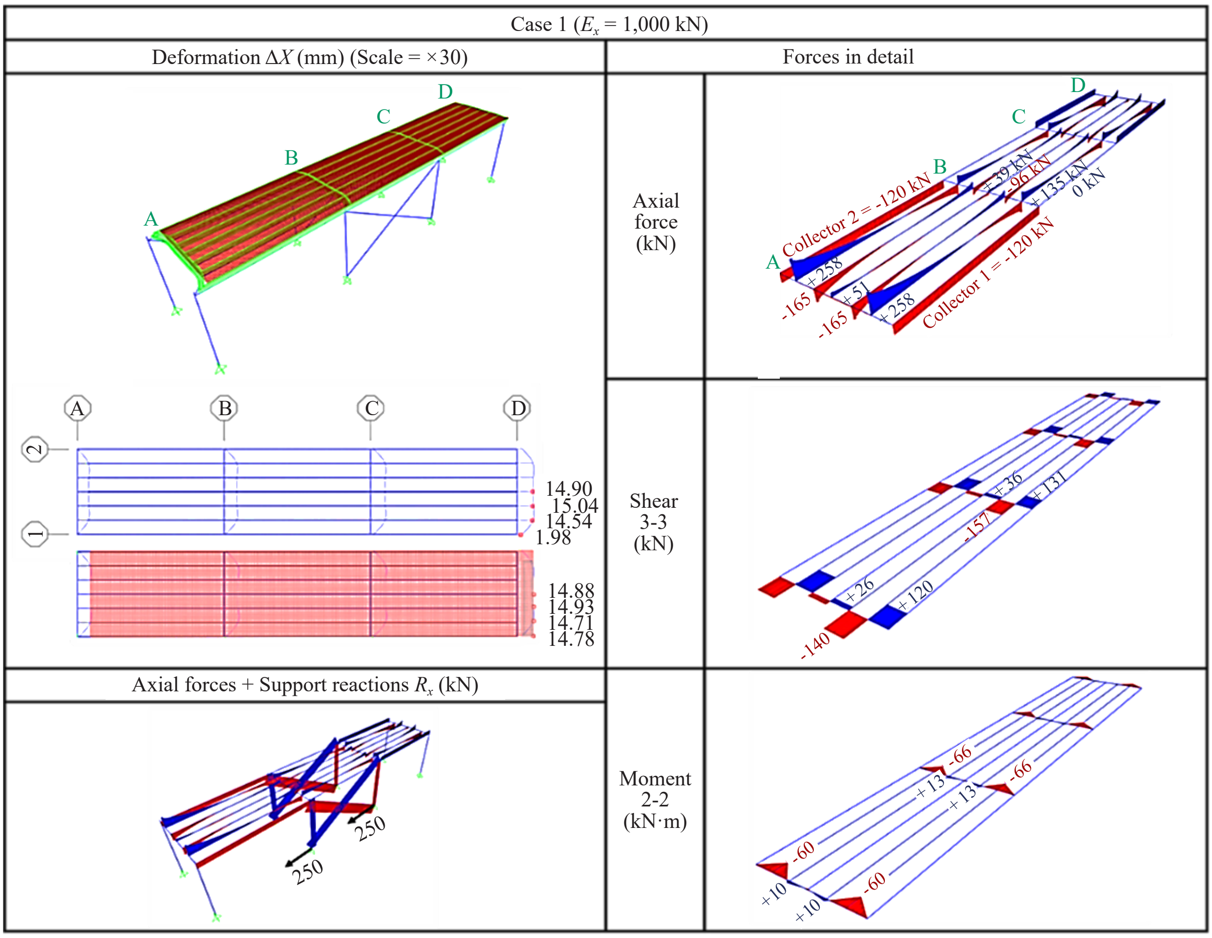


Figure 9. Force distribution in Case 1 under earthquake load

• Perpendicular Excitation: When the applied seismic force was perpendicular to the joists, axial collector forces increased progressively toward the braced bay (see Figure 10). Increasing diaphragm width (Cases 7-9 in Figure 7) did not significantly alter axial or shear demands at the joist-collector interfaces. Unlike the parallel excitation case, no diaphragm core formed. The joists were able to transfer seismic shear forces to the collectors without significant force redistribution within the diaphragm. Stress concentrations occurred primarily at the joist-collector interface, where direct diaphragm-to-collector connectivity was absent. In this configuration, inertial forces were transferred as shear from the slab to the joists and subsequently as concentrated forces at the joist-collector interfaces.

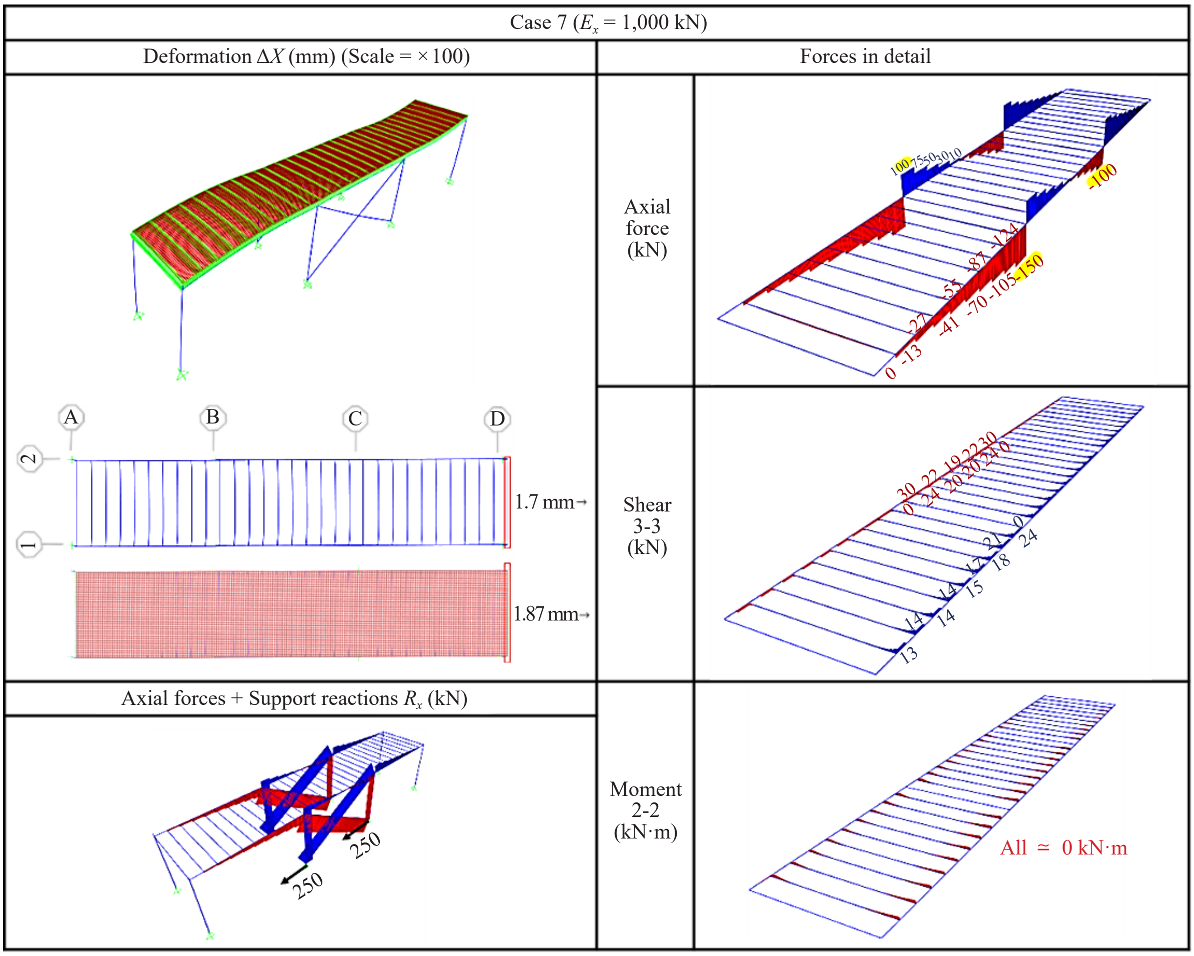


Figure 10. Force distribution in Case 7 under earthquake load

The modeling results also indicated weak-axis bending effects at joist-chord connections, producing average chord displacements of up to 1.5 mm. Such effects were not observed in the Design Models because full diaphragm-to-collector connectivity was assumed. Comparisons between the Design and Reality Models showed substantial differences in joist axial forces, collector forces, diaphragm deformations, stresses, and support reactions. These findings demonstrate that neglecting slab-collector beam slip can significantly alter the predicted force-transfer mechanism and may lead to unconservative estimates of collector and joist demands. The results further indicate that conventional modeling assumptions, in which diaphragm perimeter nodes are rigidly connected to collector beam nodes in all directions, may not accurately represent structures where perimeter beams are not provided with dedicated shear connectors for diaphragm force transfer.

3.1.3 *Checkered joist results for PJS*

In this section, the SCBF structures with 1-, 5-, and 10-story configurations and checkered joist layouts are examined for earthquake response using both the Design and Reality modeling assumptions. The results emphasized the non-uniformity of the force-transfer mechanisms within the diaphragm. Joists oriented perpendicular to the seismic load remained largely inactive in collector action, whereas joists oriented parallel to the seismic load and directly connected to perimeter collector beams exhibited significantly higher axial forces than those predicted by the Design Model. This concentration of seismic demand along specific joist lines demonstrates the limitations of the uniform force-transfer assumptions commonly adopted in conventional design models (see Figures 11-21).

In these figures, it can be clearly observed that the joists participate in the seismic force-transfer mechanism by developing axial forces. As a result, part of the diaphragm force is transferred through the joists, reducing the axial demand on the collectors. The figures compare the force distributions obtained from the Design and Reality modeling assumptions. In several cases, substantial differences were observed in the axial forces of beams and joists, indicating that the conventional Design Model may not accurately capture the actual force-transfer mechanism within the diaphragm. Similar trends were observed for collector forces, diaphragm deformations, stress distributions, and support reactions. The consistency of these observations across the analyzed structures confirms that joist participation in seismic force transfer is strongly influenced by diaphragm-to-collector connectivity and joist orientation.

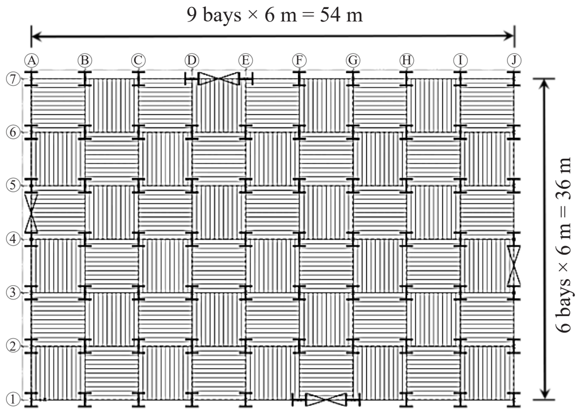


Figure 11. 1-story structure plan

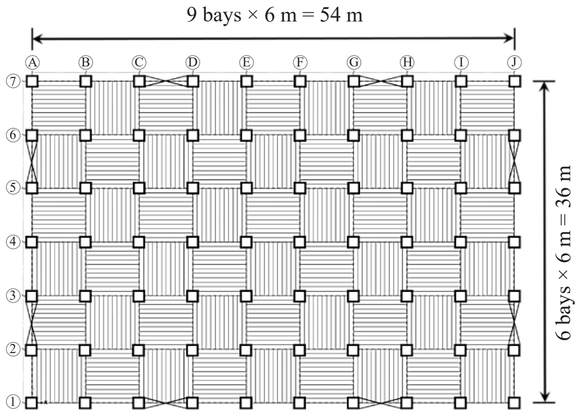


Figure 12. 5 & 10 story structure plan

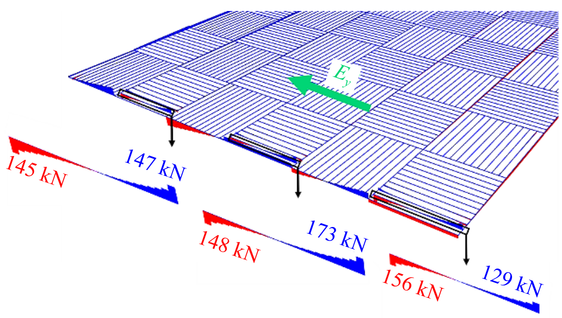


Figure 13. Force of floor beams in a 5-story structure under *y*-direction earthquake

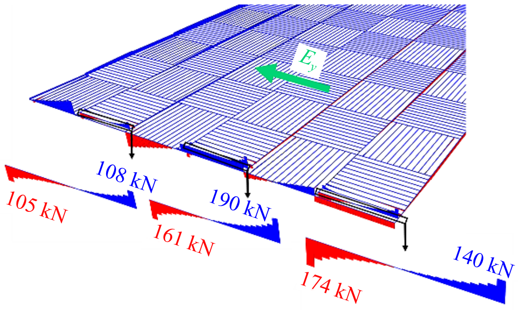


Figure 14. Force of floor beams in a 10-storey structure under *y*-direction earthquake

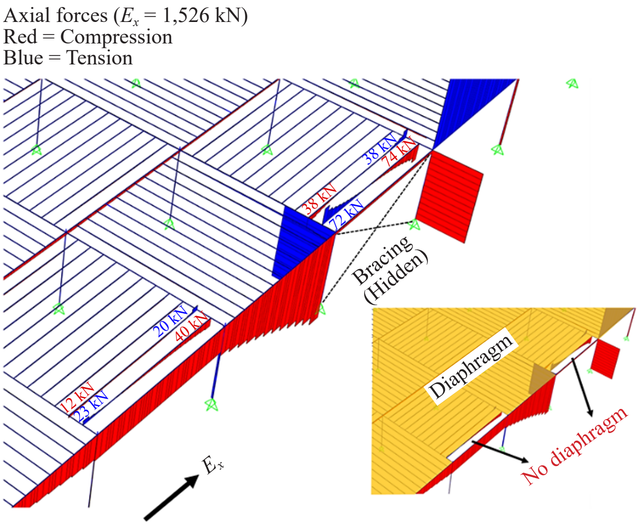


Figure 15. Axial force of beams and joists under earthquake in the *x*-direction

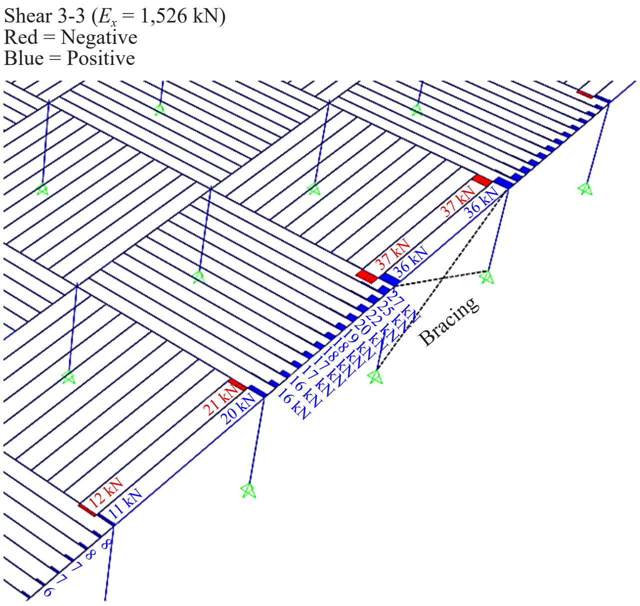


Figure 16. 3-3 axis shear in beams and girders under *x*-direction earthquake

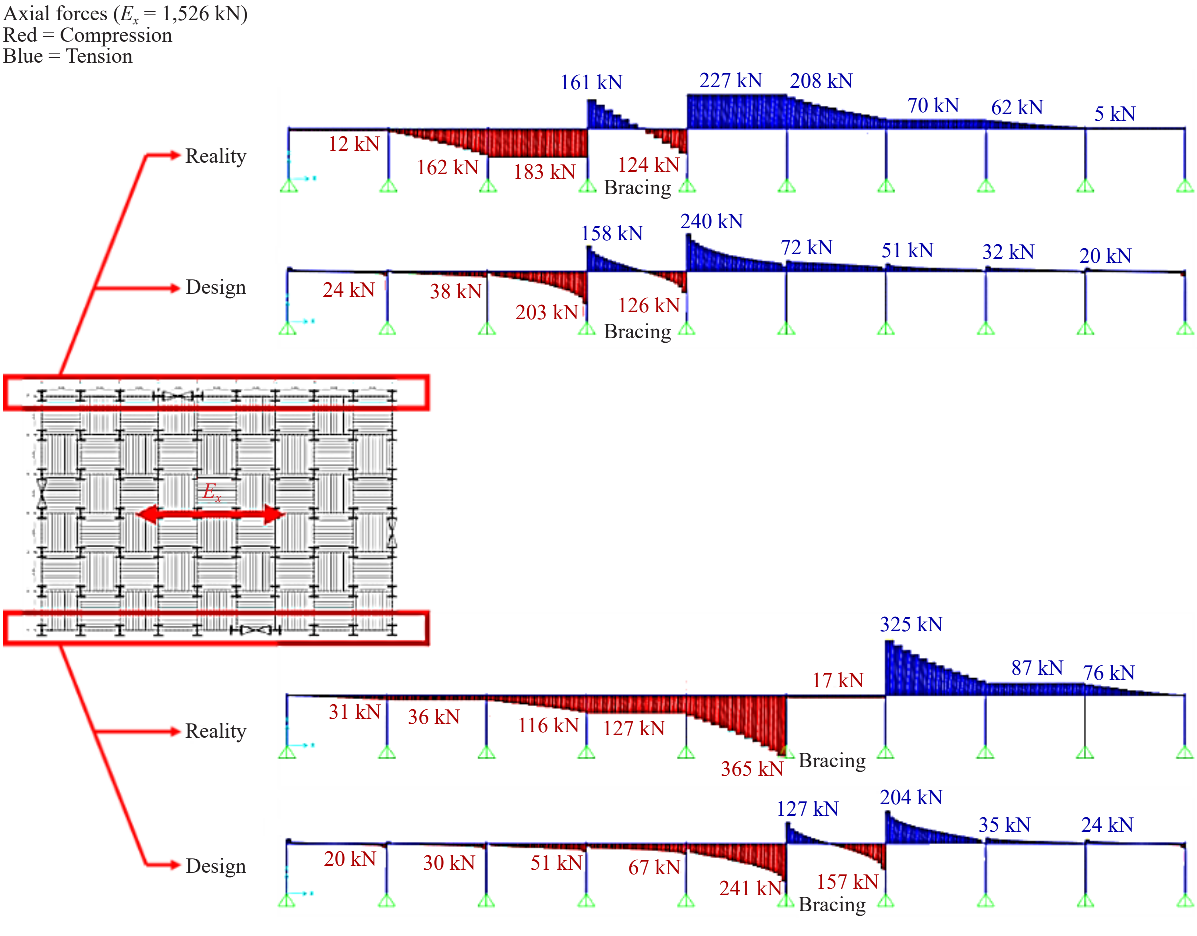


Figure 17. Axial force of roof collectors under x-direction earthquake

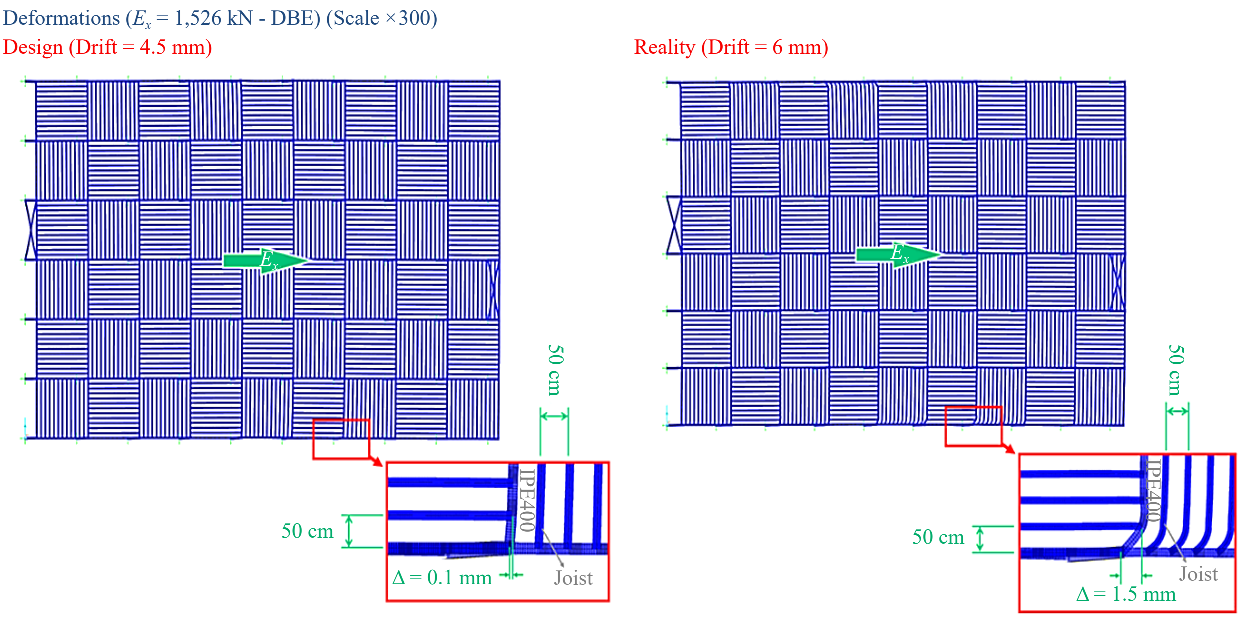


Figure 18. Comparison of deformations of joists and main beams under the x-direction earthquake of a single-story structure

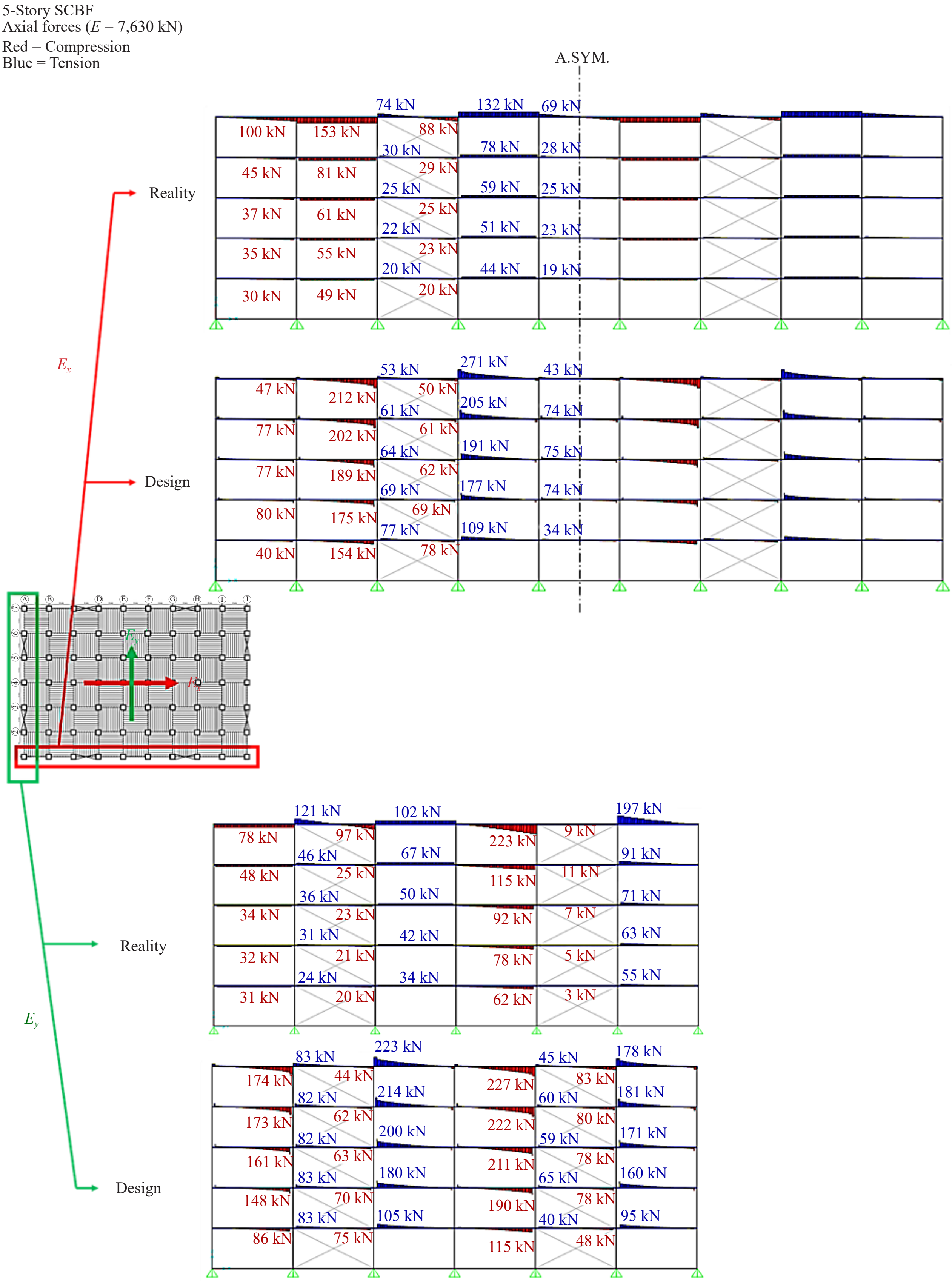


Figure 19. Axial force of perimeter beams under an earthquake in a 5-story structure

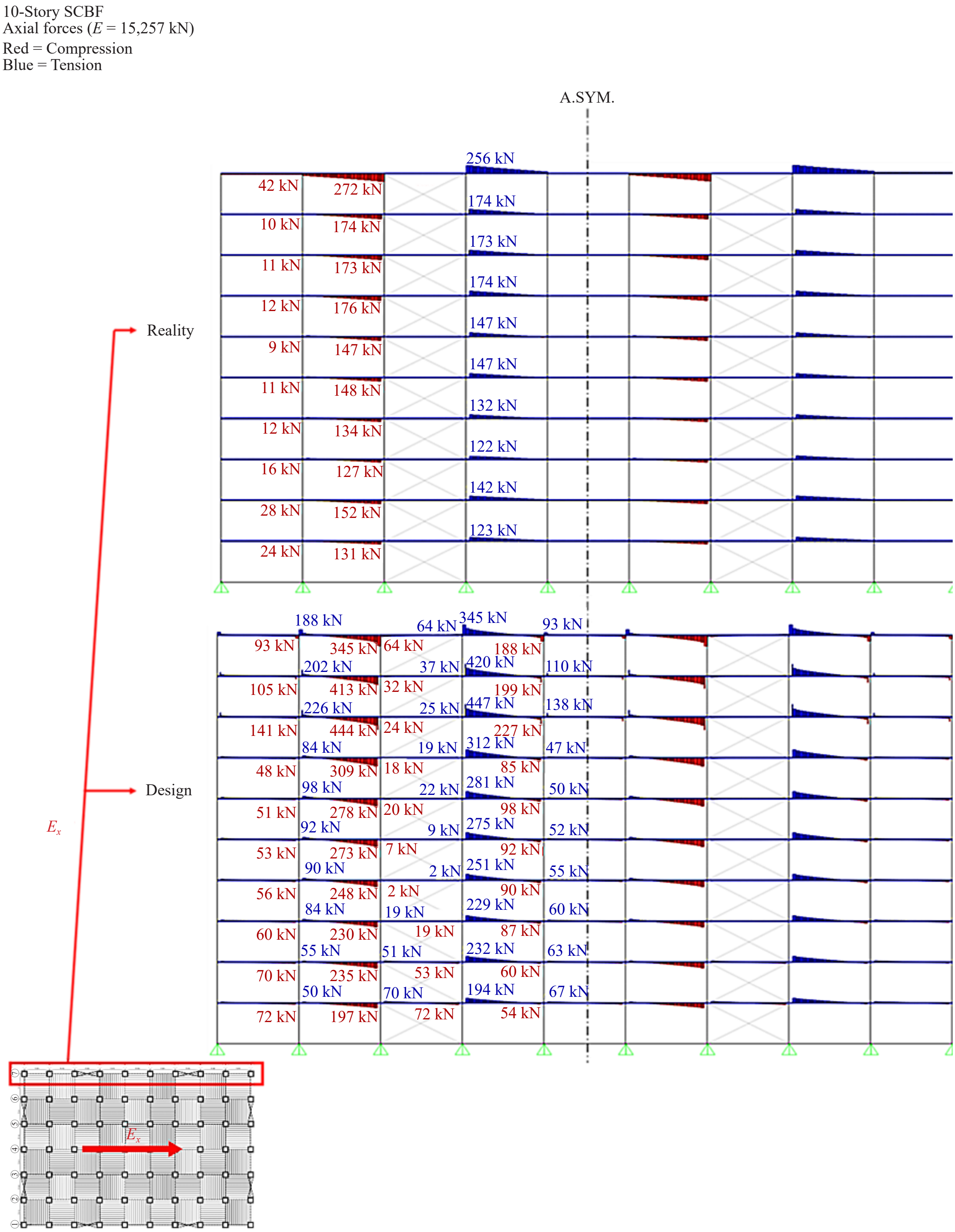


Figure 20. Axial force of peripheral beams under an x-direction earthquake in a 10-story structure

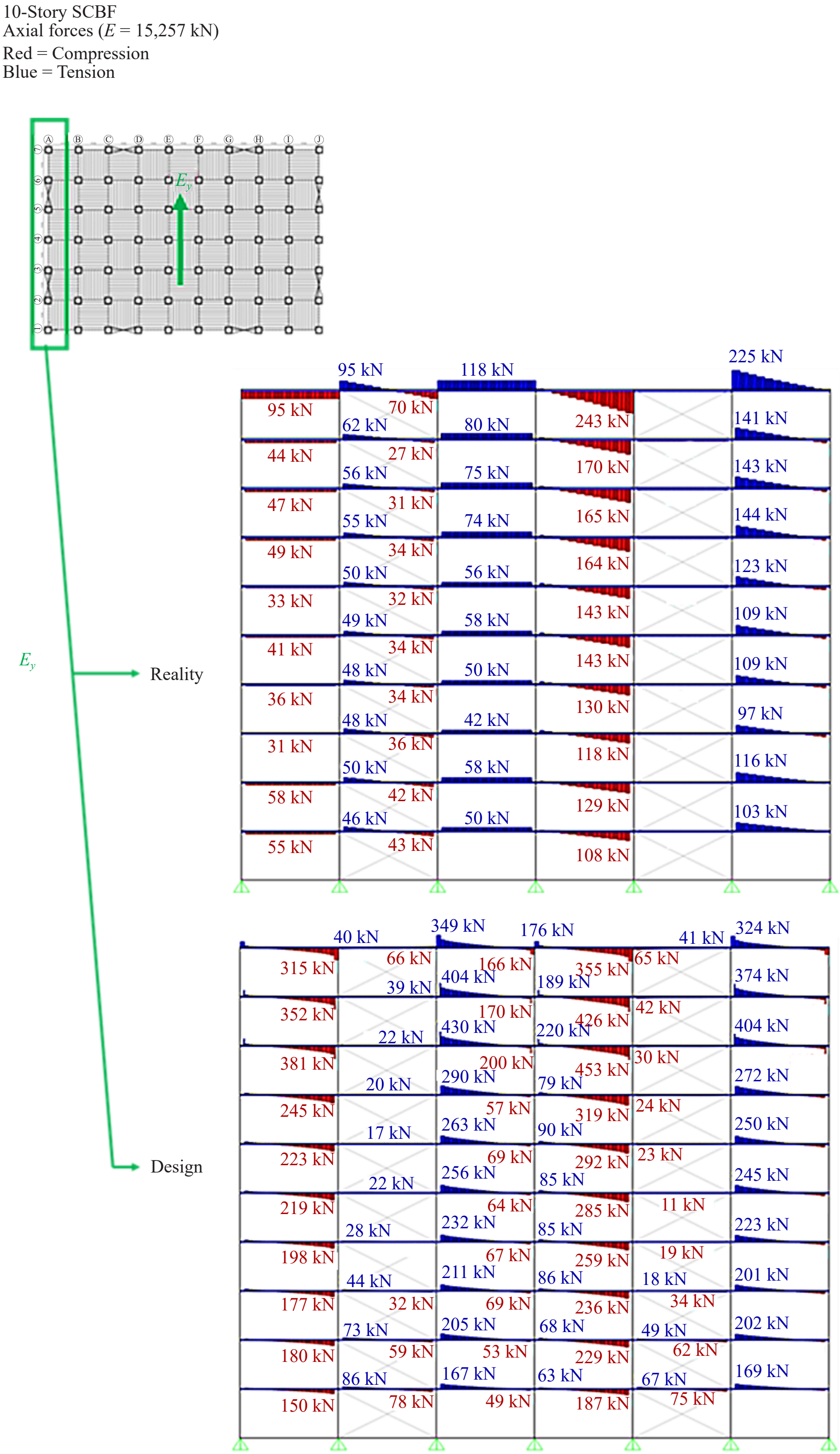


Figure 21. Axial force of peripheral beams under a *y*-direction earthquake in a 10-story structure

Note that in Figure 17, for the Reality Model, the 17 kN force in the braced bay does not change sign as observed in the upper collector bay. This behavior is attributed to the orientation of the joists within that bay and the resulting force-transfer mechanism.

3.1.4 *Results for PJS in SMF buildings*

The investigation was extended to SMF buildings with 1-, 5-, and 10-story configurations, each featuring identical floor plans comprising nine 6 m spans in the *x*-direction and six 6 m spans in the *y*-direction. All bays in these models were configured as SMFs, with the main beams designed as moment-resisting members throughout the structure. Joists were modeled in both checkered and unidirectional layouts. The Reality and Design modeling assumptions were compared in each case.

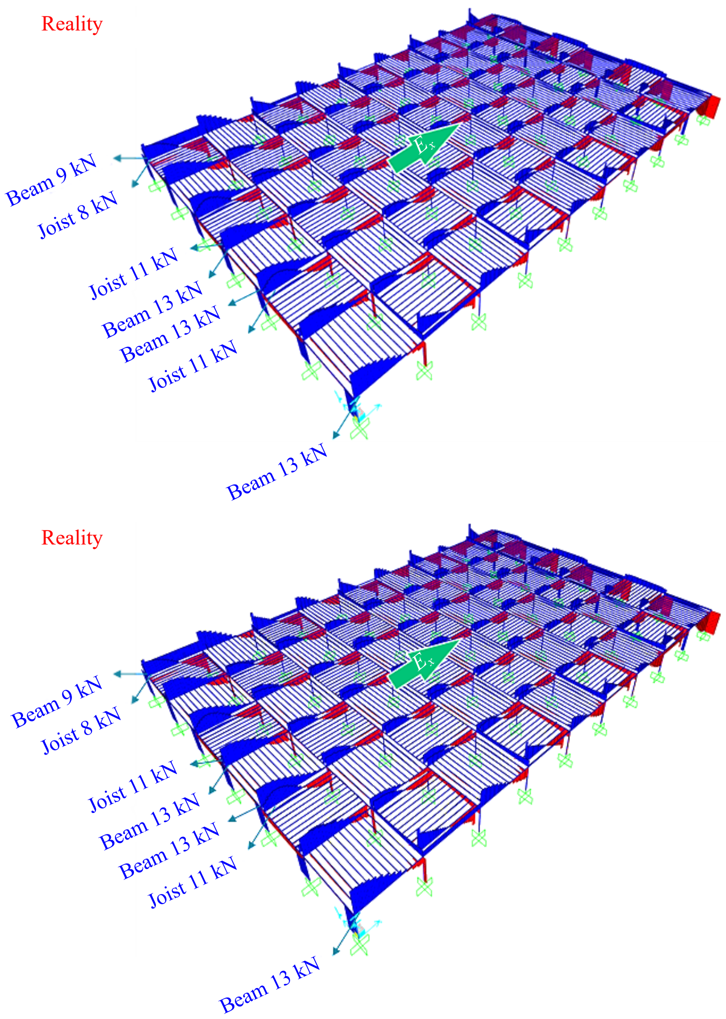


Figure 22. Axial force due to an earthquake in the *x*-direction with checkered floor joists

Checkered Joist Orientation (Figure 22).

• When seismic excitation was applied perpendicular to the joist orientation, axial force distribution shifted toward the collector beams rather than the joists.

• Exterior joists did not act as primary collectors in this orientation; instead, the collector beams carried most of the axial demand.

• The diaphragm response was more uniform compared with the parallel excitation case, and no distinct diaphragm core mechanism was observed.

• Stress concentrations occurred mainly at the slab-collector beam interfaces, particularly where dedicated shear connectors for diaphragm force transfer were absent.

• Modeling results indicated that the default software assumption of rigid slab-collector connectivity does not necessarily represent actual construction conditions, where slab-beam slip may occur and perimeter collector beams may not provide full diaphragm force transfer.

Parallel Joist Orientation (Figure 23).

• When seismic excitation was applied parallel to the joist orientation, the exterior joists along the building sides consistently acted as collectors.

• Significant axial forces developed in these exterior joists, while interior joists carried lower axial demand.

• The axial force distribution remained generally similar across the different building heights considered (1-, 5-, and 10-story structures).

• The force-transfer mechanism was strongly influenced by the presence or absence of diaphragm-to-collector connectivity along the perimeter beams.

• In the absence of dedicated shear connectors for diaphragm force transfer, the load path changed and followed the Diaphragm Core Mechanism (see Section 4). Under this condition, a significant portion of the lateral forces was transferred through the exterior joists rather than directly through the collector beams.

• Due to the relatively high in-plane stiffness of the concrete topping, the joists experienced nearly uniform lateral displacement, resulting in a coupled axial response in which the exterior joists developed the highest axial demands.

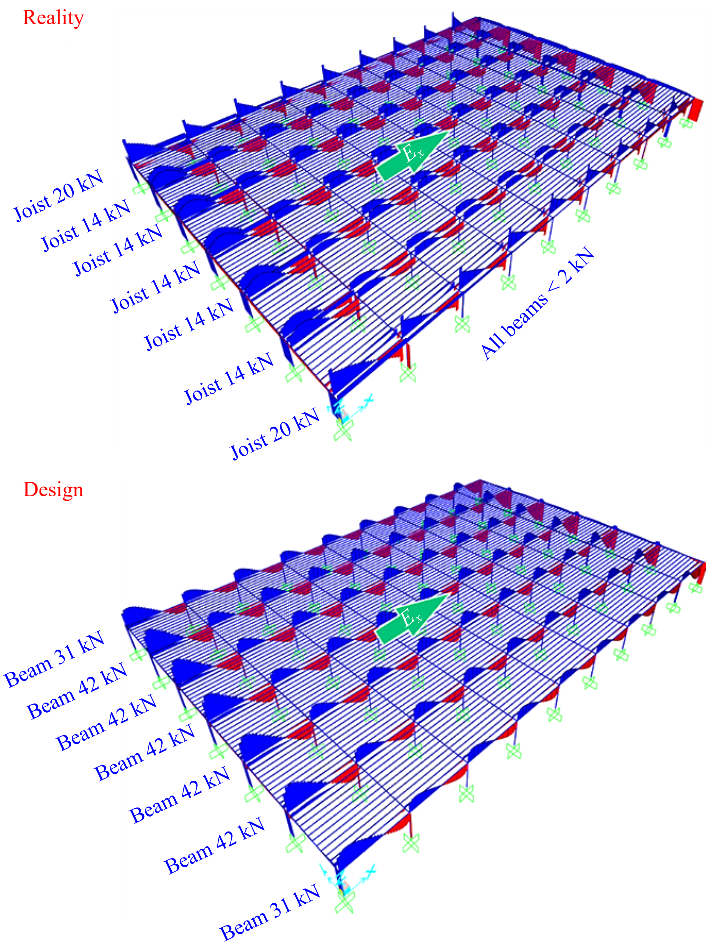


Figure 23. Axial force due to an earthquake in the *x* direction with unidirectional floor joists

Based on the modeling results, it can be observed that structural analysis and design software such as SAP2000, when used with default settings, automatically constrains diaphragm perimeter nodes to the nodes of the surrounding beams in all directions (Design Model). This assumption differs from the Reality Model presented herein, where diaphragm-to-collector connectivity is limited to vertical load transfer and in-plane slip may occur along the diaphragm boundaries. It should be emphasized that the connectivity discussed here is related to seismic force transfer and is distinct from the shear connection typically provided for gravity-load composite action.

3.1.5 *Results for joist connection detail*

To capture detailed joist behavior beyond simplified structural models, a representative roof bay from the 10-story SMF structure was extracted and modeled in ABAQUS using three-dimensional solid elements with both geometric and material nonlinearities. The model consisted of a 50 mm reinforced concrete slab, 5 m steel joists, IPB300 beams, and IPB400 columns. All structural components were modeled using solid elements to explicitly represent local stress distributions, connection behavior, and potential instability mechanisms. The applied lateral load corresponded to the seismic force demand obtained from the global SAP2000 model after distribution of the design base shear according to ASCE-7 provisions. The load was applied incrementally using the Static General procedure until the first local failure mechanism was observed.

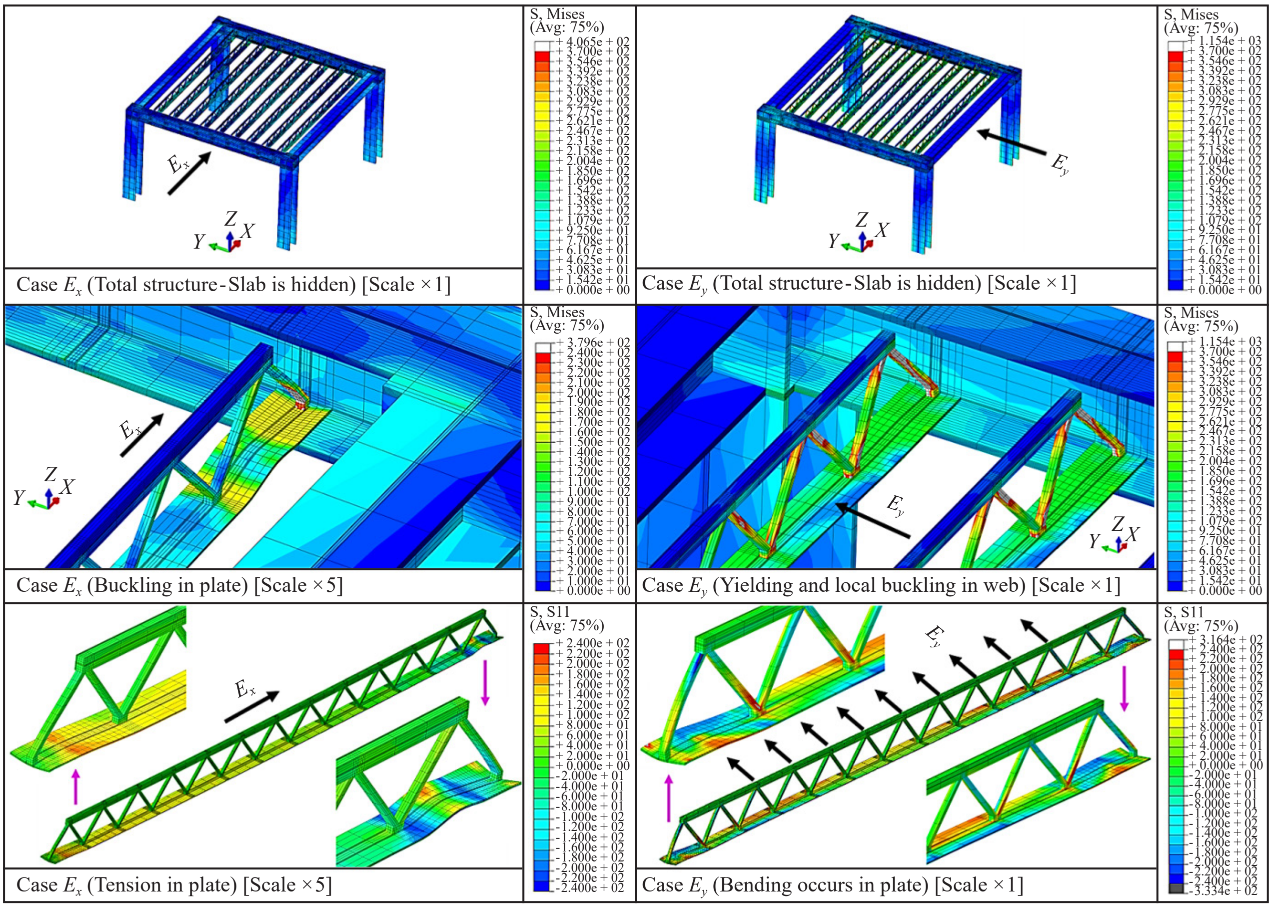


Figure 24. Modeling steel joist floor in ABAQUS

The ABAQUS model served as an independent verification of the global SAP2000 results. Comparison of axial forces, support reactions, stresses, and deformations showed agreement within 5% in the elastic range, providing confidence in the global force-transfer mechanisms predicted by the simplified structural models.

The refined model confirmed the force-transfer mechanisms observed in the SCBF and SMF analyses and revealed several local failure modes, including:

• Tensile yielding of the joist bottom plate;

• Compressive buckling of the joist bottom plate;

• Local failure of welded joist-to-beam connections;

• Excessive torsional deformation of the joists.

No significant diagonal cracking of the concrete slab, slab-joist separation, or yielding of the joist web reinforcement was observed within the range of loading considered in this study. The results indicate that the primary vulnerabilities are associated with the steel joists and their connections rather than the concrete slab itself. Failure initiation in the ABAQUS simulations was defined by the attainment of the material ultimate strength criterion, represented by von Mises stresses reaching the ultimate tensile capacity of the corresponding steel component. Once this limit was reached, the associated member or connection was considered to have experienced local failure. These localized instabilities, manifested as yielding, buckling, connection failure, or excessive torsional deformation, highlight the limitations of conventional diaphragm idealizations (Design Model) and emphasize the importance of considering slab-beam slip and local connection behavior when evaluating seismic force-transfer mechanisms. The detailed ABAQUS simulations further demonstrated that local connection failures may occur even when the global diaphragm response remains essentially elastic, underscoring the need for refined assessment of collector-force transfer mechanisms in joist-supported floor systems (see Figure 24).

3.1.6 *General observations for PJS*

The findings demonstrate that the conventional practice of applying the same response modification factor (R) used for the LFRS directly to diaphragms may not accurately represent the actual force-transfer mechanism in one-way joist systems without dedicated shear connectors for diaphragm-to-collector force transfer. In such systems, the seismic load path can differ substantially from the assumptions typically adopted in structural analysis software, resulting in significant force redistribution among collectors, chords, and joists.

The analyses consistently showed that when diaphragm-to-collector force transfer was not provided, exterior joists participated in the seismic load path and developed significant axial forces. This behavior was observed in both SCBF and SMF systems and was confirmed by detailed ABAQUS simulations. The resulting force-transfer mechanism differed from the conventional rigid-diaphragm assumption and produced localized demands that were not captured by the Design Model.

The results indicate that diaphragm design forces obtained using reduced force levels may underestimate the demands in some structural components. Therefore, diaphragm design should explicitly consider the actual force-transfer mechanism and the connectivity between the slab and collector beams.

Based on the numerical results and engineering observations obtained in this study, diaphragm response modification factors approaching unity ($R_s \leq 1$) may provide a more conservative representation of diaphragm force demands in one-way joist floor systems without positive diaphragm-to-collector force transfer. However, this recommendation should be regarded as a preliminary engineering guideline rather than a formally calibrated design value. Additional experimental studies, full-scale testing, and broader analytical investigations are required before generalized code recommendations can be established.

Reliable seismic performance may be achieved through either:

• Explicit design of joists, chords, collectors, and their connections to resist the induced axial and shear forces, including checks for local yielding, connection failure, and member instability;

• Providing positive diaphragm-to-collector force transfer through dedicated shear connectors, thereby establishing a direct load path from the diaphragm to the LFRS and making conventional diaphragm modeling assumptions more representative of actual behavior.

For practical design applications, the diaphragm core concept proposed in this study may be used as a simplified modeling approach to represent the reduced effective diaphragm width in regions where diaphragm-to-collector force transfer is not provided. The concept offers a rational explanation for the concentration of seismic forces in exterior joists and may assist engineers in identifying potential force-transfer deficiencies during design and assessment.

It should be recognized that the conclusions presented herein are based on regular building configurations and the specific floor systems investigated. Further research is required to evaluate the applicability of the proposed diaphragm core concept to irregular floor layouts, asymmetric structural systems, and other diaphragm configurations.

3.2 *Open-web steel joist floor system*

The seismic performance of OWSJ floor systems was investigated with emphasis on the role of slab-perimeter beam connectivity. This system employs steel truss joists, typically spaced at 3 m, supporting a 90 mm reinforced concrete slab. While adequate for gravity load combinations, its seismic behavior is highly sensitive to the presence or absence of diaphragm-to-collector force transfer at the slab-beam interface.

A baseline SCBF structure was designed in accordance with Steel Joist Institute specifications (Figure 25) and analyzed using linear elastic static seismic loading. The seismic design forces were determined in accordance with ASCE-7 provisions. FEMA-P695 ground-motion parameters were used only to establish representative seismic hazard levels and design spectral values; no nonlinear time-history analyses were performed in this study. The selected seismic parameters were $S_{DS} = 0.5$ g, $S_{D1} = 0.2$ g, $F_a = 1$, $F_v = 1.5$, $R = 6$, $C_d = 5$, $\Omega_0 = 2$.

The modeled structure was 4.5 m (15 ft) high with a central V-brace, 15.3 m (50 ft) joist spans at 3 m (10 ft) spacing, and dead/live loads of 4.5 kN/m^2 (94 psf) and 3.5 kN/m^2 (73 psf), respectively. Structural members included 30CJ series joists, W40 × 235 beams and columns, and Hollow Structural Section (HSS) 6 × 6 × 3/8 braces fabricated from ASTM A992 and ASTM A500 steels, together with a 90 mm (3.5 in), 42 MPa (6,000 psi) concrete slab.

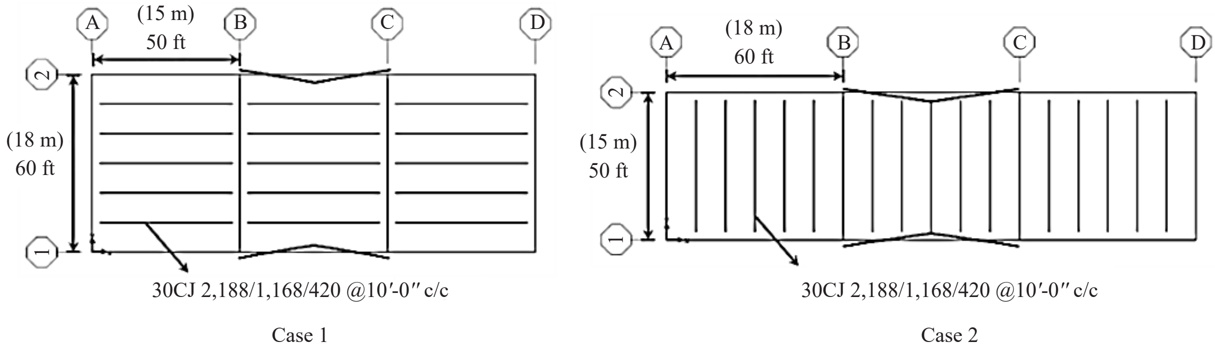


Figure 25. Basic structure plan with OWSJ

Two configurations were examined:

• Design Model: Full diaphragm-to-collector connectivity was assumed between the slab and perimeter collector beams.

• Reality Model: Shear transfer was provided through the joists only, while the slab was connected to perimeter beams through gravity-load transfer links without dedicated diaphragm shear transfer (Figure 26). This assumption reflects common construction practice in which the slab bears on the supporting beams without mechanical details specifically designed for horizontal seismic force transfer.

The Reality Model was adopted because positive diaphragm-to-collector shear transfer is frequently absent in joist-supported floor systems. In addition, frictional resistance at the slab-beam interface was neglected. Although limited friction may exist under gravity loading, it is difficult to quantify reliably, may be reduced by cracking or vertical seismic motion, and cannot be represented explicitly within the SAP2000 modeling framework used in this study. Neglecting friction also allowed direct comparison and verification of SAP2000 results against the detailed ABAQUS simulations.

Results of the SAP2000 analyses showed that, in the Design Model, diaphragm forces were distributed more uniformly and were transferred directly to the collectors and the LFRS. In contrast, the Reality Model activated the diaphragm core mechanism when the applied seismic force was parallel to the joists. Under this condition, the force-transfer path changed and a significant portion of the diaphragm force was transferred through the peripheral joists rather than directly through the collector beams (see Figure 27). This resulted in increased axial demands in the perimeter joists and elevated force concentrations at the joist-seat connections.

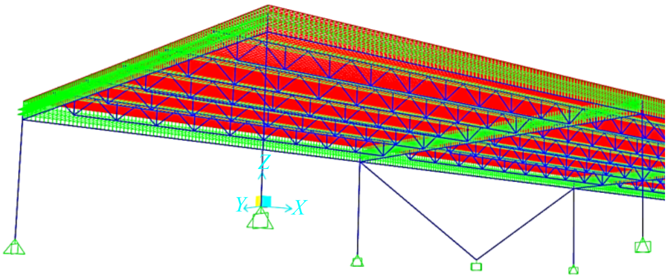


Figure 26. Modeling the slab link to beams and joists

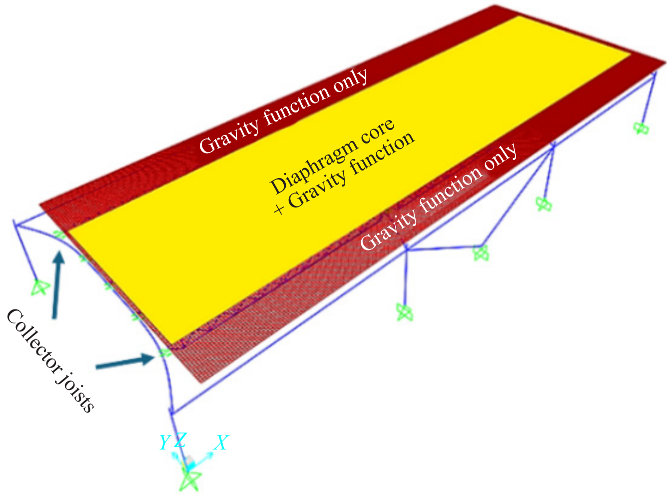
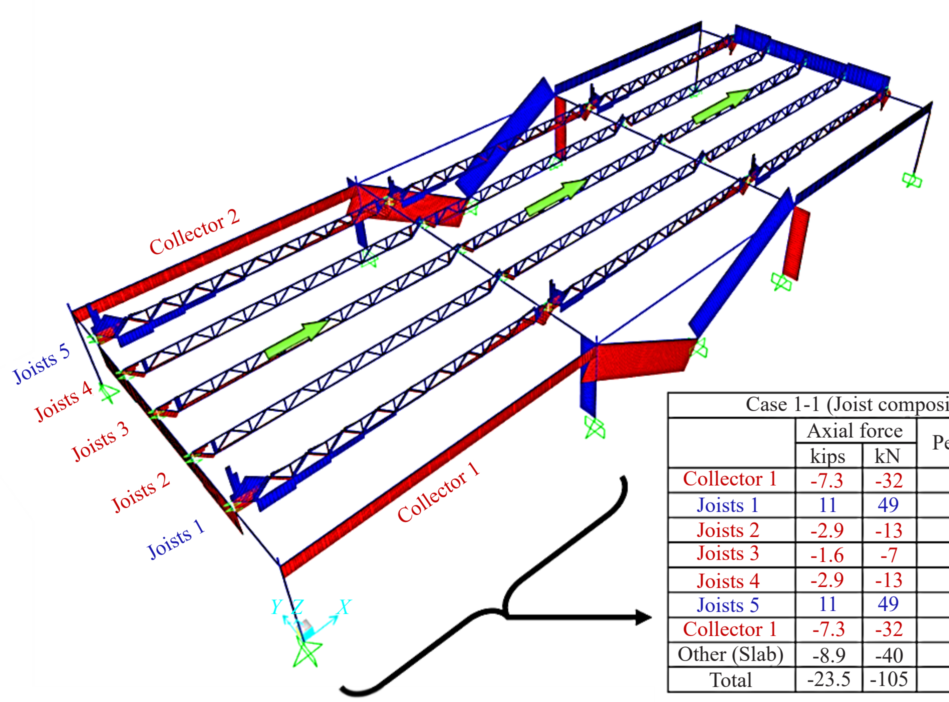


Figure 27. The diaphragm core when an earthquake is applied in the *x*-direction

Figure 28 illustrates the uneven force distributions obtained from the Reality Model, while Figure 29 demonstrates the more uniform force-transfer mechanism obtained when diaphragm-to-collector connectivity is provided along the perimeter beams (Design Model). Comparisons of axial forces, support reactions, and diaphragm deformations consistently showed increased force concentration in the perimeter joists when diaphragm-to-collector force transfer was absent.

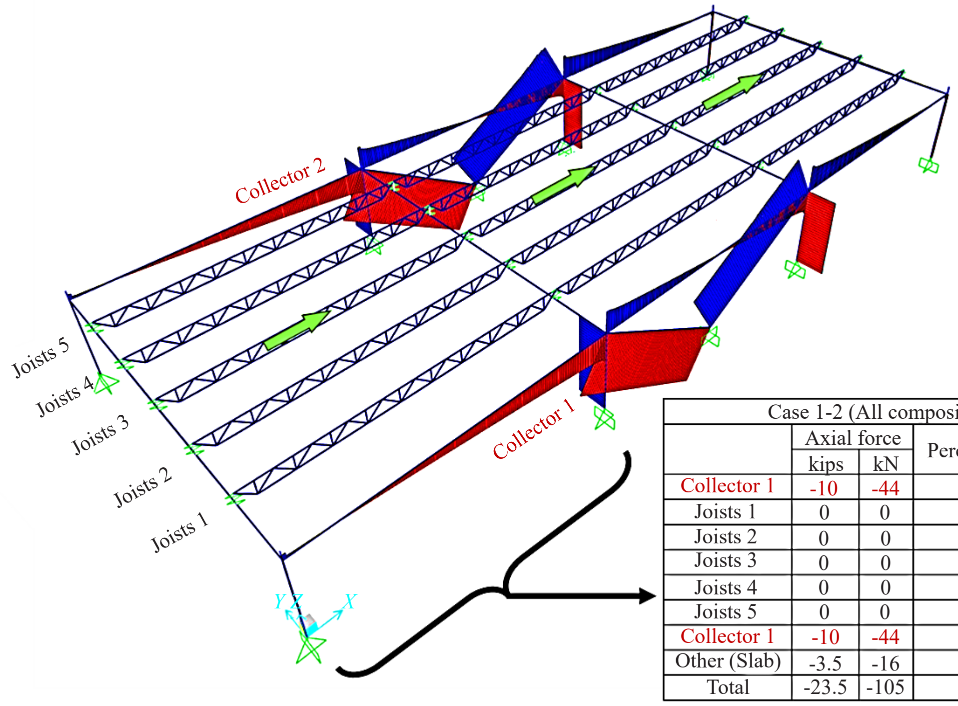
When seismic excitation was applied perpendicular to the joist orientation, the presence of diaphragm-to-collector connectivity along the perimeter beams prevented significant force transfer through the joists. In contrast, when such connectivity was absent (Reality Model), shear forces developed at the joist supports and became concentrated at the joist-perimeter beam interfaces. As illustrated in Figure 30, these forces appeared primarily as weak-axis (3-3 axis) shear demands at the support regions.

The observed force-transfer patterns were consistent with those obtained for the prefabricated steel joist systems discussed previously, indicating that the diaphragm core mechanism is not limited to a specific joist type but may develop in various joist-supported floor systems when direct diaphragm-to-collector force transfer is not provided.



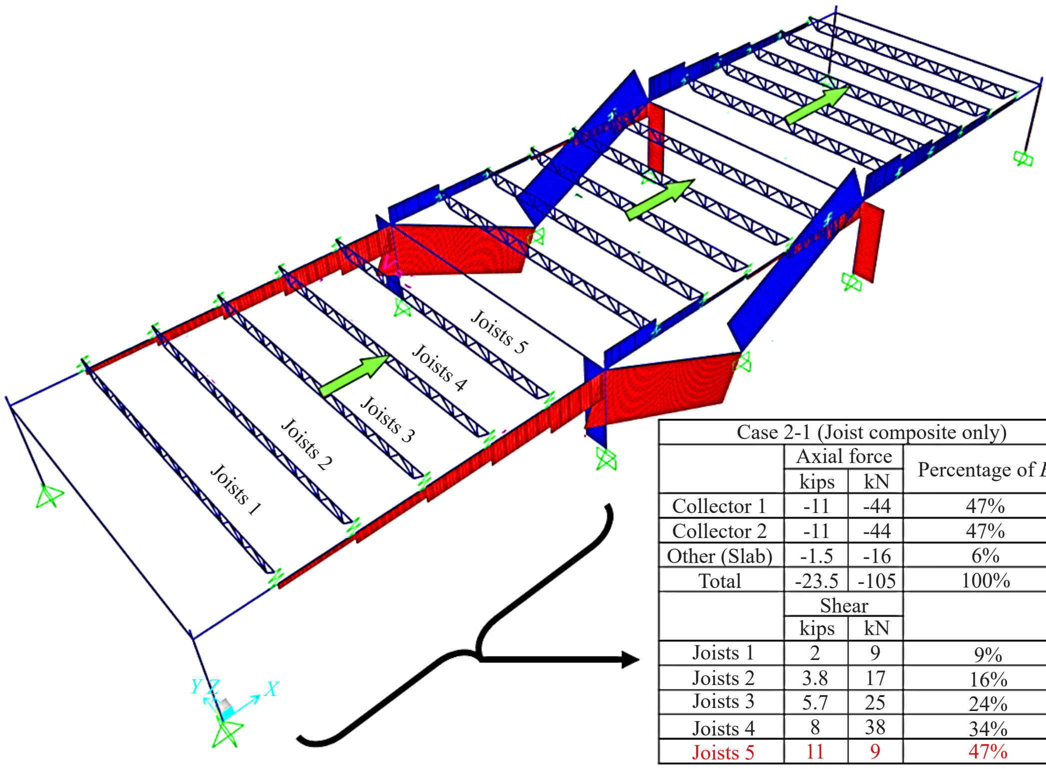
Case 1-1 (Joist composite only)			
	Axial force		Percentage of E_x
	kips	kN	
Collector 1	-7.3	-32	31%
Joists 1	11	49	47%
Joists 2	-2.9	-13	12%
Joists 3	-1.6	-7	7%
Joists 4	-2.9	-13	12%
Joists 5	11	49	47%
Collector 1	-7.3	-32	31%
Other (Slab)	-8.9	-40	38%
Total	-23.5	-105	100%

Figure 28. Values of axial forces, anchors, and shears for Case 1 in Reality Model



Case 1-2 (All composite)			
	Axial force		Percentage of E_x
	kips	kN	
Collector 1	-10	-44	15%
Joists 1	0	0	43%
Joists 2	0	0	0%
Joists 3	0	0	0%
Joists 4	0	0	0%
Joists 5	0	0	0%
Collector 1	-10	-44	43%
Other (Slab)	-3.5	-16	15%
Total	-23.5	-105	100%

Figure 29. Seismic forces in Design Model



Case 2-1 (Joist composite only)			
	Axial force		Percentage of E_x
	kips	kN	
Collector 1	-11	-44	47%
Collector 2	-11	-44	47%
Other (Slab)	-1.5	-16	6%
Total	-23.5	-105	100%
	Shear		
	kips	kN	
Joists 1	2	9	9%
Joists 2	3.8	17	16%
Joists 3	5.7	25	24%
Joists 4	8	38	34%
Joists 5	11	9	47%

Figure 30. Values of axial forces, anchors and shears for Case 2, Reality Model

3.2.1 *Results for OWSJ connection*

Refined ABAQUS models (Figures 31-33) were developed to capture the complex geometry of open-web steel joists and their connections. All structural components, including the concrete slab, joist chords, web members, seats, and supporting beams, were modeled using three-dimensional solid elements. Geometric and material nonlinearities were included to capture local stress concentrations, instability mechanisms, and connection behavior that could not be represented by simplified line-element models.

The applied lateral loading corresponded to the seismic force demand obtained from the global SAP2000 model after distribution of the design base shear according to ASCE-7 provisions. The load was applied incrementally using the ABAQUS Static General procedure until the onset of local failure. Convergence was achieved using a minimum analysis increment of 10^{-5}. The material properties adopted for the ASTM A992 steel in the ABAQUS models were calibrated based on the data reported by Cai et al. [15].

The ABAQUS simulations confirmed the global force-transfer mechanisms observed in the SAP2000 models. Comparisons of axial forces, support reactions, deformations, and stress distributions showed agreement within 5% in the elastic range, providing confidence in the simplified global models while revealing additional local behaviors.

The primary local failure modes observed in the analyses included:

- Yielding of joist bottom chords;
- Overstress at seat welds;
- Local buckling of web members;
- Failure at joist-beam connections.

These mechanisms highlight the limitations of conventional diaphragm idealizations (Design Model) and demonstrate the importance of considering slab-beam interaction and local connection behavior when evaluating seismic force-transfer mechanisms.

The prescribed 127 mm (5 in) seat weld, while adequate for gravity load transfer, was found to experience high stress demands under the applied seismic loading. ABAQUS results showed von Mises stresses approaching or exceeding the material yield strength in critical regions of the seat connection (Figure 33), indicating that the joist seat may represent a critical component in the seismic load path. Failure initiation was defined as the point at which the von Mises stress reached the ultimate strength capacity of the corresponding steel component.

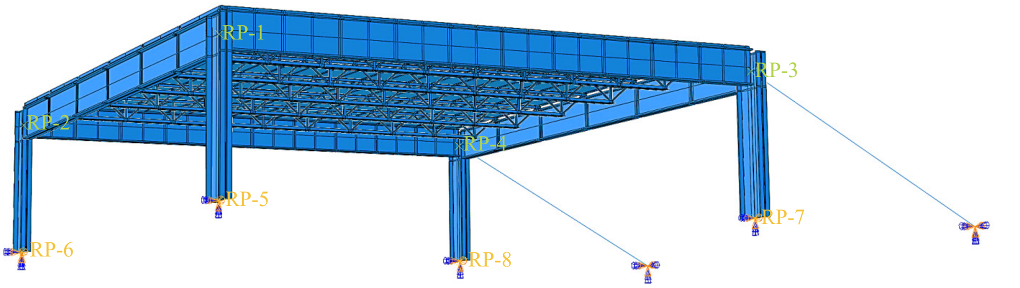


Figure 31. Modeling a roof with open web beams in ABAQUS

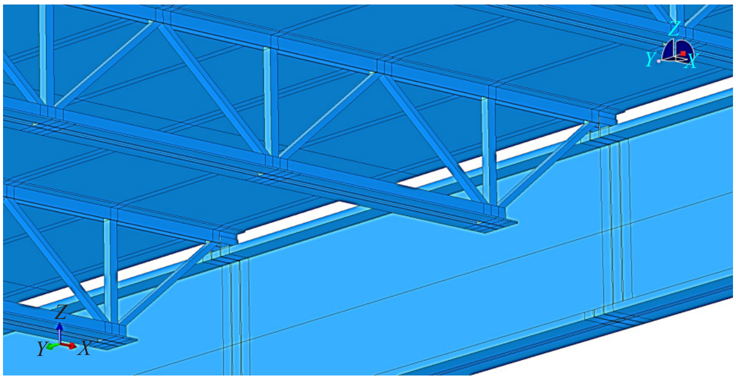


Figure 32. Details of the connection and seating of the beam to the main beam

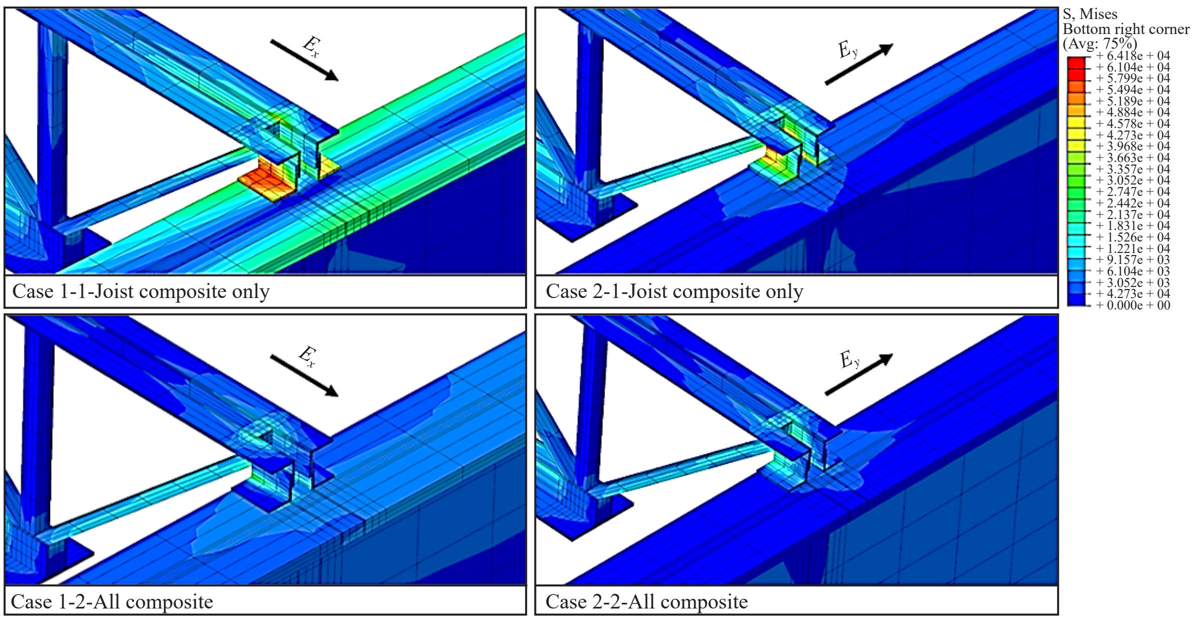


Figure 33. The von Mises and yield stresses of the beam seat are high in other cases as well

The integrated SAP2000 and ABAQUS analyses led to the following observations:

• When diaphragm-to-collector force transfer along the perimeter beams was not provided, the load path changed and the diaphragm core mechanism developed (see Figure 27 and Section 4). Under these conditions, peripheral joists participated in transferring diaphragm forces and experienced increased axial and shear demands.

• The joist seat was identified as a critical region due to the concentration of stresses associated with seismic force transfer. In several cases, local stresses exceeded those anticipated in conventional gravity-load design.

• Providing positive diaphragm-to-collector force transfer along perimeter beams resulted in a more direct load path to the LFRS, reduced force demands on the joists, and alleviated stress concentrations at joist-seat connections.

• No significant concrete slab cracking or slab-to-joist separation was observed within the loading range investigated. The dominant vulnerabilities were associated with steel components and connection details rather than the concrete slab itself.

The results demonstrate that local connection behavior can govern the seismic performance of OWSJ floor systems even when the global diaphragm response remains essentially elastic. Consequently, assessment of diaphragm force-transfer mechanisms should include verification of joist-seat connections and other local details that may not be adequately represented in conventional structural analysis models.

3.3 *CSD floor system*

The seismic performance of CSD floor systems was investigated through numerical analyses, with designs carried out in accordance with U.S. steel design codes including ASCE-7 [2], AISC-360 [16], AISC-341 [17], AISC-358 [18], ACI-318 [19], NIST GCR 10-917-4 [20], and SDI DDM4 [21]. Finite-element modeling was performed in SAP2000, supplemented by manual verification of seismic design provisions not directly handled by the software. The selected building archetypes (Figures 34-36) were based on NIST GCR 10-917-8 [22] to ensure representativeness across a broad spectrum of building configurations and lateral-force-resisting systems. Two primary systems were examined: SCBF and SMF, both featuring similar floor plans. Each system was modeled with multiple story heights and floor configurations to generalize the findings.

Two roof configurations were considered:

• Series 1: 127 mm (5 in) slabs with 1.5 m (5 ft) joist spacing.

• Series 2: 50 mm (2 in) slabs with 0.6 m (2 ft) joist spacing, resembling steel joist slabs.

Material properties conformed to ASTM A992, ASTM A500 Grade B, and ASTM A572 Grade 50, with E70 welding electrodes.

For SCBF systems, braces were configured as two-story X-braces (inverted V in the lower story and V in the upper story). Beams, columns, and connections were proportioned for capacity-protected seismic demands and detailed in accordance with ASCE-7, AISC-341, and AISC-360. Column sections varied every two stories, while beams were maintained constant within each story. The seismic design parameters were, $R = 6$, $C_d = 5$, and $\Omega_0 = 2$.

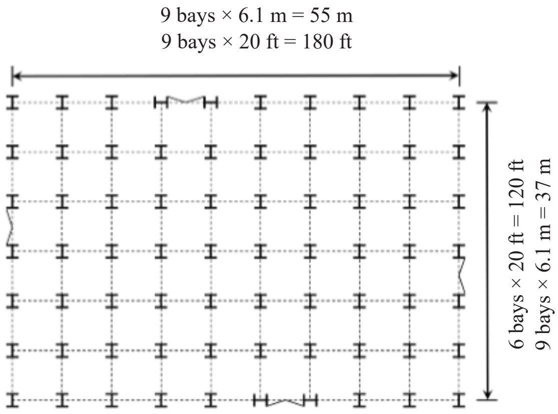


Figure 34. Plan of 2-story structures

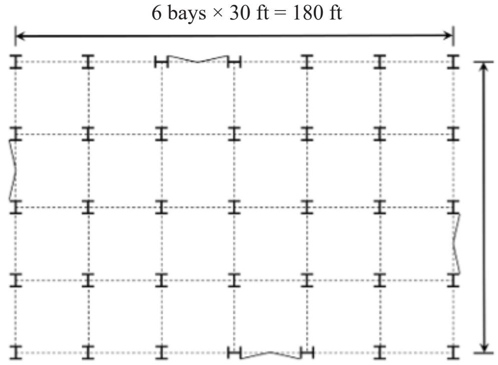


Figure 35. Plan of 3-story structures

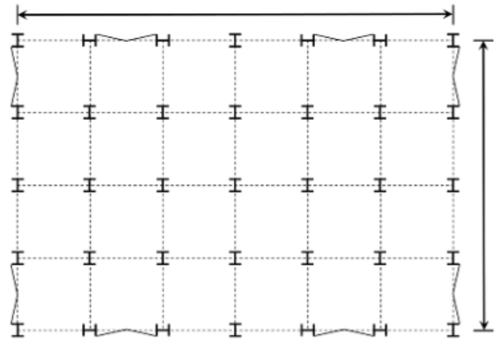


Figure 36. Plan of 6 & 12-story structures

Analysis of the 12-story SCBF archetype, representing the most critical configuration considered, revealed that omission of diaphragm-to-perimeter beam shear transfer (Reality Model) consistently altered the diaphragm force-transfer mechanism. In the Reality Model, axial forces developed in floor members that were not intended to participate in collector action, resulting in increased force demands on beams and their connections. In contrast, the Design Model provided a direct load path between the diaphragm and the LFRS, significantly reducing force redistribution and producing a more uniform axial-force pattern.

Figure 37 provides a direct comparison of axial-force distributions in the roof beams of the 12-story SCBF structure. The Reality Model exhibits larger and more irregular axial-force demands, whereas the Design Model produces substantially lower and more uniform force distributions. The differences observed between the two models demonstrate the strong influence of diaphragm-to-perimeter beam connectivity on seismic load transfer.

For SMF systems, beams were designed for seismic story forces in accordance with AISC-360 and AISC-341, while columns and connections were detailed using capacity-design principles. Reduced Beam Section (RBS) connections were implemented in accordance with AISC-358, with geometric parameters defined as a = 0.625 b_f, b = 0.75 d_b, and c = 0.25 b_f. Story heights were 4.5 m (15 ft) for the first story and 4.0 m (13 ft) for the upper stories. Column sections varied every two stories, while beams remained constant within each story. The seismic design parameters were $R = 8$, $C_d = 5.5$, and $\Omega_0 = 3$.

Analysis of the 12-story SMF archetype (Figure 38) showed trends similar to those observed for the SCBF systems. When diaphragm-to-perimeter beam shear transfer was omitted (Reality Model), diaphragm forces were redistributed through alternative load paths, producing increased force demands in floor members and their connections. Providing diaphragm-to-perimeter beam shear transfer (Design Model) reduced these demands and established a more direct force-transfer mechanism between the diaphragm and the LFRS.

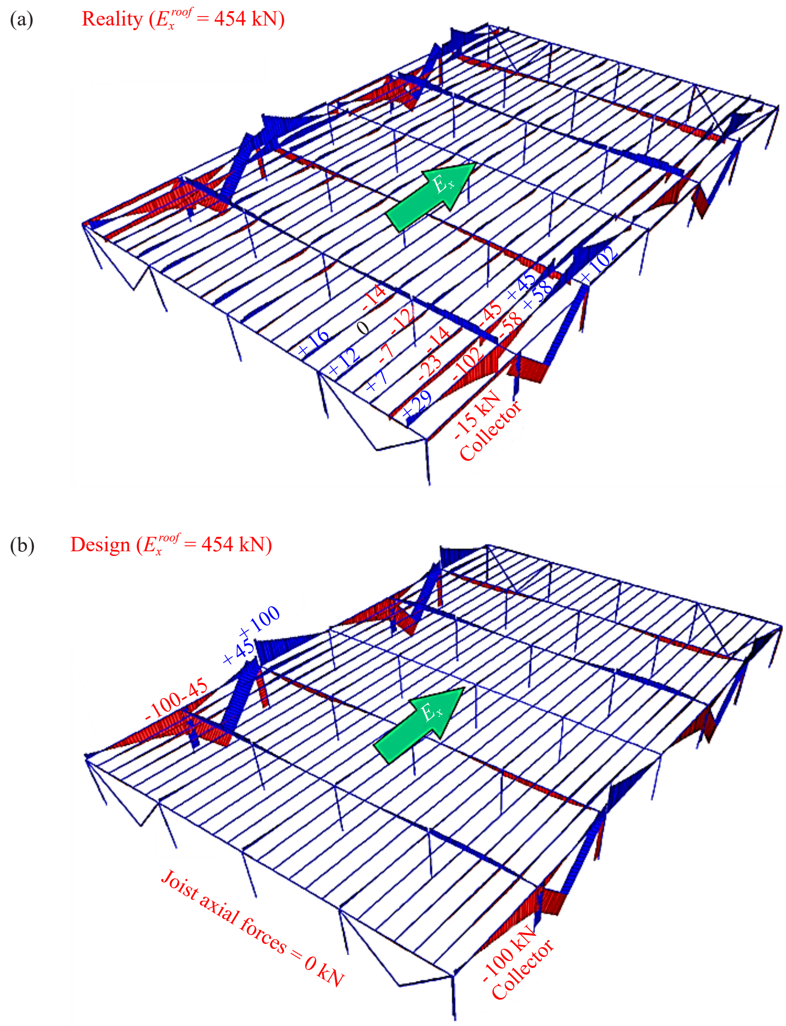
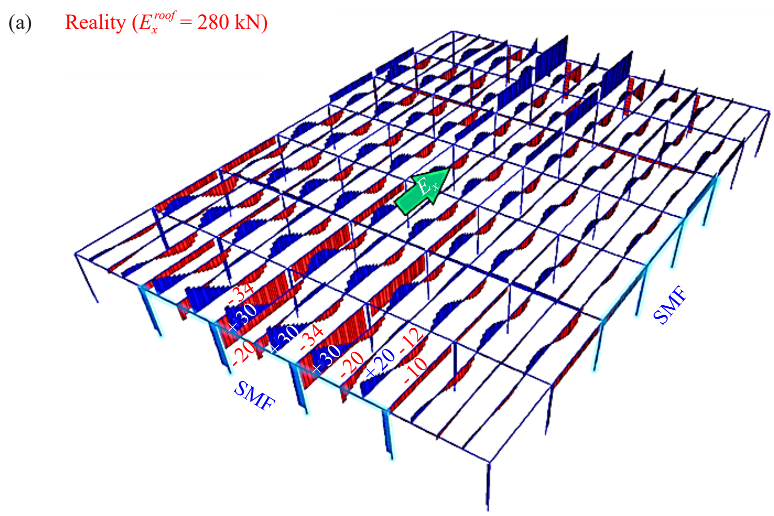


Figure 37. Axial force in beams on the roof of a 12-story SCBF structure, without (a) and with (b) shear transfer to the main beams



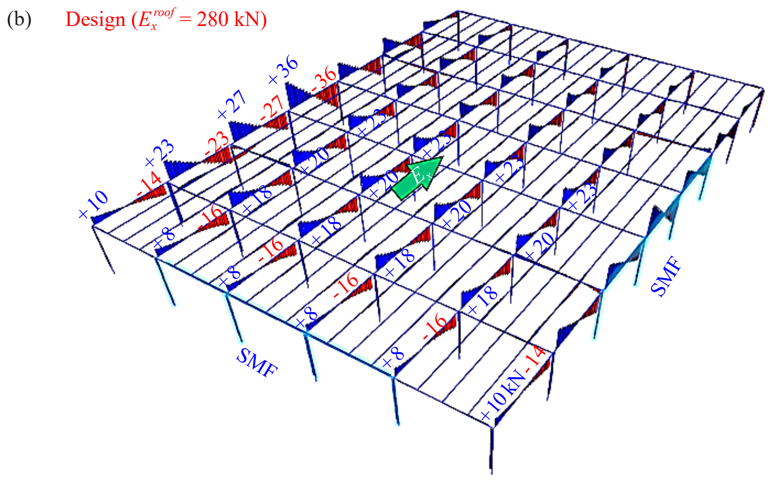


Figure 38. Axial force in beams on the roof of a 12-story SMF structure, without (a) and with (b) shear transfer to the main beams

Comparison of the Design and Reality models showed that omission of diaphragm-to-perimeter beam connectivity consistently increased axial-force demands in floor members. Depending on the structural configuration considered, the increase in force demand ranged from approximately 1.5 to 6 times that predicted by the conventional Design Model. Similar trends were observed in collector forces, member deformations, and support reactions throughout the investigated archetypes.

The consistency of these observations across both SCBF and SMF systems demonstrates the importance of diaphragm-to-perimeter beam shear transfer. Independent of lateral system type, building height, floor plan, or floor configuration, the presence of a direct force-transfer path between the diaphragm and perimeter beams significantly influenced the distribution of seismic forces within the floor system.

For composite steel deck floor systems, the results indicate that diaphragm-to-perimeter beam shear transfer plays a fundamental role in establishing an efficient load path to the LFRS. When such connectivity is provided, diaphragm forces are transferred more directly to perimeter beams and collectors, reducing unintended force demands in adjacent floor members and their connections. These findings provide practical guidance for improving the seismic modeling and design of composite floor diaphragms and highlight the importance of accurately representing diaphragm-to-collector connectivity in structural analysis models.

3.4 *Limitations of the modeling*

The findings presented in this study should be interpreted within the scope and limitations of the adopted modeling approach.

The global structural analyses were performed using equivalent static seismic forces obtained from ASCE-7 seismic procedures. The seismic demand was determined from the design base shear and distributed vertically over the building height according to code requirements. Although FEMA-P695 archetype parameters were used in selecting representative seismic design parameters, nonlinear response-history analyses were not performed. Consequently, record-to-record variability, duration effects, pulse-like ground motions, and higher-mode dynamic response were not explicitly investigated.

The proposed recommendation of diaphragm response modification factors approaching unity ($R_s \leq 1$) should therefore be regarded as a preliminary engineering recommendation based on the analyzed numerical models rather than a formally calibrated seismic design parameter. Development of code-level R_s values would require extensive nonlinear response-history analyses and experimental calibration.

The Reality Model adopted in this study represents a limiting condition in which positive diaphragm-to-collector shear transfer is absent. In actual construction, some degree of force transfer may occur through friction, incidental confinement, construction tolerances, or localized contact mechanisms. These effects were intentionally neglected because their contribution is uncertain and difficult to quantify under earthquake loading. Furthermore, frictional interaction cannot be represented consistently within the simplified SAP2000 models used herein and would complicate direct verification against the detailed ABAQUS simulations. In addition, earthquake-induced vertical accelerations may reduce slab-to-beam contact pressures and further decrease the reliability of friction-based force transfer mechanisms.

The detailed ABAQUS simulations were limited to representative diaphragm regions and connection details extracted from the global building models. Although all components were modeled using three-dimensional solid elements with geometric and material nonlinearities, full-building nonlinear simulations were beyond the scope of the present study because of their computational complexity.

Failure initiation in the ABAQUS models was defined as the point at which the von Mises stress reached the ultimate strength capacity of the corresponding steel component. More advanced damage accumulation models, fracture mechanics approaches, low-cycle fatigue effects, and connection deterioration mechanisms were not considered.

The investigated structures consisted primarily of regular building configurations with relatively uniform mass and stiffness distributions. Buildings with significant plan irregularities, discontinuous diaphragms, large openings, torsional response, transfer levels, or highly irregular collector layouts may exhibit different force-transfer mechanisms and require additional investigation.

Although good agreement was obtained between SAP2000 and ABAQUS predictions in the elastic range, with differences generally below 5% for axial forces, support reactions, stresses, and deformations, experimental validation was not available. Full-scale laboratory testing or shake-table experiments are therefore required to verify the proposed diaphragm core mechanism and to establish broader applicability of the findings.

Finally, the study focused on three common steel floor systems (PJS, OWSJ, and CSD). Other diaphragm systems, connection details, construction practices, and retrofit solutions were not investigated and may require separate evaluation.

4. Concept of diaphragm core

In joist floor systems subjected to seismic excitation parallel to the joist orientation, the diaphragm in-plane force-transfer mechanism is highly dependent on the presence of a positive shear connection between the concrete slab and the perimeter beams. When such a connection is not provided, the slab primarily transfers gravity loads to the supporting beams, while relative in-plane slip may develop at the slab-beam interface under seismic loading. Consequently, a significant portion of the diaphragm forces is transferred through the joists, then through the joist-main beam connections, and finally to the vertical LFRS. Since the contribution of slab bearing at columns is limited, the effective force-transfer region becomes concentrated within a reduced central area of the diaphragm, referred to herein as the diaphragm core, while the peripheral joists participate in collector action and develop elevated axial forces (Figure 39). This modeling assumption was adopted because dedicated diaphragm shear connectors are not commonly provided on perimeter beams in many joist-supported floor systems. In such cases, the slab is merely supported on the beam flange and no reliable mechanism exists for transferring significant in-plane seismic shear forces. Although friction may contribute some force transfer, its magnitude is uncertain and may be further reduced under earthquake-induced vertical accelerations that can partially separate the slab from the supporting beam. For this reason, frictional resistance was not considered in the present study. Furthermore, frictional contact behavior cannot be represented consistently within the simplified SAP2000 models used herein and would complicate direct comparison with the detailed ABAQUS simulations.

This alternative load path significantly alters the force distribution assumed in conventional design models. Because of the high in-plane stiffness of the concrete slab, axial forces developed in one joist can be redistributed to adjacent joists through the slab, resulting in increased force demands over a larger portion of the floor system. Across all analyzed joist-supported systems, omission of diaphragm-to-perimeter beam connectivity increased axial demands in critical members by approximately 1.5 to 6 times compared with the corresponding Design Models. Positive shear transfer between the slab and perimeter beams substantially reduced these demands by establishing a direct load path from the diaphragm to the collectors.

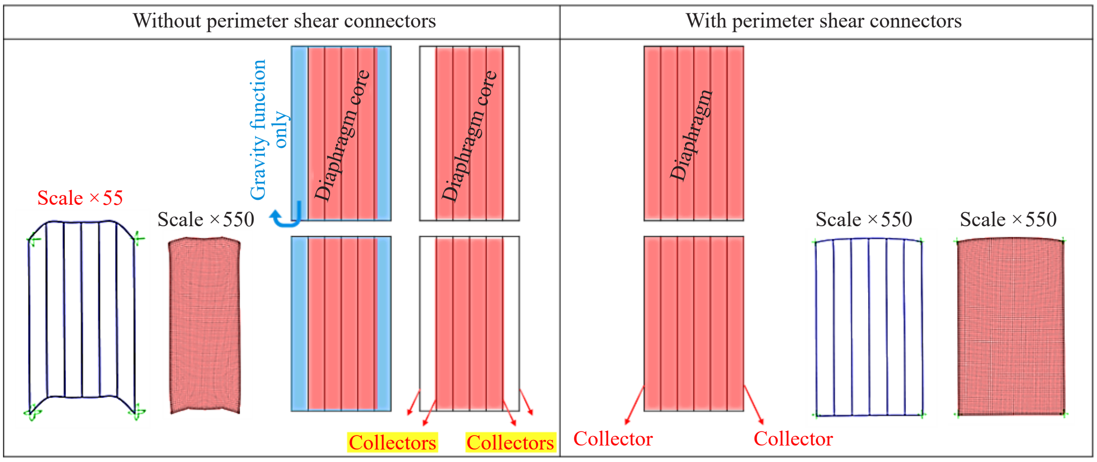


Figure 39. The concept of a diaphragm core in a joist floor system

Due to the high in-plane stiffness of even a 50 mm concrete slab, differential displacement between adjacent joists remains limited, and the joists experience nearly uniform lateral displacements during seismic excitation parallel to their orientation. This behavior imposes similar relative displacements at the joist-chord interfaces, analogous to the response of a continuous chord member subjected to uniform support settlement (Figure 40). As a result, joists on one side of the diaphragm develop tensile axial forces, while joists on the opposite side develop compressive axial forces, producing the characteristic force pattern observed in the numerical analyses.

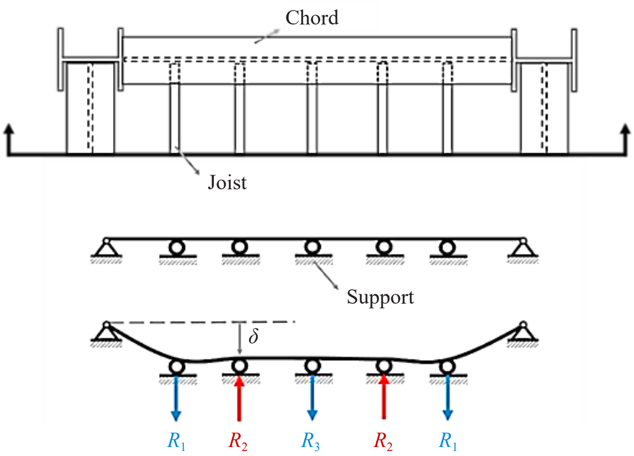


Figure 40. Equivalent behavior of diaphragm chord with support settlement

The principal force-transfer path under parallel excitation can be summarized as: Slab → Top chord of joist → Web members → Bottom chord → Main beam → LFRS.

ABAQUS simulations, in which nodal displacements corresponding to diaphragm movement were imposed, produced support reactions that closely matched the joist axial forces obtained from the SAP2000 models within the elastic range. Comparisons of axial forces, support reactions, stresses, and deformations generally showed differences of less than 5%, providing additional confidence in the proposed diaphragm core mechanism and the associated force-transfer path.

For seismic loading perpendicular to the joist orientation, the simplified SAP2000 models predicted relatively moderate force demands in the joists. However, the refined ABAQUS models revealed additional local response mechanisms that are not captured by line-element models. Load transfer from the slab to the top chord generated weak-axis bending effects in web members and bottom plates, producing localized stress concentrations that may influence the behavior of joist connections and surrounding components. Failure initiation in the detailed models was defined as the point at which the von Mises stress reached the ultimate strength capacity of the corresponding steel component.

Based on the analytical results presented in this study, two design approaches may be considered:

• Option A: Design joists as collectors—Explicitly design joists, chords, and their connections to resist the induced axial and shear forces, including appropriate checks for local and global stability. A conservative approach is to use a diaphragm response modification factor of $R_s \leq 1$, thereby maintaining essentially elastic diaphragm behavior.

• Option B: Bypass joist collector action—Provide positive shear transfer between the slab and perimeter collector beams, creating a direct load path to the LFRS and minimizing the participation of joists in collector action.

Although both approaches are feasible, Option B generally provides a simpler and more practical solution for typical building construction.

When Option B is adopted, effective shear-transfer mechanisms between the slab and collector beams are required. For thin slabs (approximately 50 mm), conventional headed shear studs may not always be practical. Possible alternatives include:

• Shear tabs welded to the top flange of perimeter beams and embedded within the slab.

• Welded reinforcing bars anchored to the beam flanges and developed within the slab.

These elements should be designed specifically for diaphragm force transfer and should not be confused with the connectors required solely for composite gravity-load action (Figure 41).

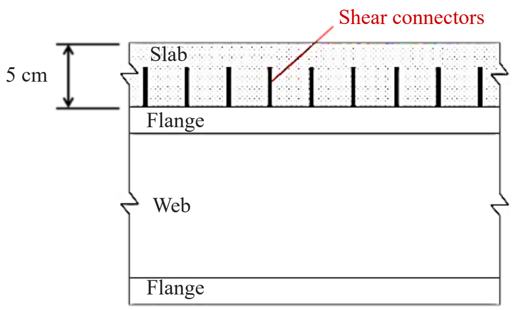


Figure 41. Implementing a shear connector on the upper flange of a steel beam

The diaphragm core concept provides a rational explanation for the force-transfer mechanisms observed in joist floor systems lacking positive diaphragm-to-perimeter beam connectivity. Without a direct shear-transfer path, the effective diaphragm action becomes concentrated within a reduced central region, forcing peripheral joists to participate in collector action and altering the expected load path. Providing positive slab-beam shear transfer mitigates this mechanism and results in a force-transfer pattern that is more consistent with conventional diaphragm design assumptions.

It should be emphasized that the recommendation of $R_s \leq 1$ is based on the numerical models and engineering observations presented in this study and should be regarded as a preliminary design recommendation rather than a formally calibrated code value. Additional experimental investigations and system-level validation are required before generalized diaphragm response-modification factors can be established for joist-supported floor systems.

5. Conclusions

This study investigated the seismic force-transfer mechanisms of three common steel floor systems: PJS, OWSJ, and CSD floor system. Although these systems differ in geometry and construction details, the analyses consistently demonstrated that diaphragm-to-collector beam connectivity is a governing parameter in the actual seismic load path.

When positive diaphragm-to-collector force transfer was not provided, the force-transfer mechanism differed significantly from that assumed in conventional design models. In these cases, a reduced effective diaphragm region, referred to herein as the diaphragm core, developed and caused peripheral joists to participate in collector action. Across the investigated configurations, this mechanism led to increases in axial force demands in critical members ranging approximately from 1.5 to 6 times compared with the Design Models. These changes were dependent on floor configuration, building height, and loading direction, and were not fully captured by conventional diaphragm idealizations.

It is important to emphasize that the differences observed between the Design Models and Reality Models cannot be represented by a simple amplification factor. Although increases in force demands ranging from approximately 1.5 to 6 times were observed in certain members, the primary effect was a fundamental change in the seismic force-transfer mechanism and load path within the diaphragm system. Depending on the floor configuration, joist orientation, and diaphragm connectivity, some members experienced increased demands while others experienced reduced demands or even changes in the nature of the forces acting on them. Consequently, no direct correlation was identified that would allow designers to apply conventional software default assumptions and subsequently multiply the resulting forces by a single correction factor. The results indicate that accurate representation of the actual force-transfer mechanism is necessary, since the structural response is governed by force redistribution rather than simple force amplification.

For seismic loading parallel to the joist orientation, axial forces developed in peripheral joists and became a significant component of the diaphragm load path. For loading perpendicular to the joist orientation, localized force concentrations occurred at joist-beam interfaces and connection regions, accompanied in some cases by weak-axis bending effects. These behaviors highlight limitations of simplified diaphragm assumptions commonly used in structural design software.

For OWSJ systems, the analyses identified the joist-seat connection as a critical region due to concentrated seismic force-transfer demands. The ABAQUS simulations further demonstrated that local stress concentrations and instability mechanisms may develop in components that are not explicitly represented in global structural models.

For CSD systems, providing diaphragm-to-perimeter beam force transfer resulted in a more direct and uniform load path to the lateral-force-resisting system. Similar trends were observed in both SCBF and SMF structures, indicating that the influence of diaphragm connectivity is largely independent of the selected lateral system.

Comparison between SAP2000 and ABAQUS models showed good agreement in the elastic range, with differences generally within 5% for key response parameters such as axial forces and support reactions. The refined ABAQUS models additionally captured local stress concentrations and instability mechanisms that could not be represented in simplified global models.

Based on the analytical results, two design approaches may be considered. The first is to explicitly design joists, chords, and their connections to resist the induced diaphragm forces, including associated axial and shear demands. The second, and more practical approach for typical construction, is to provide positive diaphragm-to-collector force transfer along perimeter beams, thereby establishing a direct and predictable load path between the diaphragm and the lateral-force-resisting system.

For the floor systems investigated herein, the results indicate that assuming substantial diaphragm ductility may not always be appropriate when diaphragm-to-collector connectivity is absent. Consequently, the use of conservative diaphragm design forces corresponding to diaphragm response modification factors approaching unity ($R_s \leq 1$) may be appropriate for such configurations. However, this recommendation should be interpreted as a preliminary engineering guideline derived from numerical simulations rather than a formally calibrated design parameter.

The findings emphasize that accurate representation of diaphragm-to-collector connectivity is essential for realistic seismic analysis and design. The study is primarily based on numerical modeling (SAP2000 and ABAQUS) and linear/static and idealized loading procedures; therefore, future research should include experimental validation, shake-table or full-scale testing, and calibration of the proposed diaphragm core mechanism to support development of diaphragm-specific seismic design provisions. A concise summary of the principal findings and quantitative observations obtained in this study is presented in Table 3.

Table 3. Summary of key findings and quantitative observations from the investigated floor systems

Category	Observation	Quantitative result/comment
PJS (without shear transfer)	Diaphragm core mechanism developed and exterior joists acted as collectors	Joist axial forces increased by approximately 1.5-6 times compared with Design Models
PJS (with shear transfer)	Direct load path established between diaphragm and LFRS	Joist participation in collector action became negligible
OWSJ (without shear transfer)	Force transfer occurred through peripheral joists and seat connections	Significant increases in axial and shear demands were observed at joist seats
OWSJ local behavior	Critical local failure modes identified	Bottom-chord yielding, web-member buckling, seat-weld overstress, and connection distress
CSD (with shear transfer)	More uniform force distribution and direct load path	Reduced force demands in beams, collectors, and connections
SCBF vs. SMF	Similar force-transfer mechanisms observed	SCBF systems generally produced higher diaphragm force concentrations
SAP2000-ABAQUS comparison	Global and detailed models showed good agreement	Differences in axial forces, stresses, deformations, and reactions remained below 5% in the elastic range
Modeling assumptions	Global analyses used linear elastic SAP2000 models; detailed behavior evaluated using nonlinear ABAQUS Static General analyses	All ABAQUS components were modeled using C3D8R solid elements; minimum increment = 10^{-5}
Study limitations	No experimental calibration or nonlinear dynamic time-history validation was performed	Results are limited to the investigated regular floor layouts and loading conditions
Design implication	Diaphragm behavior strongly depends on slab-to-collector connectivity	Conservative diaphragm design may require $R_s \leq 1$ when positive shear transfer is not provided

Authorship statement

Alireza Sheykhaleslami: Methodology, Software, Formal analysis, Visualization, Writing original draft.
Shervin Maleki: Conceptualization, Writing, Review & Editing, Supervision.

Conflict of interest

The authors 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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