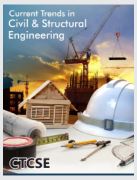

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Research Article

Advanced Optimization of Structural Integrity in Beam-Slab-Column Design, Stiffness, and Seismic Performance of Concrete Frames

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Abstract

This study contains comprehensive assessments of the construction and operational aspects of reinforced concrete frames focusing on the beam-slab-column system. The analysis investigates the fundamental components of design: axial frame modelling, primary section choice, and estimation of the beam, slab, and column size for structural stability and safety. The paper proposes a novel approach to calculating vertical and lateral stiffness for different components of the frame based on real data and formal techniques used to compute section size. The manuscript describes the lateral stiffness of a frame system subjected to lateral earthquake loading and consists of a set of pre-determined stiffness values for every type of floor and column. The study also addresses the conduction of the internal forces of the system encompassing the seismic shear force and bending moment of the beam-column connection during ground shaking. The natural vibration period, the lateral deflection due to earthquake loading, the axial forces counteracting the lead of a concrete column, and the concrete column system's earthquake resisting articulations determine the results of the study, and these results aid structural engineers in fine-tuning the details of reinforced concrete structures. The analysis focuses on the developing reinforced concrete structures with functional and adequate earthquake resisting features and addresses the improvement of the construction and design of high-rise concrete structures in earthquake prone areas.

Keywords: Beam-Slab-Column System; Seismic Performance; Concrete Frame Design; Stiffness Calculation; Earthquake Resistance; Structural Optimization

Introduction

Reinforced concrete frames are the backbone of modern structural systems, particularly in high-rise buildings and seismic zones.

The beam-slab-column system, a key component of reinforced concrete frames, plays a pivotal role in ensuring the overall stability, strength, and functionality of the structure. The design and performance of these systems are critical, as they directly impact the structural integrity and resilience of the building, particularly under the influence of vertical and lateral loads such as seismic forces. The efficient design of beam-slab-column systems not only enhances safety but also contributes to the sustainability and longevity of buildings in seismic regions [1-3].

The optimization of structural integrity and seismic performance in reinforced concrete (RC) beam-slab-column systems has been extensively explored, focusing on advanced reinforcement, retrofitting, and material innovations. Beam-column joints (BCJs) are critical under seismic loading, and reinforcement congestion can compromise earthquake resistance. Research has shown that X-shaped diagonal reinforcements significantly reduce core damage and enhance rotational stiffness, promoting a weak beam-strong column mechanism [4]. Retrofitting using engineering cementitious composites (ECC) and high-strength steel mesh has demonstrated superior performance over traditional methods, improving strength, energy dissipation, and deformation capacity [5].

Slit brace retrofitting can delay shear cracking and enhance energy dissipation, resulting in higher load capacity [6]. Steel fiber reinforced concrete (SFRC) in BCJs improves crack resistance and ductility, supporting hybrid fiber systems and AI modeling for optimization [7] (Noor et al., 2025). FRP retrofitting increases peak shear force by 25% and displacement capacity by 20%, while prestressed prefabricated frames improve load-bearing capacity, stiffness, and ductility [8,9].

CFRP retrofitting boosts load capacity and ductility by over 30%, altering failure modes and enhancing seismic performance [10]. Studies confirm CFRP integration enhances ductility and load-carrying capacity, with steel strips and ultra-high-performance concrete (UHPC) increasing peak load and ductility by up to 85% and 50%, respectively [11]. Advances in slab-column connections, including the use of UHPC and smart self-healing materials, improve resilience against punching shear and cyclic displacement [12].

Retrofitted RC frames with proper column sizing and lateral stiffness prevent upper floor softening and improve seismic resistance [13]. Eccentric steel braces shift plastic hinges and increase ductility, while natural fibers like sisal improve ductility and energy absorption in BCJs [14,15]. High-strength reinforcing bars in BCJs enhance energy dissipation and load capacity [16]. Additionally, prefabricated concrete-filled steel tube trusses and ultra-high-performance steel fiber reinforced concrete (UHPSFRC) enhance seismic performance, and innovative beam-column-slab joint designs improve seismic resilience [17-23].

This particular analysis centres on improving the beam-slab-column system, focusing on stiffness, structural integrity and seismic analysis. Developing a system that accurately predicts the beam, slab, and column dimensions analytically and considering load and axial frame system is proposed. A unique method for improving the vertical and horizontal stiffness is proposed, along with the period of the system's natural vibration and the horizontal sway due to ground shaking.

Urban centres expand into seismic regions, reinforcing concrete frames. This research assists engineers with the design and safety of reinforced concrete frames in high buildings and seismic regions. The study integrates conventional design and methodology with modern seismic analysis. This further develops construction techniques to improve the safety of structures in seismic areas.

Methodology

The present analysis incorporates all fundamental aspects concerning the design, stiffness, and seismic behaviour of reinforced concrete frames, focusing mainly on the beam-slab-column system. The approach is segmented into a number of components, aimed at maintaining the structural integrity of the frame and the performance of the frame under seismic conditions.

Structural Design and Section Size Determination

First, the study uses some field data to compute the required beam, slab, and column section sizes of the frame. The design approach complies with the rules of the profession in computing the axial forces and the sizes to be used, based on the structural load bearing capacity. The main aspects include:

Estimation of Beam and Slab Section Sizes

The slab thickness and the reinforcement are determined in consideration of the span of the floor, and the floor slab aspect ratio. The beam size is determined based on span to height ratio, and is balanced to have enough strength and stiffness to avoid failure in bending under vertical and lateral loads.

Estimation of Column Section Sizes

The sizes of the column sections are determined based on load resisting capacity, seismic criteria, height to width ratio to prevent short column effect, and the floor load distribution in columns is taken into account when sizing the columns, with differences in section size of the side and centre columns. Calculations regarding beam, slab, and column sections are executed in compliance with structural design codes and standards, including the Chinese National Standard for Concrete Structures (GB 50010) and applicable codes for seismic design.

Stiffness Calculation

In the following step, the vertical and lateral stiffnesses of the frame components are calculated:

Vertical Stiffness

This is obtained from the beam and column sections' bending stiffness. For each section, the moment of inertia (I) is calculated, and the stiffness is obtained using the linear stiffness equation.

Lateral Stiffness

Lateral stiffness is obtained using the vertical stiffnesses of the frames, adjusted with a factor for the storey. The lateral stiffness is determined by summing the stiffnesses of the frame members for each storey.

Seismic Load Calculation

This study employs the calculation of seismic loads to assess the

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internal forces acting on the frame in the event of an earthquake.

Seismic Shear Forces and Bending Moments

The lateral seismic forces acting on the structure are obtained using the seismic design parameters which include seismic acceleration, natural period of vibration of the structure, and the damping ratio. Using static equilibrium and the method of distributed forces, the shear forces and bending moments are computed for each member of the frame including the earthquake dynamics.

Internal Forces in the Frame Columns and Beams

The internal forces comprising shear force, axial force, and moments are determined using the conventional equations which equilibrate the external seismic forces with the internal responses of the frame structure. The findings of these calculations are essential in determining the structural sufficiency and the seismic resistance of the structure.

Natural Frequency and Vibration Period

Finding the natural period of oscillation of the structure helps estimate the impact of seismic events. To estimate the period of oscillation, the vertex displacement method is employed, which is accomplished by applying gravitational loads at the mass points of each floor and calculating the displacement at the vertex.

Verification of Structural Integrity

As a final step, the methodology incorporates a set of verification processes to confirm that the frame design complies with the required safety and performance measures:

Shear-to-Weight Ratio

For each floor, verification of the shear-to-weight ratio is conducted to confirm that the frame will be able to withstand lateral forces without excessive shifting.

Lateral Displacement Under Seismic Loads

The inter-storey displacement is calculated and verified that the displacement is within the acceptable range. The results are verified with the codes to determine maximum displacement.

Data Analysis and Validation

All calculations are based on a given set of assumptions and data. The results obtained are verified against experimental data, simulations, and other advanced techniques. Moreover, sensitivity analyses are used to determine the seismic response of the structure due to changes in material properties, load conditions, and other structural parameters.

Results and Discussions

Calculation of beam-slab-column section size and lateral stiffness

Calculation diagram

The axial frame is the research object of hand calculation, and the embedded end of the plane frame is located on the top of the foundation. -1m, so the height of one layer is 5.8m, the height of the top layer is 4.5m, the height of the middle layer is 4.5m, the calculation diagram is shown below. The frame calculation is shown in Figure 1.

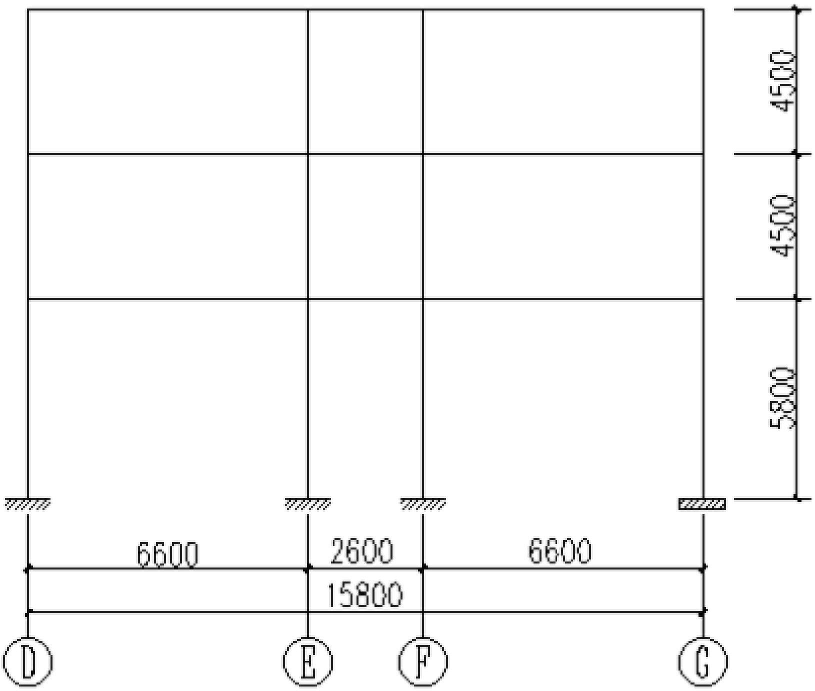

Figure 1: Framework calculation diagram.

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Primary selection of section

Beam and slab section estimation

The floor and roof panels of this project are all cast-in-place concrete slabs, and the aspect ratio of the slabs is 6.6/3.75=1.76, according to the two-way board design. Plate thickness should be greater than 4200/40=105mm, taking the thickness of the floor slab as 120mm in addition, considering the use environment of the roof panel and the heavy load, the roof panel needs to adopt double-layer two-way reinforcement to prevent the roof panel from cracking and leaking. The thickness of the roof panel is taken as120mm.

As an important force-transmitting component of the frame structure, the frame beam should be designed with sufficient strength and rigidity to ensure the safety of the component; the frame beam height h is generally taken as span/14~span/8, and the beam width is h/3~h/ 2. For larger loads or larger fortification earthquakes, the size of the beam section can be appropriately increased. In addition, the beam height and width should meet the modulus of 50mm.

As a force-transmitting member, the secondary beam transmits the floor load to the main beam, and the beam end is hinged with the frame beam. The secondary beam height h generally takes span/18~span/12, and the beam width is h/3~h/2. In addition, the beam height and width should both meet the modulus of 50mm. It can be seen from the structural layout diagram that the span lo of the secondary beam is 6600mm, 1/18lo=367mm, 1/12lo=550mm, take the beam height as 550mm; h/3=183, h/2=275mm, take the beam width as 250mm.

Column section estimation

The cross-sectional size of the frame column should consider factors such as the number of floors, the load-bearing area of the column, and the seismic rating. In addition, in order to avoid short columns, the height-to-width ratio of the column should be controlled during design.

$$N = \beta F g_E n \qquad A_C = b_c h_c \ge \frac{N}{\mu_N f_c}$$

side column β=1.3, center column β=1.25,F is the loaded area of the column, g_E is 12kN/m^2, n number of floors.

side column:

F =6.6/2×(7.5+7.5)/2=24.75m^2

N =1.3×12×24.75×3=1158.3kN

$\mu_N f_c$ = 0.85×14.3=12.155N/mm^2

$A_C \ge N/\mu_N f_c$ = 1158.3×1000/12.155=95294mm^2

$b_c \ge \sqrt{A_c}$ =308.7mm

Center column:

F =(2.6+6.6)/2×(7.5+7.5)/2=34.5m^2

N =1.25×12×34.5×3=1552.5kN

$\mu_N f_c$ = 0.85×14.3=12.155N/mm^2

$A_C \ge N/\mu_N f_c$ = 1552.5×1000/12.155=127725mm^2

$b_c \ge \sqrt{A_c}$ =357.39mm

Take the side column and the center column as the same section, both are 600mm×600mm

Calculation of line stiffness of frame beams and columns

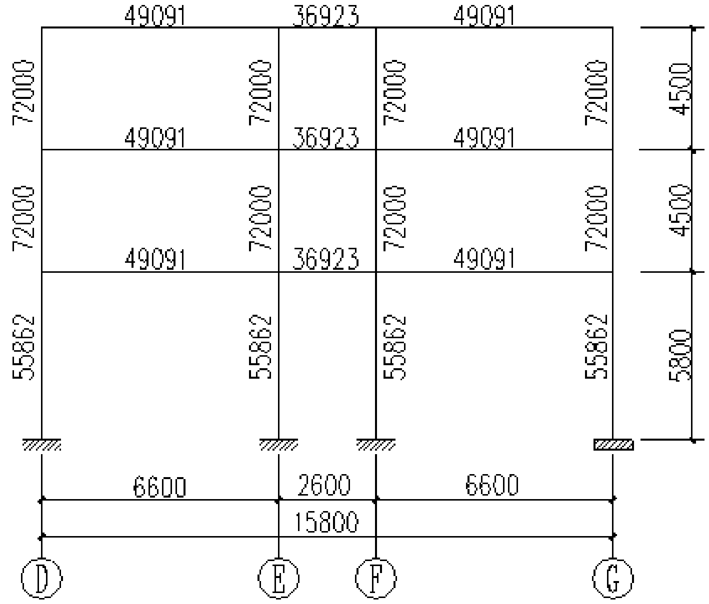

Figure 2: The beam and column line stiffness of the central frame (kN.m)

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Member linear stiffness $i_b = E_c I_b / l_b$, $I_b = 1/12\,bh^3$.This design is a cast-in-place reinforced concrete frame structure, the beam and the floor are poured together, and there are floors on both sides of the middle frame beam, which effectively increases the moment of inertia of the beam section $I = 2I_b$; while the edge frame beam has only one side of the floor, Pick $I = 1.5I_b$; for column sections, $I = I_b$.

Figure 2

Calculation of frame lateral stiffness

Lateral stiffness of reinforced concrete frame columns $D = \alpha_c \frac{12i_c}{h^2}$, in by table 2-5 Formula calculation.,is the linear stiffness and height of the column.

Tables 5-7

Table 1: Beam Section Table (mm).

component name	span lo	lo/14~ lo/8	Liang Gao (h)	h/3~h/2	beam width (b)	Section b×h
longitudinal frame beam	7500	536~938	650	217~325	300	300×650
Lateral span	6600	471~825	600	200~300	300	300×600
horizontal midspan	2600	186~325	400	133~200	300	300×400

Table 2: Calculation of Line Stiffness of Side Frame Beams.

beam span	Ec(N/mm^2)	b×h(mm)	l$_b$(mm)	I(×10^{9}mm^4)	ib=EcI/lb(kN.m)
Side span beam	30000	300×600	6600	8.1	36818
Mid span beam	30000	300×400	2600	2.4	27692

Table 3: Calculation of frame beam line stiffness.

beam span	Ec(N/mm^2)	b×h(mm)	l$_b$(mm)	I(×10^{9}mm^4)	ib=EcI/lb(kN.m)
Side span beam	30000	300×600	6600	10.8	49091
Mid span beam	30000	300×400	2600	3.2	36923

Table 4: Column stiffness calculates.

Floor	Ec(N/mm2)	b×h(mm)	l$_b$(mm)	I(×10^{9}mm^4)	ib=EcI/lb(kN.m)
Top floor	30000	600×600	4500	10.8	72000
Mid floor	30000	600×600	4500	10.8	72000
First floor	30000	600×600	5800	10.8	55862

Table 5: Column stiffness correction factor table.

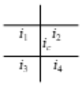
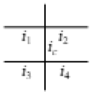
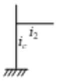
floor category	side column		Center column		$\acute{a}_c$
Top Floor		$\bar{K} = \frac{i_2 + i_4}{2i_c}$		$\bar{K} = \frac{i_1 + i_2 + i_3 + i_4}{2i_c}$	$\acute{a}_c = \frac{\bar{K}}{2 + \bar{K}}$
Mid Floor		$\bar{K} = \frac{i_2 + i_4}{2i_c}$		$\bar{K} = \frac{i_1 + i_2 + i_3 + i_4}{2i_c}$	$\acute{a}_c = \frac{\bar{K}}{2 + \bar{K}}$
Bottom Floor		$\bar{K} = \frac{i_2}{i_c}$		$\bar{K} = \frac{i_1 + i_2}{i_c}$	$\alpha_c = \frac{0.5 + \bar{K}}{2 + \bar{K}}$

Table 6: D value of a side frame (kN/m).

floor	$h_{i(m)}$	$ic(kN.m)$	Side column			Center column			$\sum D$
			$\bar{K}$	α_c	D_i	$\bar{K}$	α_c	D_i	
top floor	4.5	72000	0.68	0.25	10667	1.19	0.37	15787	52908
Mid floor	4.5	72000	0.68	0.25	10667	1.19	0.37	15787	52908
Bottom floor	5.8	55862	0.68	0.48	9565	1.54	0.58	11558	42246

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Table 7: D value of a medium frame (kN/m).

floor	$h_{i(m)}$	$ic(kN.m)$	Side column			Center column			$\sum D$
			$\overline{K}$	α_c	D_i	$\overline{K}$	α_c	D_i	
top floor	4.5	72000	0.68	0.25	10667	1.19	0.37	15787	52908
Mid floor	4.5	72000	0.68	0.25	10667	1.19	0.37	15787	52908
Bottom floor	5.8	55862	0.68	0.48	9565	1.54	0.58	11558	42246

Calculation of vertical load of structure

Standard values of floor and roof loads

Floor and roof dead load

Table 8

Table 8: Floor and roof practice table.

Function	specific methods	thicknessm	severek kN/m³	label value kN/m²	Subtotal kN/m²
common floor	Decorative layer:12mm1:2.5Cement colored stone floor, surface polished and waxed	0.012	25	0.012×25=0.3	4.36
	Screed:30mm1:3cement mortar	0.03	20	0.03×20=0.6	
	Adhesive layer: a cement paste			0.2	
	Structure layer:120mmreinforced concrete floor slab	0.12	25	0.12×25=3	
	Plaster layer:15mmlime mortar plastering	0.015	17	0.015×17=0.26	
corridor	Decorative layer:12mm1:2.5Cement colored stone floor, surface polished and waxed	0.012	25	0.012×25=0.3	4.36
	Screed:30mm1:3cement mortar	0.03	20	0.03×20=0.6	
	Adhesive layer: a cement paste			0.2	
	Structure layer:120mmreinforced concrete floor slab	0.12	25	0.12×25=3	
	Plaster layer:15mmlime mortar plastering	0.015	17	0.015×17=0.26	
the roof	The protective layer:50mmC20fine stone concrete	0.05	twenty-two	0.05×22=1.1	6.5
	Isolation layer:10mmlow strength mortar	0.01	20	0.01×20=0.2	
	Isolation layer: waterproof membrane or coating layer			0.3	
	Screed:30mm1:3cement mortar screed	0.03	20	0.03×20=0.6	
	Insulation:60mmthick polystyrene	0.06	4	0.06×4=0.24	
	Find slope layer:80mmLC5.0light aggregate concrete	0.08	10	0.08×10=0.8	
	Structure layer:120mmReinforced Concrete Roof Slabs	0.12	25	0.12×25=3	
	Plaster layer:15mmlime mortar plastering	0.015	17	0.015×17=0.26	

Standard value of floor and roof live load

Live load on the roof of non-masters: 0.5kN/m^2

Roof snow load: Sk=μrSo=1×0.4=0.4kN/m^2

Common room live load on the floor: 2.5kN/m^2

Floor corridor live load: 3kN/m^2

Stair live load: 3.5kN/m^2

Self-weight of components

a. self-weight of beam and column(kN/m)

Taking roof side span beams as an example, calculate its weight, the process is shown as follows. The beam section size is 300×600mm, the thickness of the roof panel is 120mm, the concrete bulk density is 25kN/m^3, the beam plastering thickness is 15mm, the plaster bulk density is 17kN/m^3.

Therefore, the self-weight line load of the beam is 25×0.3×(0.6-0.12)+2×17×0.015×(0.6-0.12)=3.84kN/m, and the self-weight of other components is shown in the table below.

Tables 9,10

b. self-weight of inner wall(kN/m^2)

200mm aerated concrete block 0.2×7.5=1.5kN/m^2

20mm lime mortar plastering on both sides 0.02×17×2=0.68kN/m^2

Total:1.5+0.68=2.18kN/m^2

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Table 9: Self-weight calculation of floor beams and columns.

component name	section(mm)	plate thickness(mm)	Plaster thickness(mm)	Concrete bulk density(kN/m³)	Plaster density(kN/m³)	Component weight(kN/m)
DE beam	300×600	120	15	25	17	3.84
EF beam	300×400	120	15	25	17	2.24
longitudinal frame beam	300×650	120	15	25	17	4.25
secondary beam	250×550	120	15	25	17	2.91
column	600×600	—	15	25	17	9.61

Table 10: Calculation of self-weight of roof layer beams and columns.

component name	section(mm)	plate thickness(mm)	Plaster thickness(mm)	Concrete bulk density(kN/m³)	Plaster density(kN/m³)	Component weight(kN/m)
DE beam	300×600	120	15	25	17	3.84
EF beam	300×400	120	15	25	17	2.24
longitudinal frame beam	300×650	120	15	25	17	4.25
secondary beam	250×550	120	15	25	17	2.91
column	600×600	—	15	25	17	9.61

c. **self-weight of external wall(kN/m^2)**

200mm aerated concrete block 0.2×7.5=1.5kN/m^2

External cement plastered walls 0.36kN/m^2

20mm lime mortar plastering inside 0.02×17=0.34kN/m^2

Total: 1.5+0.36+0.34 =2.2kN/m^2

d. **parapet self-weight(kN/m^2)**

In order to improve the stability of the parapet wall, the distance between the structural columns of the parapet wall shall not be greater than 4m, and it shall be cast in place together with the reinforced concrete capping at the top of the parapet wall.

200mm parapet wall 0.2×18=3.6kN/m^2

External cement plastered walls 0.36kN/m^2

20mm lime mortar plastering inside 0.02×17=0.34kN/m^2

Total: 3.6+0.36+0.34=4.3kN/m^2

Calculation of vertical load

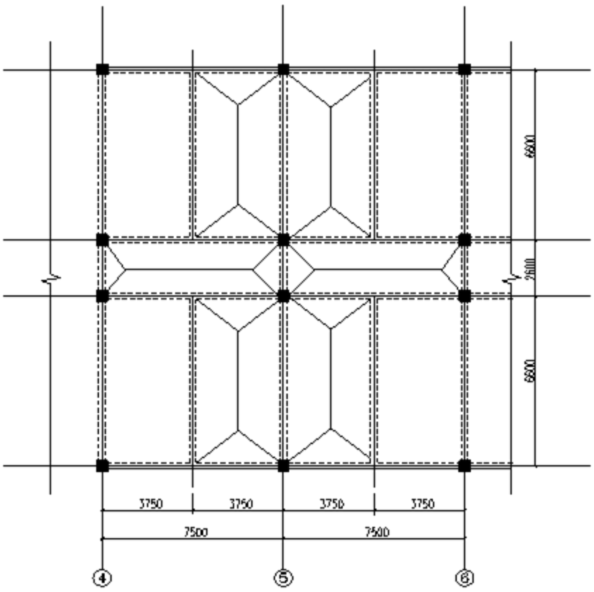

Figure 3: Plate Load Transfer Diagram.

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It can be seen from the code that for reinforced concrete slabs with an aspect ratio greater than 3, it is designed as a one-way slab, otherwise it is calculated as a two-way slab. Among them, if the aspect ratio is less than 2, it should be designed as a two-way plate; if the aspect ratio is greater than 2 but less than 3, it should be calculated as a two-way plate. It can be seen from figure that the length-to-width ratios of the calculated floor slabs on both sides are less than 3, so the analysis is based on two-way slabs (Figure 3).

Calculation of dead load standard value

Table a, Figure 4

Live load standard value calculation

Table b Figure 5

Table a:

(1) Roof frame beam line load	
Liang Zizhong	2.24kN/m
Roof dead load derivation	2.6/2×6.5×2=16.9kN/m
(2) frame beam line load in the floor	
Liang Zizhong	2.24kN/m
Wall self-weight	-
Floor dead load derivation	2.6/2×4.36×2=11.34kN/m
(3) Roof side frame beam line load	
Liang Zizhong	3.84kN/m
Roof dead load derivation	(3.75/2+3.75/2)×6.5=24.38kN/m
(4) floor side frame beam line load	
Liang Zizhong	3.84kN/m
Wall self-weight	2.18×(4.5-0.6)=8.5kN/m
Floor dead load derivation	(3.75/2+3.75/2)×4.36=16.35kN/m
(5) Concentrated force in the center column of the roof	
Self-weight of secondary beam	2.91×6.6/2=9.6kN
Roof dead load derivation	6.5×((3.75/2×3.75/2+3.75×3.3)+(3.75×2.6-0.5×2.6×0.5×2.6))=155.68kN
Self-weight of longitudinal frame beam	4.25×(3.75+3.75)=31.88kN
Subtotal	197.16kN
(6) Concentrated force in the center column of the floor	
Self-weight of secondary beam	2.91×6.6/2=9.6kN
Self-weight of the wall on the secondary beam	(4.5-0.55)×2.18×3.3=28.42kN
Floor dead load derivation	4.36×((3.75/2×3.75/2+3.75×3.3)+(3.75×2.6-0.5×2.6×0.5×2.6))=104.42kN
self weight of vertical wall	7.5×2.18×(4.5-0.65)=62.93kN
Self-weight of longitudinal frame beam	4.25×(3.75+3.75)=31.88kN
Subtotal	237.25kN
(7) Concentrated force of roof side column	
Self-weight of secondary beam	2.91×6.6/2=9.6kN
Parapet self-respect	0.6×4.3×7.5=19.35kN
Roof dead load derivation	6.5×(3.75/2×3.75/2+3.75×3.3)=103.29kN
Self-weight of longitudinal frame beam	4.25×(3.75+3.75)=31.88kN
Subtotal	164.12kN
(8) Concentrated force on floor side columns	
Self-weight of secondary beam	2.91×6.6/2=9.6kN
Self-weight of the wall on the secondary beam	(4.5-0.55)×2.18×3.3=28.42kN
Floor dead load derivation	4.36×(3.75/2×3.75/2+3.75×3.3)=69.28kN
self weight of vertical wall	2.2×(4.5-0.65)×7.5=63.53kN
Self-weight of longitudinal frame beam	4.25×(3.75+3.75)=31.88kN
Subtotal	202.71kN

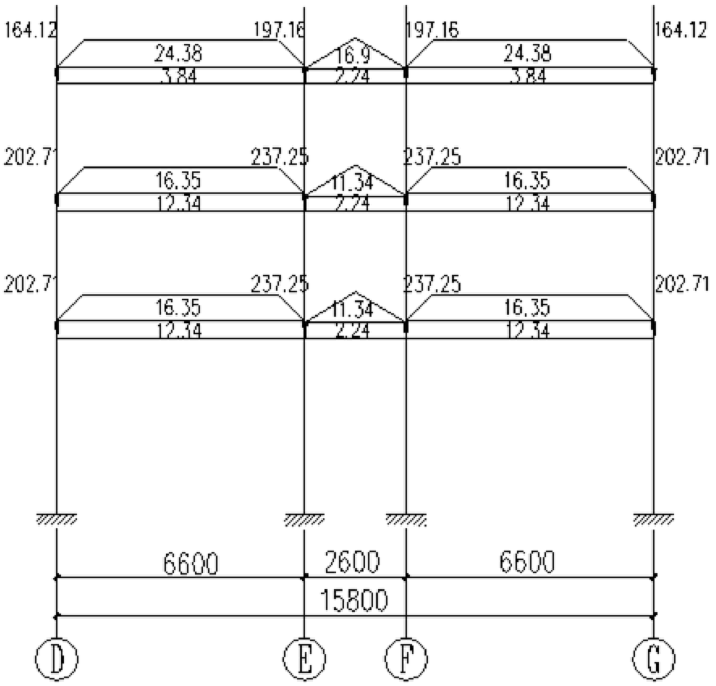

Figure 4: Dead load calculation diagram.

Table b:

(1) Roof mid-span beam line load	
Roof Live Load Derivation	2.6/2×0.5×2=1.3kN/m
(2) floor mid-span beam line load	
floor live load calculation	2.6/2×3×2=7.8kN/m
(3) Roof side span beam line load	
Roof Live Load Derivation	(3.75/2+3.75/2)×0.5=1.88kN/m
(4) floor side span beam line load	
floor live load calculation	(3.75/2+3.75/2)×2.5=9.4kN/m
(5) Concentrated force in the center column of the roof	
Roof Live Load Derivation	0.5×((3.75/2×3.75/2+3.75×3.3)+(3.75×2.6-0.5×2.6×0.5×2.6))=11.98kN
(6) Concentrated force in the center column of the floor	
floor live load calculation	2.5×(3.75/2×3.75/2+3.75×3.3)+3×(3.75×2.6-0.5×2.6×0.5×2.6)=63.91kN
(7) Concentrated force of roof side column	
Roof Live Load Derivation	0.5×(3.75/2×3.75/2+3.75×3.3)=7.95kN
(8) Concentrated force on floor side columns	
floor live load calculation	2.5×(3.75/2×3.75/2+3.75×3.3)=39.73kN

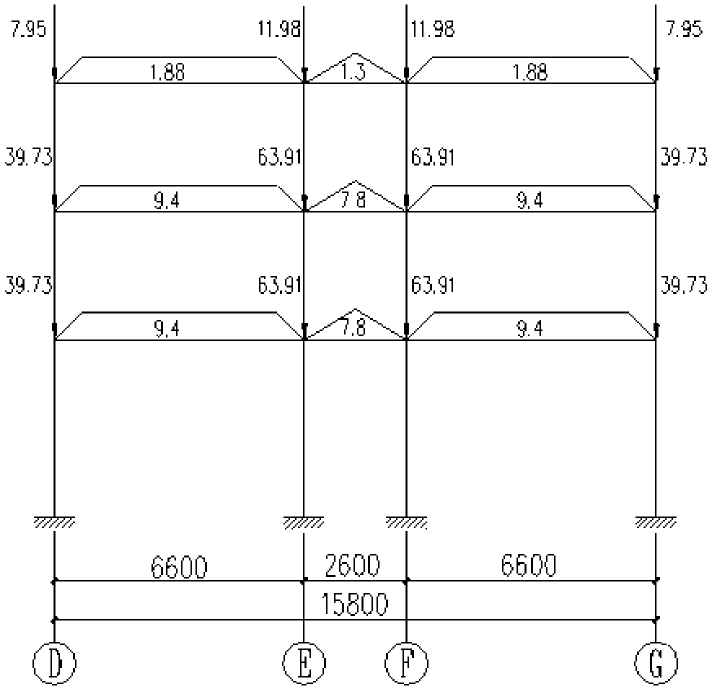

Figure 5: Live load calculation diagram.

Calculation of frame internal force under earthquake

Representative value of gravity load

Table c:

Representative value of gravity load on the top floor

Table c

Dead load:	
Top layer weight	1085.5×6.5=7055.75kN
Top side span beam weight	20×(6.6-0.6-0.6+0.3+0.3)×3.84=460.8kN
Top mid-span beam weight	10×(2.6-0.3-0.3)×2.24=44.8kN
top level beam weight	2.91×6.3×18=329.99kN
Top longitudinal beam weight	4.25×6.9×36=1055.7kN
Top column weight	9.61×4.5×40=1729.8kN
Weight of exterior transverse wall (except windows) on the top floor	2×2.2×((4.5-0.6)×6×2+(4.5-0.4)×2)×0.8=193.6kN
Weight of exterior longitudinal walls (except windows) on the top floor	(2.2×(4.5-0.65)×137.4×0.8=931.02kN
The weight of the top interior wall (except the door)	((2.18×(4.5-0.55)×6.6×20×0.8)+(2.18×(4.5-0.65)×7.5×17×0.8))=1765.41kN
parapet weight	4.3×0.6×169=436.02kN
Weight of stairwell	-
Total dead load	7055.75+460.8+44.8+329.99+1055.7+1729.8/2+193.6/2+931.02/2+1765.41/2+436.02 =11692.97kN
Live Load: Roof Snow Load	0.4×1085.5=434.2kN
Representative value of gravity load	11692.97+0.5×434.2=11910.07kN

Representative value of standard layer gravity load

Table d

Dead load:	
Standard laminate weight	1030.06×4.36=4491.06kN
Standard storey side span beam weight	20×(6.6-0.6-0.6+0.3+0.3)×3.84=460.8kN
Standard floor mid-span beam weight	10×(2.6-0.3-0.3)×2.24=44.8kN
Standard Level Beam Weight	2.91×6.3×18=329.99kN
Longitudinal Beam Weight of Standard Floor	4.25×6.9×36=1055.7kN

Citation: Hamza Shams*, Zahoor Ahmad, Yanjun QIU*, Hamid Abdrhman and Hanif Ullah. Advanced Optimization of Structural Integrity in Beam-Slab-Column Design, Stiffness, and Seismic Performance of Concrete Frames. Cur Trends Civil & Struct Eng. 12(3): 2026. CTCSE.MS.ID.000781. **DOI:** 10.33552/CTCSE.2026.12.000781.

Standard layer column weight	9.61×4.5×40=1729.8kN
Weight of external transverse wall (except windows) of standard storey	2×2.2×((4.5-0.6)×6×2+(4.5-0.4)×2)×0.8=193.6kN
Weight of exterior longitudinal wall (excluding windows) of standard storey	(2.2×(4.5-0.65)×137.4×0.8=931.02kN
Standard floor interior wall (except door) weight	(2.18×(4.5-0.55)×6.6×20×0.8)+(2.18×(4.5-0.65)×7.5×17×0.8)=1765.41kN
Weight of stairwell	7×55.44=388.08kN
Total dead load	4491.06+460.8+44.8+329.99+1055.7+1729.8+193.6+931.02+1765.41+388.08=11390.26kN
live load	3×178.6+3.5×55.44+2.5×(1085.5-178.6-55.44)=2858.49kN
Representative value of gravity load	11390.26+0.5×2858.49=12819.51kN

Representative value of gravity load on the first floor **Table e, Figure 6**

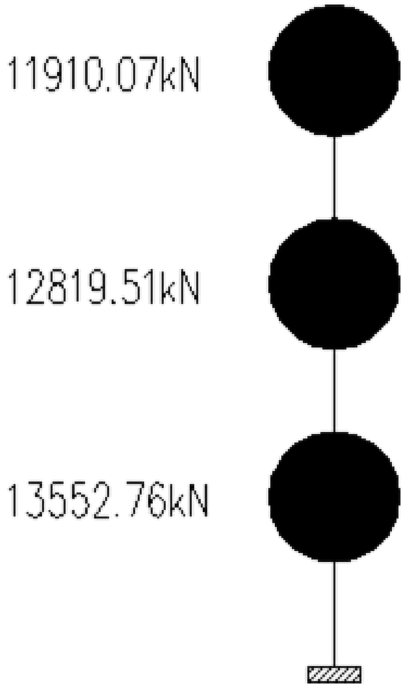

Figure 6: Representative value of gravity load.

Table e:

Weight of the first layer	1030.06×4.36=4491.06kN
First floor side span beam weight	20×(6.6-0.6-0.6+0.3+0.3)×3.84=460.8kN
First floor mid-span beam weight	10×(2.6-0.3-0.3)×2.24=44.8kN
First level beam weight	2.91×6.3×18=329.99kN
First floor longitudinal beam weight	4.25×6.9×36=1055.7kN
First floor column weight	9.61×5.8×40=2229.52kN
The weight of the outer transverse wall (except windows) on the first floor	2×2.2×((5.8-0.6)×6×2+(5.8-0.4)×2)×0.8=257.66kN
Weight of exterior longitudinal walls (except windows) on the first floor	(2.2×(5.8-0.65)×137.4×0.8=1245.39kN
First floor interior wall (except door) weight	(2.18×(5.8-0.55)×6.6×20×0.8)+(2.18×(5.8-0.65)×7.5×17×0.8)=2353.75kN
Second floor column weight	9.61×4.5×40=1729.8kN
Second-floor exterior transverse wall (excluding windows) weight	2×2.2×((4.5-0.6)×6×2+(4.5-0.4)×2)×0.8=193.6kN
Second-floor exterior longitudinal wall (excluding windows) weight	(2.2×(4.5-0.65)×137.4×0.8=931.02kN
The weight of the second floor interior wall (excluding the door)	(2.18×(4.5-0.55)×6.6×20×0.8)+(2.18×(4.5-0.65)×7.5×17×0.8)=1765.41kN
Weight of stairwell	7×55.44=388.08kN
Total dead load:	4491.06+460.8+44.8+329.99+1055.7+(2229.52+1729.8)/2+(257.66+193.6)/2+(1245.39+931.02)/2+(2353.75+1765.41)/2+388.08=12123. 51kN
live load:	3×178.6+3.5×55.44+2.5×(1085.5-178.6-55.44)=2858.49kN
Representative value of gravity load	12123.51+0.5×2858.49=13552.76kN

Calculation of overall lateral stiffness

In the second chapter, the lateral stiffness of each floor of the side frame and the middle frame has been calculated. Through these stiffnesses and the number of frames, the lateral stiffness of the overall frame can be calculated, and the calculation is as follows.

The lateral stiffnesses of the top side and the middle frame are respectively43520kN/m,52908kN/m, so the overall lateral stiffness of the top layer is 43520×2+52908×8=510304kN/m.

The lateral stiffnesses of the standard storey side and middle frames are respectively43520kN/m,52908kN/m, so the overall lateral stiffness of the standard layer is 43520×2+52908×8=510304kN/m.

The lateral stiffnesses of the side and middle frames of the first floor are respectively38260kN/m,42246kN/m, so the overall lateral stiffness of the standard layer is38260×2+42246×8=414488kN/m.

Natural vibration period

The calculation of the natural vibration period of the structure adopts the vertex displacement method. The representative value of the gravity load of each layer is applied to the mass point of each layer in the form of horizontal force, and the displacement of the vertex is obtained, and then the formula $T_1 = 1.7\psi_T\sqrt{u_T}$ calculate.

In ψ_T=0.7, u_T is the displacement of the vertex.

Table 11

Table 11: Vertex displacement calculation.

floor	$G_i(kN)$	$\sum G_i(kN)$	$\sum D_S kN/m$	$\Delta\mu_i(m)$	$\mu_i(m)$
3F	11910.07	11910.07	510304	0.02334	0.16416
2F	12819.51	24729.58	510304	0.04846	0.14082
1F	13552.76	38282.34	414488	0.09236	0.09236

It can be seen that the vertex displacement is0.16416m, so the natural oscillation period

$$T_1 = 1.7\psi_T\sqrt{u_T} = 0.7×1.7×0.16416\text{^}0.5=0.482s$$

Calculation of horizontal seismic force and checking calculation of shear-to-weight ratio

$$\sum_{i=1}^{n} G_i = 11910.07+13552.76+12819.51×1=38282.34kN$$

Earthquakes are grouped into the second group, the site category is Class II, and Tg=0.4s.

For reinforced concrete frame structures, $\gamma = 0.9$, $\eta_2 = 1$

when $T_g < T \le 5T_g$, $\alpha_1 = \left(\frac{T_g}{T}\right)^{\gamma}\eta_2\alpha_{\max}$;and $0.1 \le T \le T_g$, $\alpha_1 = \eta_2\alpha_{\max}$;

The seismic acceleration is 0.15g, and the maximum value of the horizontal seismic influence coefficient is 0.12. The natural vibration period of the structure is 0.482∈ (0.4,2), so α=0.101.

$$F_{EK} = 0.85\alpha_1\sum_{i=1}^{n} G_i = 0.85×0.101×38282.34=3286.54kN$$

According to the values of the natural vibration period of the structure and the characteristic period of the site, look up the anti-regulation table to find

$$\delta_n = 0=0$$

$$\Delta F_n = \delta_n F_{EK} = 0×3286.54=0kN$$

$$F_{EK}(1-\delta_n) = (1-0)×3286.54=3286.54kN$$

Horizontal seismic action of each floor is;

$$F_i = \frac{G_i H_i}{\sum_{j=1}^{n} G_j H_j} F_{EK}(1-\delta_n)$$

Table 12

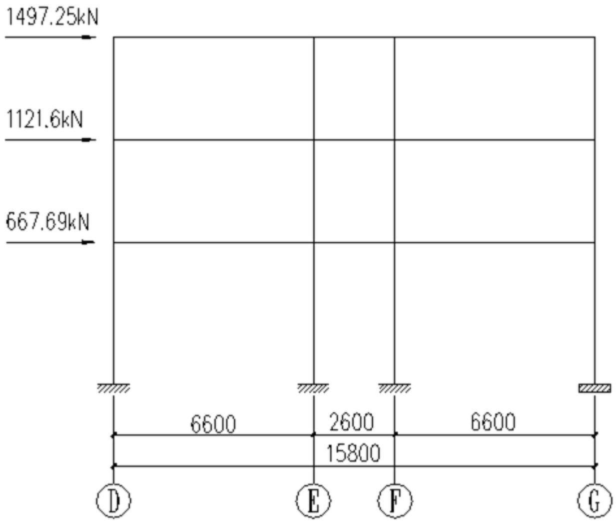

Figure 7: Representative value of gravity load.

Citation: Hamza Shams*, Zahoor Ahmad, Yanjun QIU*, Hamid Abdrhman and Hanif Ullah. Advanced Optimization of Structural Integrity in Beam-Slab-Column Design, Stiffness, and Seismic Performance of Concrete Frames. Cur Trends Civil & Struct Eng. 12(3): 2026. CTCSE.MS.ID.000781. **DOI:** 10.33552/CTCSE.2026.12.000781.

Table 12: Transverse seismic action and seismic shear force of each story.

floor	$G_i(kN)$	$H_i(m)$	G_iH_i **(kN.m)**	$\sum G_iH_i$ **(kN.m)**	$F_i(kN)$	$V_i(kN)$	$\lambda\sum_{j=i}^{n} G_j(kN)$
3F	11910.07	14.8	176269	386916	1497.25	1497.25	285.84
2F	12819.51	10.3	132041		1121.6	2618.85	593.51
1F	13552.76	5.8	78606.01		667.69	3286.54	918.78

It can be seen from the table that the shear-to-weight ratio of each floor meets the requirements.

Figure 7

Check calculation of lateral movement under earthquake action

According to the seismic shear force and lateral stiffness of each floor, according to the formula $\Delta\mu_e = \frac{V_i}{\sum D_S} \le [\theta_e] h_i$, to calculate the inter-story displacement of each floor.

Table 13

Table 13: Check calculation of displacement under earthquake.

floor	$V_i(kN)$	$h_{i(m)}$	$\square D_S(kN/m)$	$(\square u)_i(m)$	$(\square u)_i / h_i$	limit value
3F	1497.25	4.5	510304	0.00293	1/1538	1/550
2F	2618.85	4.5	510304	0.00513	1/877	
1F	3286.54	5.8	414488	0.00793	1/730	

Calculation of frame internal force under earthquake

Inflection point

When the frame column undergoes double-curvature deformation, the bending moment at both ends of the column rotates in the same direction, and the zero point of the bending moment in the column is the inflection point. The calculation formula is as follows.

$$y = y_0 + y_1 + y_2 + y_3$$

The beam section of each floor of the frame is the same, and the $y_{1=0;}$

Since the height of the bottom column is different from that of other layer columns, and the y_3 *correction, after calculating the underlying* $y_1=0, y_2=0, y_3=0$;

Similarly, the rest of the floors *the* $y_1=0, y_2=0, y_3=0$;

Table 14

Table 14: Calculation of inflection point.

floor	$h_{i(m)}$	K		y_0		y		$yh_{i(m)}$	
		Side column	Center column	side column	Center column	side column	Center column	side column	Center column
3F	4.5	0.68	1.19	0.35	0.41	0.35	0.41	1.58	1.84
2F	4.5	0.68	1.19	0.45	0.46	0.45	0.46	2.03	2.07
1F	5.8	0.88	1.54	0.65	0.623	0.65	0.623	3.77	3.61

Shear force and bending moment of frame columns under earthquake action

The seismic shear force of each floor has been obtained from Table, and the shear force of each frame column can be obtained by multiplying the ratio of the lateral stiffness of the side column and the central column to the lateral stiffness of the floor and multiplying it by the total seismic shear force of the floor, calculated as shown in the table below.

Table 15

Table 15: Column shear force under earthquake action.

floor	$\square D_S(kN/m)$	$V_i(kN)$	$D(kN/m)$		$V(kN)$	
			side column	Center column	side column	Center column
3F	510304	1497.25	10667	15787	31.3	46.32
2F	510304	2618.85	10667	15787	54.74	81.02
1F	414488	3286.54	9565	11558	75.84	91.65

The upper column bending moment is equal to the column shear force multiplied by the distance from the inflection point to the upper end of the column, and the lower column bending moment is equal to the column shear force multiplied by the distance from the inflection point to the lower end of the column. The calculation formula is as follows:

$$Mt=-Vh(1-y)$$

$$Mb=-Vhy$$

Table 16

Table 16: Bending moment at column end under earthquake.

floor	$h_{i(m)}$	$V(kN)$		$yh_{i(m)}$		$Mt(kN.m)$		$Mb(kN.m)$	
		side column	Center column	side column	Center column	side column	Center column	side column	Center column
3F	4.5	31.3	46.32	1.58	1.84	-91.4	-123.21	-49.45	-85.23
2F	4.5	54.74	81.02	2.03	2.07	-135.21	-196.88	-111.12	-167.71
1F	5.8	75.84	91.65	3.77	3.61	-153.96	-200.71	-285.92	-330.86

Bending Moment Calculation of Frame Beam Ends Under Earthquake

The bending moments at the beam-column joints of the frame are balanced, so the sum of the bending moments at the beam ends at the joints is equal to the sum of the bending moments at the column ends, and then according to the stiffness of the beam lines on both sides of the joints, the bending moments are distributed to the beam ends. The calculation formula is as follows.

Beam left bending moment: $M_b^l = -\frac{i_b^l}{i_b^l + i_b^r}\left(M_c^i + M_c^{i-1}\right)$

Beam right bending moment: $M_b^r = -\frac{i_b^r}{i_b^l + i_b^r}\left(M_c^i + M_c^{i-1}\right)$

$$i_b^l + i_b^r = 49091+36923=86014\text{kN.m}$$

$$\mu_1 = \frac{i_b^r}{i_b^l + i_b^r} = 49091/86014=0.571$$

$$\mu_2 = \frac{i_b^r}{i_b^l + i_b^r} = 36923/86014=0.429$$

Table 17

Table 17: Beam end bending moment under earthquake action.

floor	$Mt(kN.m)$		$Mb(kN.m)$		$Ml(kN.m)$		$Mr(kN.m)$	
	side column	Center column	side column	Center column	side beam	middle beam	side beam	middle beam
3f	-91.4	-123.21	-49.45	-85.23	91.4	52.86	70.35	52.86
2f	-135.21	-196.88	-111.12	-167.71	184.66	121.03	161.08	121.03
1f	-153.96	-200.71	-285.92	-330.86	265.08	158.05	210.37	158.05

Calculation of frame beam shear force and column axial force under earthquake action

Calculate the bending moment at the beam end of the frame according to Table 4-7. Due to the moment balance, it can be known that the shear force at the beam end $V=-(M_l+M_r)/l$.

Selecting the beam-column joints for force analysis shows that the axial force of the column is related to the axial force of the upper column and the shear force of the beam end on both sides of the column of this storey. The calculation formula is as follows

$$N_i = N_{i-1} + V_r - V_l$$

Where Vr is the shear force of the beam at the right end of the column, and Vl is the shear force of the beam at the left end of the column.

Table 18, Figures 8-10

Table 18: Beam Shear Force and Column Axial Force Under Earthquake.

layer number	$Ml(kN.m)$		$Mr(kN.m)$		$l(m)$		$V(kN)$		$N(kN)$	
	side beam	middle beam	side beam	middle beam	side beam	middle beam	side beam	middle beam	side column	Center column
3f	91.4	52.86	70.35	52.86	6.6	2.6	-24.51	-40.66	-24.51	-16.15
2f	184.66	121.03	161.08	121.03	6.6	2.6	-52.38	-93.1	-76.89	-56.87
1f	265.08	158.05	210.37	158.05	6.6	2.6	-72.04	-121.58	-148.93	-106.41

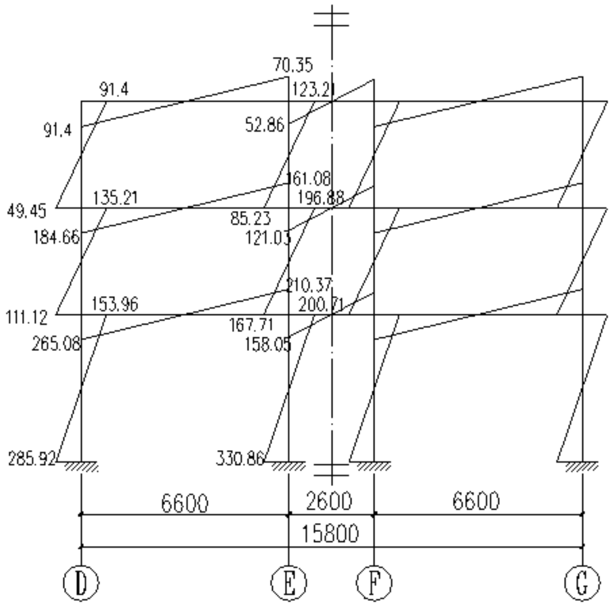

Figure 8: Bending moment diagram of frame under earthquake.

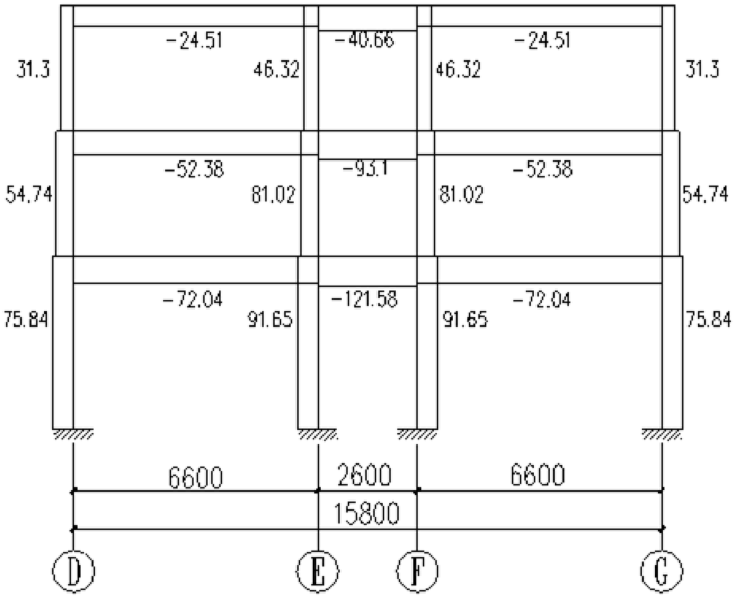

Figure 9: Shear force diagram of frame under earthquake.

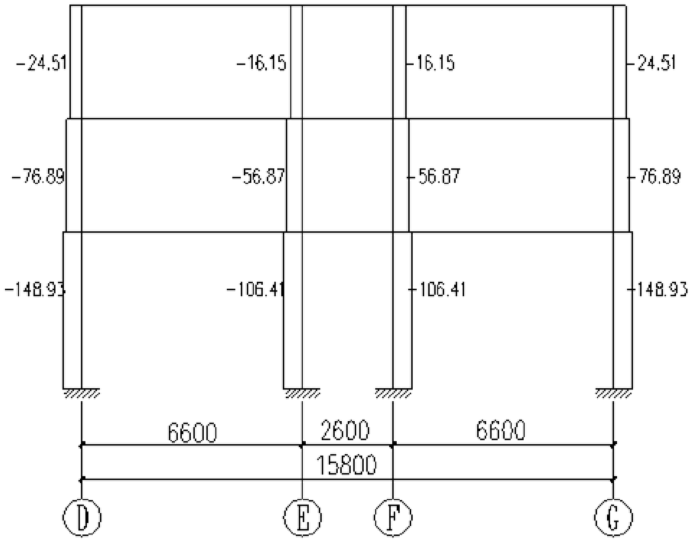

Figure 10: Axial Force Diagram of Frame under Earthquake.

Citation: Hamza Shams*, Zahoor Ahmad, Yanjun QIU*, Hamid Abdrhman and Hanif Ullah. Advanced Optimization of Structural Integrity in Beam-Slab-Column Design, Stiffness, and Seismic Performance of Concrete Frames. Cur Trends Civil & Struct Eng. 12(3): 2026. CTCSE.MS.ID.000781. **DOI:** 10.33552/CTCSE.2026.12.000781.

Conclusion

This study delves into the design process, analysis, and systems of reinforced concrete frames, particularly the beam-slab-column configuration during the initial, mid, and post stages of construction. The research addresses the fine-tuning of beam dimensions, slabs, and column structures necessary to achieve the overall mechanical stability of construction. Moreover, the study addresses the calculation of vertical and horizontal (lateral) stiffness, an attribute necessary in the optimisation of the frames to resist the rocking of the structures during and after an earthquake. The research utilizes earthquake-related shear seismic frames, bending moments, and static and dynamic equilibrium (natural period of frame) in determining the performance of reinforced concrete frames. The information contained in the research informs and enhances the work carried out by engineers, especially in raising the incendiary matters of high construction concrete frames. The study lays the groundwork of design, construction, and performance of concrete frames. The frames' performance during and after seismic-related events guarantees the frames continue to sustain vital construction with the frame. The research addresses the optimisation of frameworks to sustain primary and secondary earthquake-related loading; the research is geared toward fostering frameworks that adhere to long-term sustainability goals.

Author Contributions

Hamza Shams, Zahoor Ahmad Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing—original draft preparation, Writing—review and editing, Yanjun QIU Supervision, Review and editing, Project administration, Funding acquisition, Hamid Abdrhman Writing and editing, Chengxiang Wang Writing and editing, Hanif Ullah Writing and editing, Muhammad Kashif Writing and editing Costel PLEŞCAN Writing and editing, Elena Loredana PLEŞCAN Writing and editing, Daniel TAUS Writing and editing

Data Availability Statement

The data used in this research have been appropriately cited and reported in the main text.

Conflicts of Interest

The authors declare no conflict of interest.

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