

Numerical Investigation of Reinforced Concrete Column with Various Intermediate Tie configurations

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Abstract

Reinforced concrete columns rely on transverse reinforcement to provide shear resistance, prevent local buckling of longitudinal reinforcement, and confine the concrete core. Intermediate ties are type of transverse reinforcement used to support non-corner longitudinal bars; however, their structural effectiveness under different tie configurations remains insufficiently investigated. This study numerically investigates the behavior of reinforced concrete columns with various intermediate tie configurations, hoop spacings, and hook anchorage angles subjected to combined constant axial and lateral loading. Finite element modeling was performed using ANSYS Mechanical APDL 2020 R2. The developed model was first validated using experimental results from the literature and then used for a detailed parametric study. The validation model was a cantilever RC column with a 450 mm × 450 mm cross-section and 1800 mm height, while the parametric study considered columns with a 550 mm × 550 mm cross-section. A total of 53 finite element models with identical material properties and dimensions but different tie configurations were analyzed to evaluate their effects on lateral load capacity and ductility. Finite element analysis results showed that different intermediate tie configuration improved lateral load capacity from 4.18% to 6.08% and ductility also from 5.25%–22.76% relative to the reference column due to better lateral restraint against longitudinal bar buckling and core confinement. Increasing hoop spacing from 100 mm to 300 mm reduced lateral load resistance from 7.33% to 4.02% and ductility also from 32.18% to 21.52%. Increasing tie hook angles from 45° to 135° increased maximum lateral load strength from 0.31% to 2.77% but decreased in ductility by 8.28%. These results show that intermediate tie configuration strongly impacts the reinforced concrete column confinement and deformation.

1. Introduction

Columns are essential structural members subjected to axial loads, with or without moments whose failure leads to collapse overall structure. In reinforced concrete (RC) columns, transverse reinforcement provides shear resistance, prevents shear failure, restrains lap splice slip, prevent local buckling of longitudinal bars and laterally confines core concrete.

Grid-type transverse reinforcement enhances concrete cover protection and core confinement, improving strength and ductility when aligned with the column axis (Sha et al., 2020). To study the effect of tie configurations on column behavior, the volumetric ratio of transverse reinforcement should be kept constant (Shin et al., 2010). Buch and Sharma (2026) reported that improved tie confinement enhanced the fire resistance and structural integrity of reinforced concrete columns through better concrete core confinement and reduced longitudinal bar instability. Confinement reinforcement types such as crossed ties, further improve deformation capacity and confinement of concrete, and also is crucial under seismic conditions to minimize cover spalling. Current codes, such as ACI 318 – 14 and ES EN 1992-1-1:2015, provide guidance on tie extension lengths, hook angles, spacing, and transverse reinforcement diameter to ensure ductility and confinement, but practical evaluation of these parameters for non-standard tie shapes is limited. Experimental results from Kim et al. (2020), including backbone curves,

peak lateral load resistance, ductility and concrete damage were used to validate the finite element model.

Existing codes and studies focus on V-shaped, triangular, and conventional C-shaped ties, but not conduct the influence of other intermediate tie configurations. This study addresses existing gaps by developing and validating a nonlinear finite element model to simulate the lateral load response by conducting a parametric investigation on the effects of intermediate tie configurations, hoop spacing, and hook anchorage angles on lateral strength, ductility, and concrete damage behavior of column.

3. Material and Methodology

This section includes nonlinear finite element analysis was performed using ANSYS Mechanical APDL 2020 R2. The finite element (FE) model included materials (concrete and reinforcement), boundary conditions and failure criteria for each material.

3.1 Overview of Numerical Modelling Approach

A detailed 3D finite element model was developed in ANSYS Mechanical APDL to simulate the behavior of a reinforced concrete column subjected to constant axial and lateral loading. The geometry, material properties and loading protocol were adopted from the full-scale experimental study of Kim et al. (2020) for validation is demonstrated on Fig. 3(a &b).

3.2 Geometry and Reinforcement Details

The validation model consisted of a cantilever reinforced concrete column with a square cross-section of 450 mm × 450 mm and a height of 1800 mm, adopted from the experimental study of Kim et al. (2020). After successful validation of the finite element ANSYS model, a parametric study was conducted using reinforced concrete columns with a square cross-section of 550 mm × 550 mm to investigate the effects of intermediate tie configuration, hoop spacing, and hook anchorage angle. Longitudinal steel reinforcement and transverse stirrups (hoop and intermediate tie) were modeled discretely using REINF264 elements with different yield strengths is presented under Table 1. The compressive strength of concrete was 23 MPa.

Table 1
Material strength of steel reinforcing bar from tested column (Kim et al. 2020)

Bar grade and size	Yield strength fy (Mpa)	Type reinforcement
SD400D10	493	Intermediate tie
SD400 D13	551	Peripheral hoop
SD500 D22	572	Longitudinal

3.3 Element type and Material models

- 1. **Concrete:** Modeled using CPT215 (3D eight-node) solid elements with a coupled damage-plasticity formulation to capture cracking, crushing and stiffness degradation present on Fig. 2a).
- 2. **Steel reinforcement:** Modeled using REINF264 (3D discrete) elements with bilinear isotropic hardening. (ANSYS User Manual, 2020) as shown Fig. 2b.

3.4 Loading Protocol and boundary conditions

The analysis consisted of two sequential stages:

- 1. **Loading protocol:** A constant axial load corresponding to 35% of the nominal axial load capacity (1630.125 kN) was applied at the top of the column; next the cyclic lateral displacement was applied up to 90 mm as shown on Fig. 3b.
- 2. **Boundary conditions:** The RC column was modelled as a cantilever, fully fixed at the base presented on Fig. 3b.

3.5 Parametric Study

After validation, the model was used to investigate:

- 1. various intermediate tie configurations (evaluated at a constant volumetric ratio) are presented on Fig. 4 and Table 2.
- 2. hook anchorage angles
- 3. hoop spacing

The influence of these parameters on the lateral strength, ductility, and damage behavior of RC columns was examined.

Table 2 Various tie configuration at constant volumetric ratio

Parameter type	Transverse reinforcement				No. of model
	Specimen	ρ_s (%)	Diameter(mm)	Spacing(mm)	
Configurations of intermediate tie	□	1.202	12	80	9
	C1	1.202	12	133	
	C2	1.202	12	133	
	N-N	1.202	12,10	170.5	
	N-U	1.202	10	156.5	
	N-V	1.202	10	152.2	
	N-X	1.202	12,10	160.5	
	X-U	1.202	12,10	170.5	
	X-V	1.202	12,10	166.5	

4. Result and discussion

In this section, finite element analysis (FE) was used to validate the model and investigate parametric effects on reinforced concrete columns. A total of 53 models were studied, examining peak lateral load, ductility and damage.

4.1 Validation Results of the Finite Element Model

The nonlinear FE analysis results were compared with the experimental data from Kim et al. (2020) using backbone curves (lateral load–lateral displacement curve), displacement, ductility, and column damage of the validated column. All these values showed agreement within the tolerance limit, indicating nearly close results, as presented in Fig. 5 and Table 3.

Table 3
Accuracy of FE Analysis Results

Parameter	Experimental Result	FE Result	Percentage difference
Maximum Lateral Load (V_u , kN)	312	304.472	2.4%
Yield Displacement (U_y)	7.25	7.21	0.55%
Ultimate Displacement (U_u)	84.98	89.8	5.67%
Ductility ($\mu\Delta$)	11.72	12.48	6.48%
Post-peak lateral loads	235.58	248.7	5.56%

4.2 Finite element parametric study

After validating the finite element (FE) model, a parametric study was conducted on RC columns. The study independently examined the effects of tie configuration, spacing and hook anchorage angle on lateral strength, ductility, and damage.

4.2.1 Effect of intermediate tie configurations

This section compared result of RC columns with various intermediate tie configurations with reference column. To isolate the effect of tie configuration on column behavior, the volumetric ratio of transverse reinforcement was kept constant by adjusting the hoop spacing (133–170 mm) and the bar diameter (10–12 mm). All specimens exhibited similar initial stiffness, but columns with X-U, N-U, N-V, N-X, X-V, N-N, C1, and C2 configurations showed different increasing lateral load capacity from 4.18% to 6.08% respectively compared with the reference column. Furthermore, the ductility (measured as the displacement ratio $\mu\Delta$) increased from 5.25% to 22.76% respectively for column with N-V, X-V, N-U, X-U, N-X, N-N, C2 and C1 configurations observe the detail value of lateral resistance and ductility on Fig. 6 and in Table 4. Because, the application of intermediate tie configurations significantly enhances the post-elastic performance of RC columns that means these configurations increase in lateral load capacity and ductility driven by more concrete core confinement and the effective prevention of longitudinal bar buckling.

Table 4
Effect of tie configuration on lateral load resistance and ductility

Specimen	Lateral Load (kN)	%Increase (Load)	Displacement (mm)	Ductility (U_u/U_y)	% Increase (Ductility)
□	387.25	Refer.	3	19.6	Refer.
C1	409.086	5.64	3.201	24.061	22.76
C2	410.786	6.08	3.234	22.865	16.66
N-N	408.591	5.51	3.204	22.015	12.32
X-V	407.855	5.32	3.191	21.373	9.05
N-X	405.737	4.77	3.157	21.965	12.07
N-V	405.577	4.73	3.14	20.628	5.25
N-U	403.887	4.3	3.101	21.853	11.5
X-U	403.423	4.18	3.082	21.95	11.99

4.2.2 Effect of Hoop Spacing on RC Column Behavior

The lateral load–lateral displacement curves of all specimens showed similar initial stiffness due to identical column geometry and material. But, as hoop spacing increased from 100 mm to 300 mm, peak lateral load and ductility decreased due to reduced concrete core confinement and less lateral restraint

of longitudinal bars which is illustrated in table 5. The graph expressed the column with a C1 configuration showed a 5.06% reduction in lateral resistance (415.98 kN to 395.96 kN) and a 32.18% decrease in ductility (24.4 to 18.4) as shown on Fig. 7 and table 5. The results show that closer tie spacing enhances both lateral load capacity and ductility.

Table 5 Effect of hoop spacing on lateral load capacity and ductility

Specimen	Ultimate lateral load (kN)			Stiffness (kN/mm)	Displacement at Damage Point				Ductility ratio (δ_u/δ_y)	Residual drift (%)			
	10th cycle	20th cycle	30th cycle		10mm	20mm	30mm	40mm		10 mm	20 mm	30 mm	40 mm
C1	443.49	442.31	266.08	5.05	2.91	9.06	27.71	46.08	9.24	2.65	13.64	23.18	33.02
C2	413.56	403.62	265.00	4.08	2.44	8.43	24.65	42.62	9.48	2.44	13.63	23.06	32.63
C3	398.59	384.82	234.85	3.91	2.92	9.11	25.13	44.84	7.93	2.17	11.90	20.33	28.77
SC1	528.97	492.92	295.48	4.09	3.51	9.90	31.11	55.08	9.55	2.28	12.83	23.33	32.92
SC2	526.92	442.72	257.11	3.70	2.96	8.57	26.29	45.77	9.37	2.19	12.84	23.58	33.83
SC3	482.70	442.72	204.81	3.06	3.05	9.22	25.09	44.44	7.89	2.10	12.18	22.52	32.05
E1	423.19	382.78	210.67	3.68	3.29	10.32	26.19	45.48	9.26	2.34	13.63	24.34	34.78
E2	457.81	389.78	196.23	3.18	2.88	9.53	24.39	42.23	9.83	2.14	12.24	21.62	30.31

4.2.3 Effect of Tie Hook Anchorage Angles

Three different tie hook anchorage angles (45°, 90° and 135°) were analyzed with constant spacing and configuration, taking 135° as the reference. The results showed that increasing the hook anchorage angle enhanced the peak lateral load resistance of all specimens from 0.31% to 2.77%. This improvement occurred because larger hook angles provided better confinement of the core concrete, prevented early tie extraction, and enhanced the bond between reinforcement and concrete.

Increasing the tie hook anchorage angle from 90° to 135° improved the ductility of N-X and N-N specimens by 3.9% and 2.04% respectively, due to longer anchorage lengths and better restraint of longitudinal bars, while C1 and C2 showed reductions of 1.26% and 5.07%. Similarly, increasing the hook angle from 45° to 135° led to ductility gains of 4.07% and 2.52% in columns with N-U and X-U tie configurations, resulting from improved tie embedment, enhanced bond with core concrete, and delayed damage; in contrast, N-V and X-V exhibited larger reductions of 7.73% and 8.28%. The larger hook angles also provided more effective confinement of core concrete, although they reduced the confined concrete area. Generally, tie hook anchorage angles significantly influence column ductility, with effects varying according to the tie configuration.

5. Conclusions

The FE model developed using ANSYS APDL 2020 accurately simulated the behavior of RC columns with different tie configurations, spacing, and hook angles.

Key findings are:

- The validation of FE model matched with the experimental results by 2.4% difference in lateral load capacity and 6.48% in ductility within acceptance tolerance.
- Columns with modified tie shapes (N-V, X-V, N-U, X-U, N-X, N-N, C2 and C1 configurations) improved lateral strength and ductility of column behavior from 4.18% to 6.08% and from 5.25% to 22.76% respectively.
- Increasing tie spacing from 100 mm to 300 mm reduced lateral load capacity from 7.33% to 4.02% and ductility from 32.18% to 21.52%.
- Increasing tie hook angle from 45° to 135° improved ductility for N-N, N-X, N-U, and X-U by up to 4.07%, but decreased ductility for C1, C2, N-V, and X-V by up to 8.28%.

Declarations

Author Contributions

Emebet Fentahun Ejigu led the study through conceptualization, methodology development, numerical analysis, validation, result interpretation, and manuscript preparation. Tesfaye Alemu Mohammed provided supervision, methodological guidance, and technical review. Bitania Sewnet Tegegne and Selamawit Ayal Chanie contributed to the numerical work, methodology, and interpretation of findings. Getasew Kindie Mihretu, Girma Moges Teshager, and Nigusie Tsehay Demeke, and Amelmal Gelaye Berie assisted with data analysis, validation, and interpretation. All authors reviewed and agreed to publish the final manuscript.

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Data availability

The numerical datasets generated and analyzed during the study are available from the corresponding author upon reasonable request. All necessary data were included in the manuscript

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Ethics declaration

not applicable.

Consent to Publish declaration

not applicable

Consent to Participate declaration

not applicable

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Figures

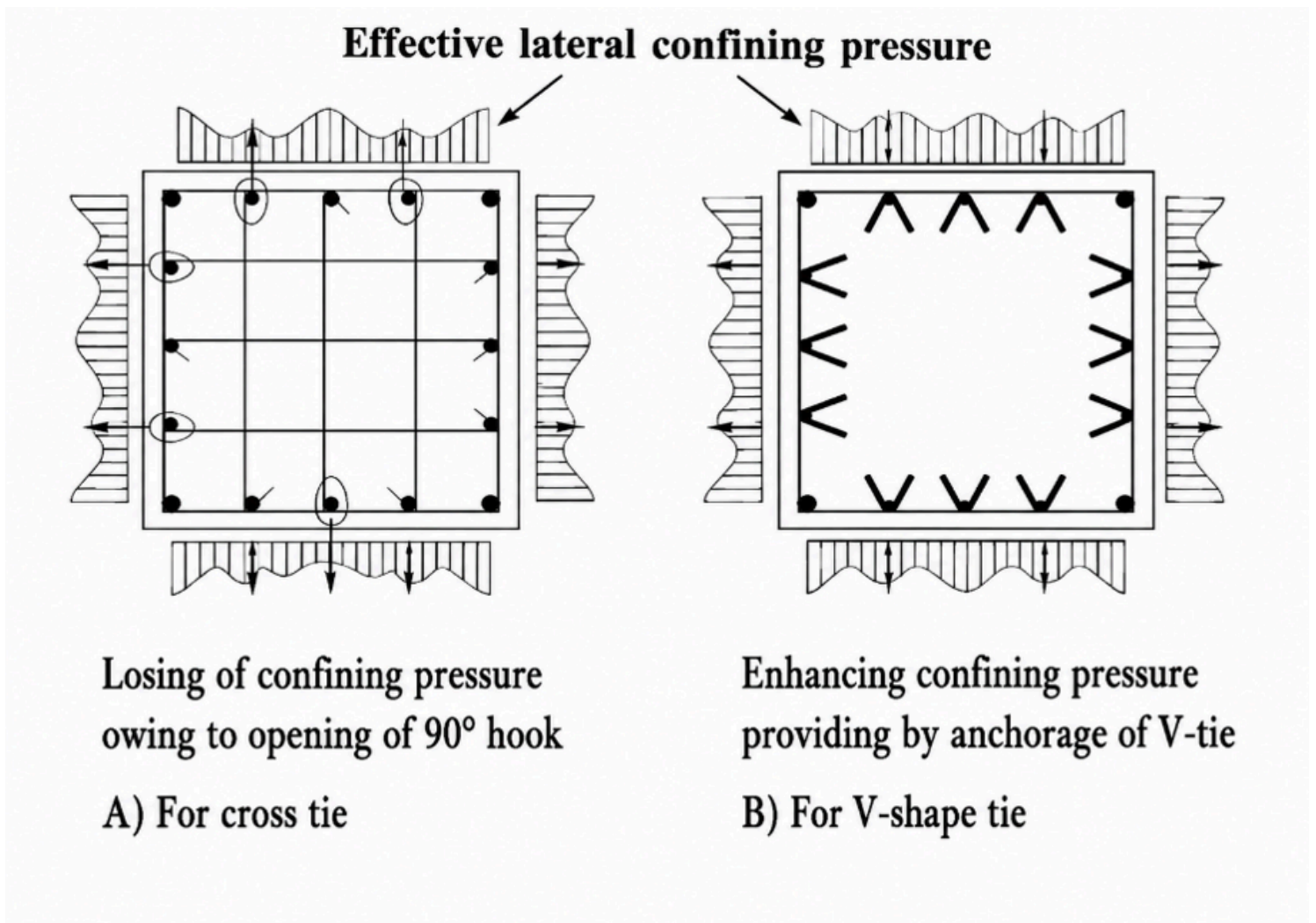


Figure 1

Effect of intermediate ties on confinement pressure

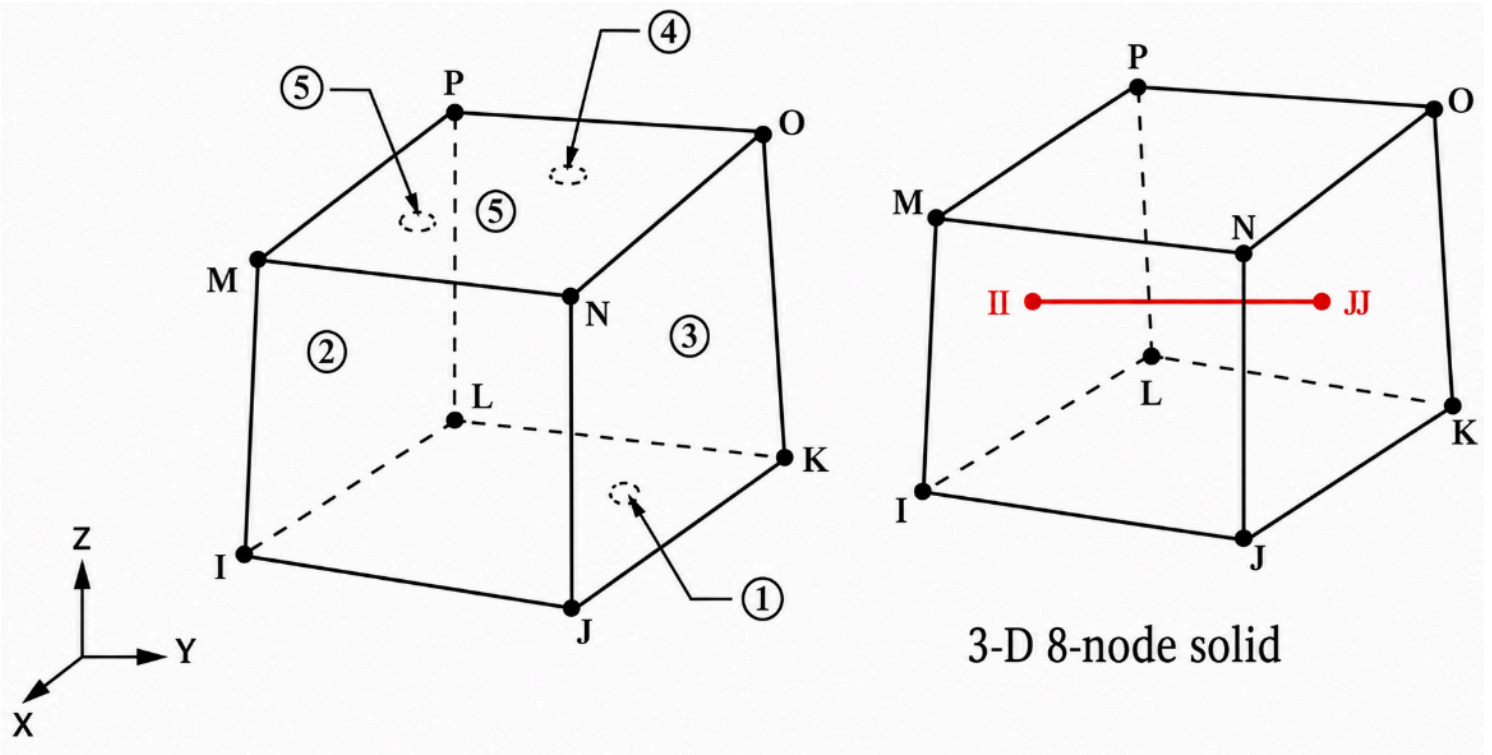


Figure 2

- a) CPT215 solid geometry elements and
- b) REINF264 geometry with the base element

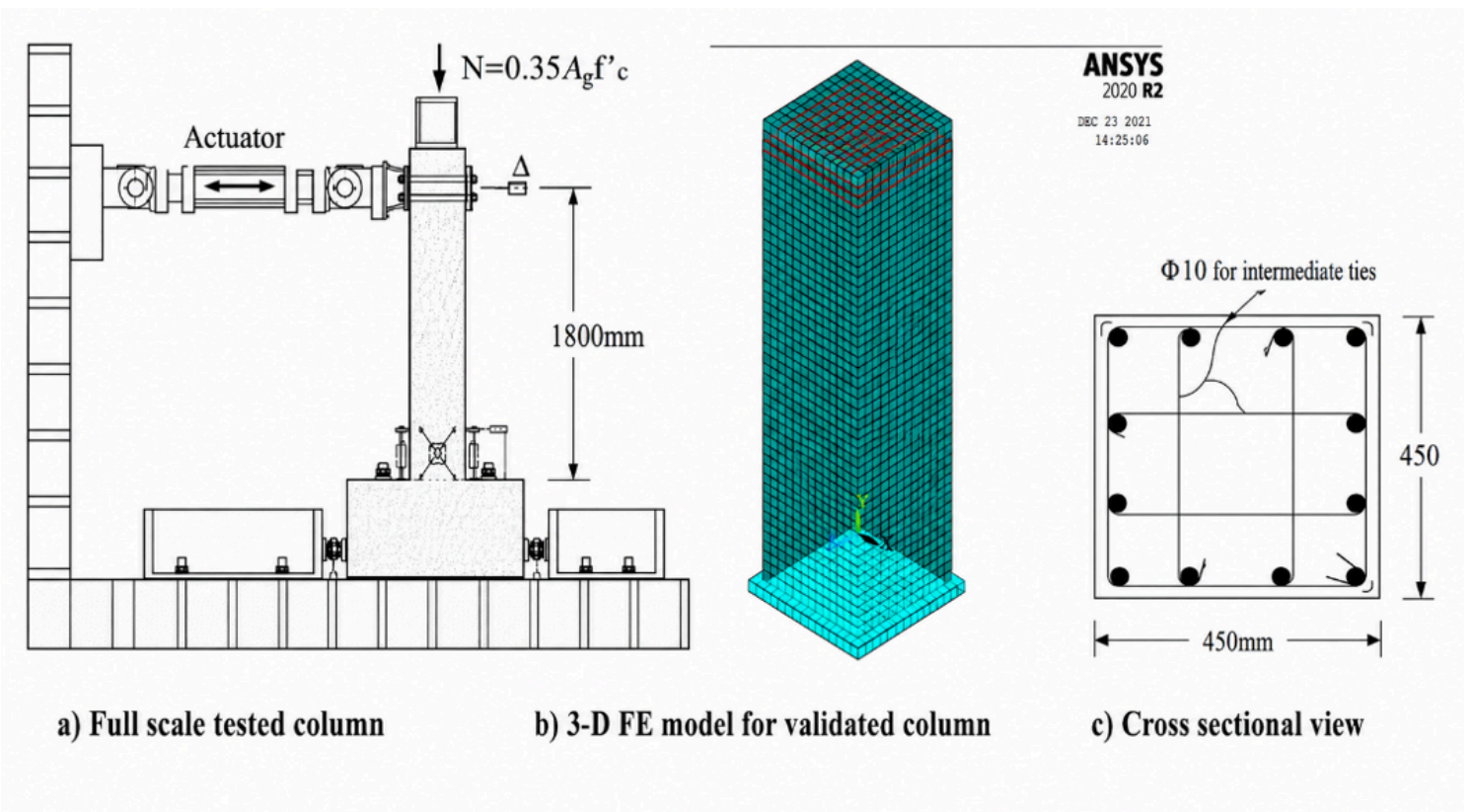


Figure 3

Loading and boundary condition of cantilever column

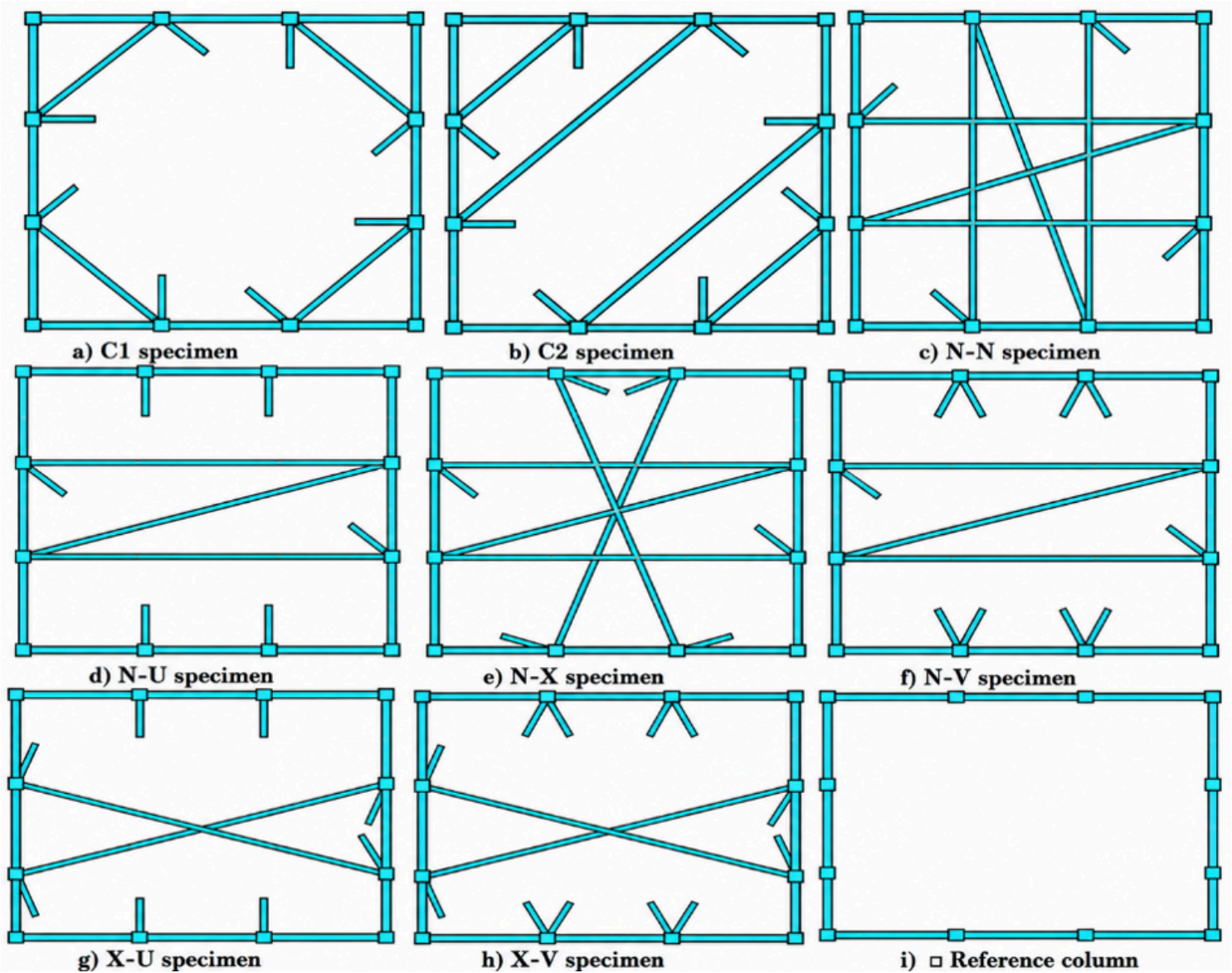


Figure 4

Details and layout of intermediate tie configurations



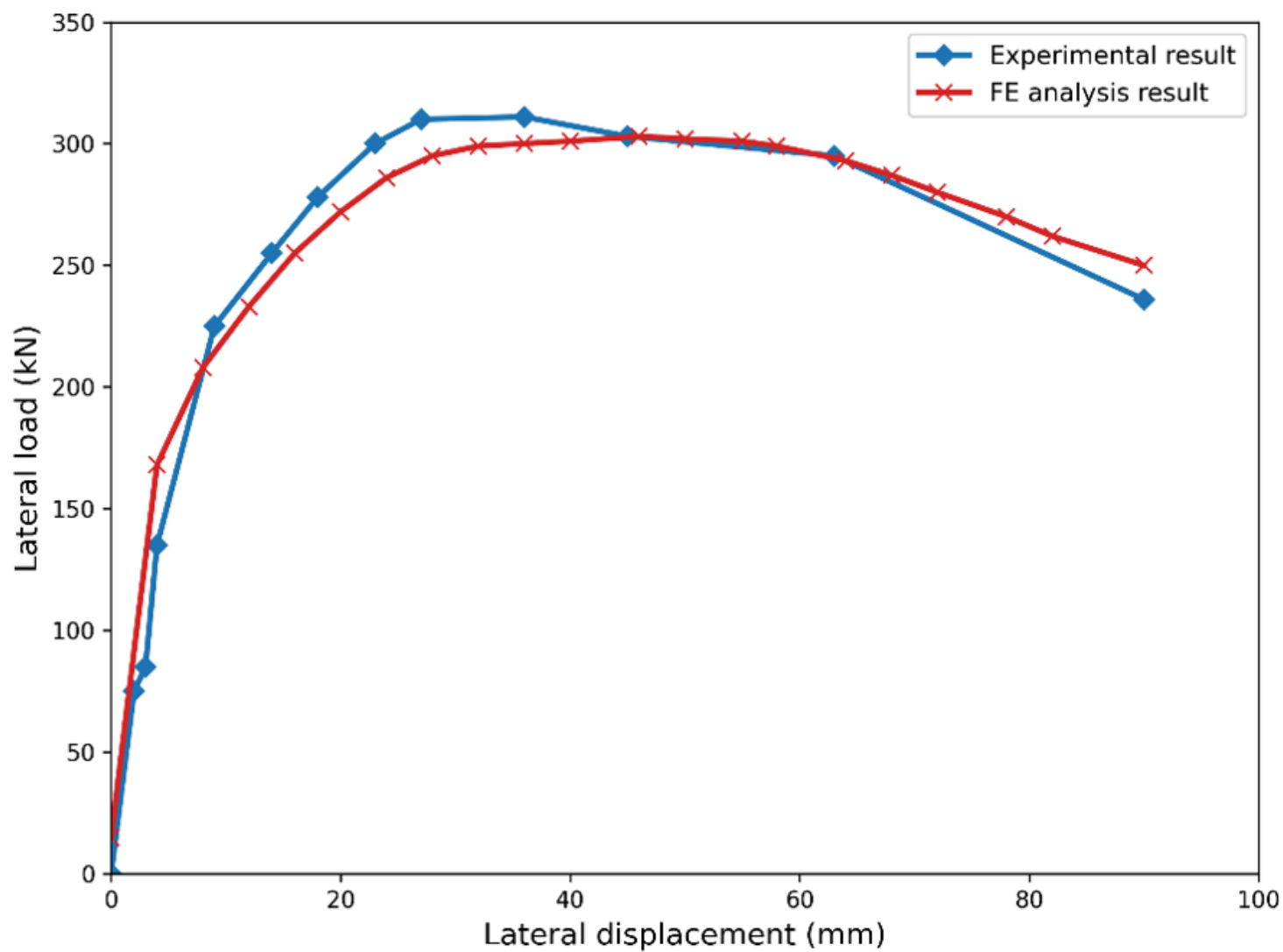


Figure 5

Lateral load-lateral displacement curve for the FE analysis and experimental results

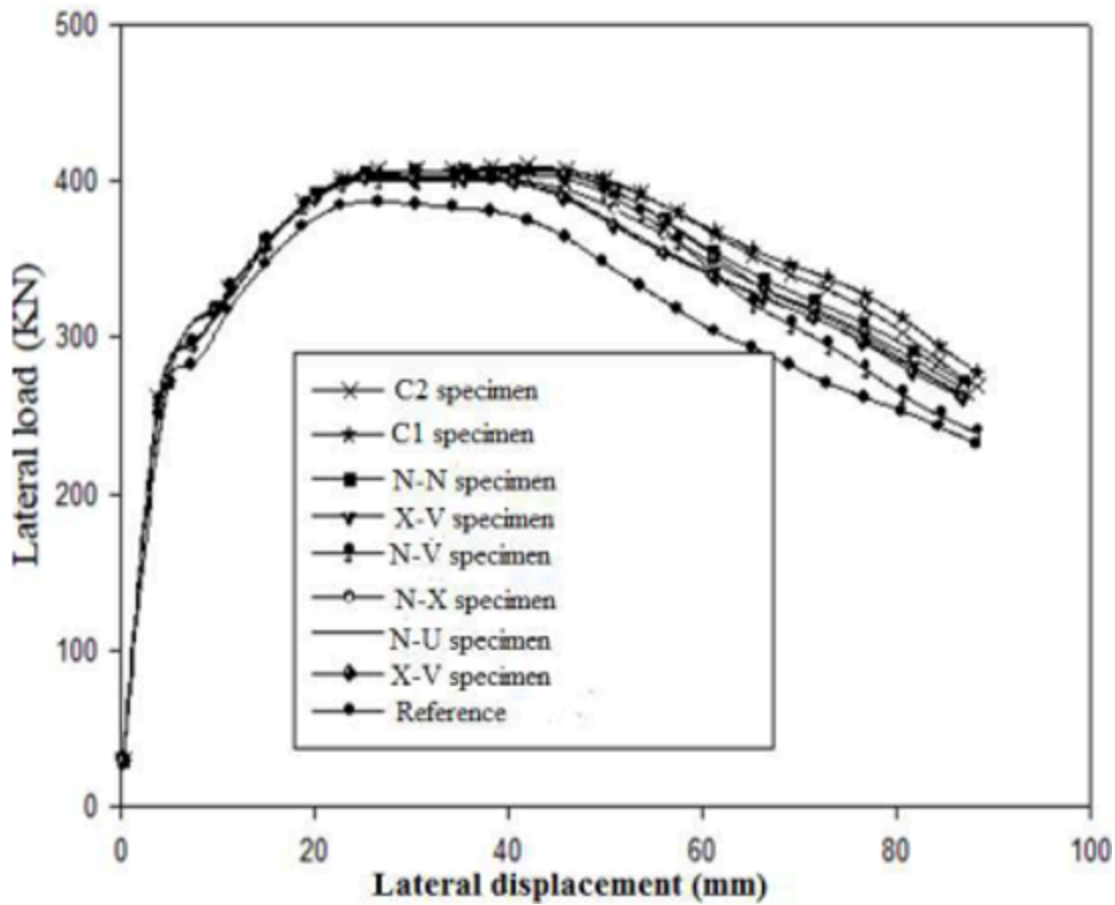


Figure 6

Effect of tie configuration on lateral load resistance

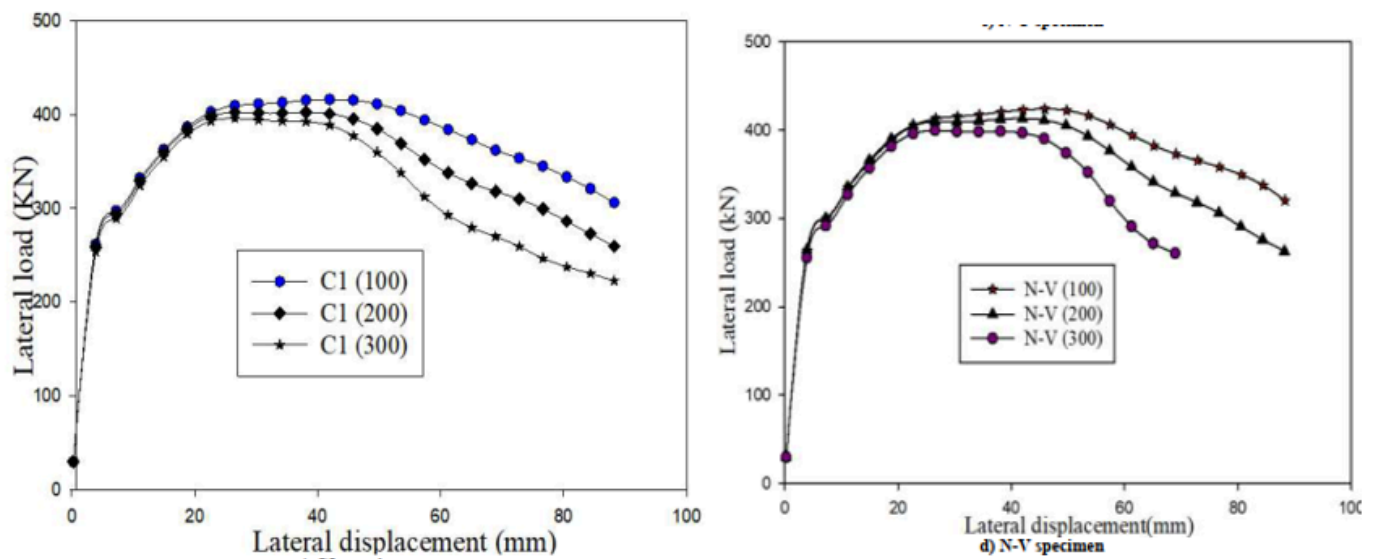


Figure 7

Effect of hoop spacing on lateral load capacity for C1 and N-V configuration