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INTERACTION EFFECT OF SPACE FRAME-STRAP FOOTING-SOIL SYSTEM ON FORCES IN SUPERSTRUCTURE

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ABSTRACT

The conventional method of building frame analysis assumes that columns are resting on unyielding supports. In reality, the supporting soil strata deforms unevenly under the action of loads, which causes redistribution of forces in the frame members and stresses in the supporting soil media. In the past, many researchers investigated and emphasized the need of soil-structure interaction analysis. There may exist a situation where column(s) of a building are located near adjoining property line. In this situation, an eccentric footing is generally provided. This causes angular rotation in such individual footings due to moment developed by eccentric loading. The strap beams may be provided under such circumstances in order to control the rotation within permissible values. However, in India the normal practice is to provide individual column footings without strap beams. In the present work, the interaction analysis of a three-bay three-storey RCC space frame- footing-strap beam-soil system is carried out to investigate the interaction behavior using the finite element method. The frame, foundation and supporting soil mass are considered to be linear elastic and to act as a single compatible structural unit for more realistic analysis. The analyses have been carried out to evaluate the axial force and moment in columns, bending moments and shear force in floor, plinth and strap beams. The comparison is made between the non-interaction and interaction analyses. The emphasis is made on the necessity of interaction analysis using strap beams. The inclusion of strap beams in the foundation will prevent failure/distress of the structure likely to be caused by heavy moments induced when only eccentric isolated footings are used.

Keywords: strap footing, space frame, soil-structure interaction, isolated footing, finite element analysis, truncation boundary.

1. INTRODUCTION

Soil-structure interaction is a complex phenomenon which involves mechanism of interaction between various components of a building system. In common design practice interaction between soil, foundation and structure is neglected to simplify the structural analysis. A stress analyst generally ignores the influence of the settlements of supporting soil on the structural behavior of the super-structure. In addition to this, the effect of the stiffness of the structure is disregarded in evaluating the foundation settlements. Earlier studies have indicated that interaction effects are quite significant, particularly for the structures resting on highly compressible soils. The differential settlements, rotation of footing and stiffness of the frame cause redistribution of forces/stresses in the frame members. A more rational solution of a soil-structure interaction problem can be achieved by appropriate analysis.

A strap footing may be provided when one or more columns exist on the common property line. It comprises of two or more footings of individual columns, connected by a beam called strap beam. These footings are provided when there are heavy loads on adjoining footings and no overlapping exists between their areas.

2. LITERATURE REVIEW

A lot of investigations have taken place in the area of soil-structure interaction of framed structures. Various investigators have proposed different approaches for solution of interaction problems from time to time in attempt to obtain more realistic analysis. They have quantified the effect of interaction behaviour and established that there is redistribution of forces in the frame members.

Desai *et al*. (1982) presented a finite element procedure for the general problem of three-dimensional soil-structure interaction involving nonlinearities caused by material behavior, geometrical changes, and interface behavior. The formulation is based on the updated LaGrange or approximate Eulerian approach with appropriate provision for constitutive laws.

Brown and Yu (1986) examined the effect of progressive loading during the construction of the frame on the frame-foundation-soil interaction. The interaction analysis results of plane and space frames shows that the effective stiffness for interaction purposes, of a building that is loaded progressively during construction, is about half the stiffness of the completed building.

Aljanabi *et al*. (1990) studied the interaction behaviour of plane frames with an elastic foundation of the Winkler's type, having normal and shear moduli of sub-grade reactions. An exact stiffness matrix for a beam element on an elastic foundation having only a normal modulus of sub-grade reaction was modified to include the shear modulus of sub-grade reaction of the foundation as well as the axial force in the beam. The results indicated that bending moments might be considerably affected according to the type of frame and loading.

Viladkar *et al*. (1994) presented a new approach for the physical and material modelling of a space frame-raft-soil system. The beams and columns of the superstructure is discretized by a modified Timoshenko

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beam bending element with six degrees of freedom per node and structural slabs and raft are discretized by a modified Mindlin's plate bending element with five degrees of freedom per node. The soil media is represented by the coupled finite-infinite elements with three degrees of freedom per node. The constitutive modelling involves the use of the hyperbolic model to account for the soil nonlinearity. They compared the behaviour of the space frame-raft-soil system under the linear and nonlinear interaction.

Noorzaei (1996) investigated the efficiency of the coupled finite-infinite elements formulation with respect to computational effort, data preparation and the far field representation of the unbounded domain.

Mandal *et al*. (1998) presented a computational iterative scheme for studying the effect of soil-structure interaction on axial force and column moments. The results obtained from the computational scheme were validated from experimental study. A small-scale two-storey two-bay frame made of perspex was analyzed. The frame was placed on a kaolin bed with adequate arrangement of drainage. The proposed computational scheme could be used to predict increase in axial force and moments in structural members due to the effect of soil-structure interaction.

Roy and Dutta (2001) studied the effect of the differential settlement on design force quantities for frame members of building frames with isolated footings. They presented various representative case studies for frames resting on sandy soil and clayey soil by idealizing the soil medium below the footing as linear and nonlinear, respectively.

Al-Shamrani and Al-Mashary (2003) presented a simplified procedure for the analysis of soil-structure interaction behavior of two-dimensional skeletal steel or reinforced concrete frame structures resting on isolated footings that are supported by different types of soil. The main program is made of two major modules; one for soil settlement calculations and another for the analysis of structure. They evaluated the effect of interaction on the predicted settlements, footing loads, and internal bending moments of the structural members.

Hora (2006) presented the computational methodology adopted for nonlinear soil-structure interaction analysis of infilled frame-foundation-soil system. The unbounded domain of the soil mass has been discretized with coupled finite-infinite elements to achieve computational economy. The nonlinear behaviour of the soil mass is modelled using hyperbolic model. The incremental-iterative nonlinear solution algorithm has been adopted for carrying out the nonlinear elastic interaction analysis. The interaction analysis showed that the nonlinearity of soil mass plays an important role in redistribution of forces in the superstructure.

Nataralan and Vidivelli (2009) studied the influence of column spacing on the behavior of a space frame-raft-soil system under static load. The analyses are carried out for linear and non-linear conditions, in which soil is treated as a homogeneous and isotropic continuum. Settlement was greater in the non-linear analysis and the settlements were higher for higher column spacing. Contact pressure distribution was more uniform in the non-linear case and its magnitude was less than that of linear soil, particularly in the end panels of the raft.

Guzman (2010) studied the effect of contact between strap beam and bearing stratum. Results indicate that when a strap footing is used as part of a foundation system, a detail that allow for pressure to be relieved from the strap beam is necessary on construction documents. Without it, a considerable unforeseen load path could be created that may result in the failure of strap beam followed by overstress of the soil under the eccentric footing.

Thangaraj and Ilamparuthi (2010) compared interaction and non-interaction analyses for the space frame-raft foundation-soil system using ANSYS finite element code. The soil was treated as an isotropic, homogenous and elastic half space medium. A detailed parametric study was conducted by varying the soil and raft stiffness for a constant building stiffness. The interaction analysis showed less total and differential settlements than the non-interaction analysis and relative stiffness of soil plays major role in the performance of the raft.

Swamy Rajashekhar *et al*. (2011) studied the effects of horizontal stresses and horizontal displacements in loaded raft foundation by developing three dimensional mathematical models and performing numerical experiments. The results of uncoupled analysis i.e., complete slip/frictionless interface between foundation and soil and the coupled analysis i.e., complete welding/bonding of joints between foundation and soil elements are compared with the results of non-interactive analysis. They concluded that the response of the structure does change in soil-structure-interaction analysis when compared to non-interactive analysis but member end actions for beams and columns are almost same in coupled and uncoupled analysis.

Agrawal and Hora (2012) studied the interaction effect of frame, isolated footing and soil media under seismic loading. Various analyses were performed on frame-footing-soil system by considering plane frame, infill frame, homogeneous soil and layered soil mass. The frame was considered to act in linear elastic manner while the soil mass to act as nonlinear elastic manner. They concluded that the shear forces and bending moments in superstructure get significantly altered due to differential settlements of the soil mass.

3. PROBLEM UNDER INVESTIGATION

In present problem a 3 bay x 3 bay three-storey RCC space frame founded on strap footing and resting on homogeneous soil mass and subjected to gravity loading is analyzed. The problem under consideration is symmetric about both axes in terms of geometry, material properties and loading. However, to make the model computationally economical only half of the model is considered for

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analysis. The superstructure of proposed model is depicted in Figure-1.

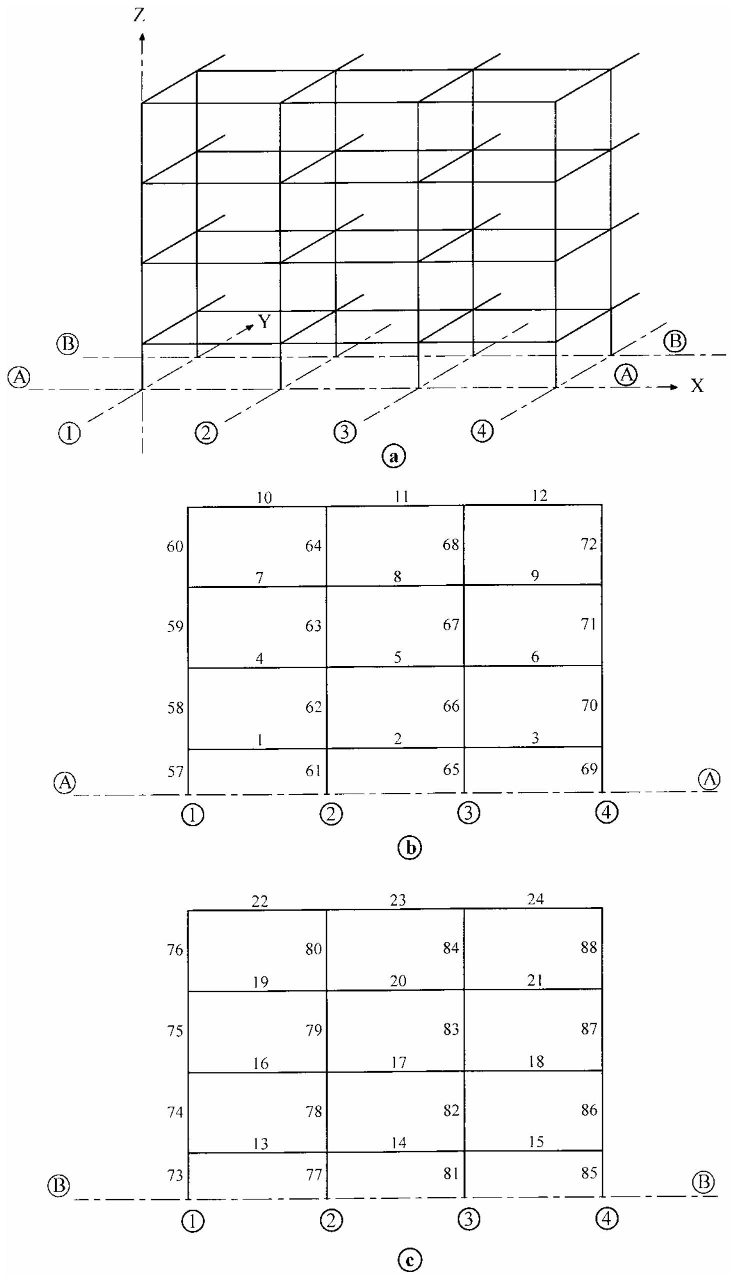

Figure-1 (a, b, c). Symmetric half model of the frame.

To investigate the interaction behavior, the interaction analyses are carried out for the following three cases.

Case-1: The conventional non-interaction analysis (NIA) considering the columns fixed at their bases.

Case-2: The linear interaction analysis of space frame-isolated footing-soil system (LIA-ISO) considering the columns supported on individual column footings and resting on soil media.

Case-3: The linear interaction analysis of space frame-strap footing-soil system (LIA-STR) considering the individual footings of Case-2 connected by strap beams.

The frame, foundation and supporting soil mass are considered to be linear elastic and to act as a single compatible structural unit for more realistic analysis. The geometric and material properties of proposed model are given in Table-1.

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Table-1. Geometric and material properties of frame, strap beam, footing and soil mass.

Component	Description	Data
Frame	Number of storeys	3
	Number of bays in X direction	3
	Number of bays in Y direction	3
	Storey height	3.5 m
	Column height below plinth beam	2.0 m
	Bay width in X direction	6.0 m
	Bay width in Y direction	6.0 m
	Size of beam	0.3 m × 0.5 m
	Size of column	0.4 m × 0.4 m
	Thickness of all slabs	0.15 m
Foundation	Isolated footing size	2 m x 2 m x 0.5 m
	Size of strap beam	0.4 m x 1.1 m
	Elastic modulus of concrete	2.5×10^7 kN/m^2
	Poisson's ratio of concrete	0.15
Soil	Extent of soil mass	200 m x 100 m x 90 m
	Modulus of elasticity of soil	1.47×10^4 kN/m^2
	Poisson's ratio of soil	0.35

Uniformly distributed loads are applied on floor beams and plinth beams which include self weight and imposed load on building components shown in Table-2.

Table-2. Loads on various beams (kN/m).

Structural component	Intensity of U.D.L.
Inner plinth beams	13.0
Outer plinth beams	19.0
Floor beams (1st and 2nd storeys) Inner beams Outer beams	 45.0 35.0
Floor beams (3rd storey) Inner beams Outer beams	 29.0 22.0

The symmetric half model of foundation plan with strap beam numbering is depicted in Figure-2.

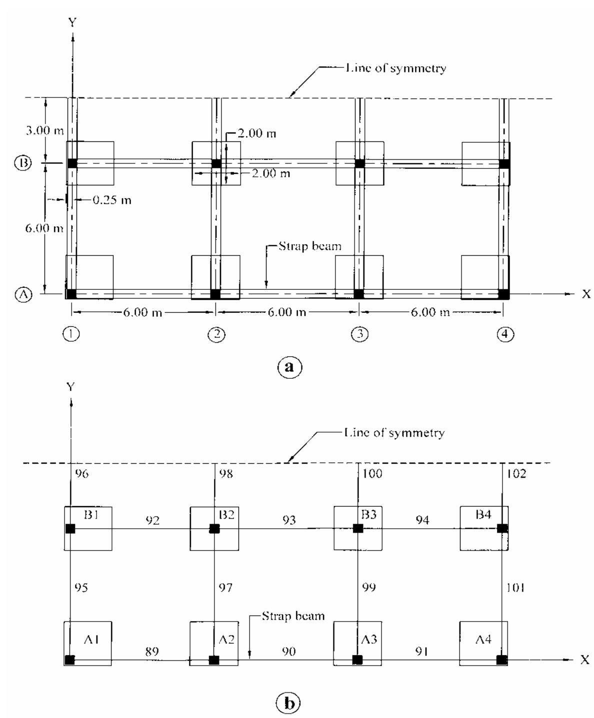

Figure-2 (a-b). Symmetric half model of foundation plan.

4. FINITE ELEMENT MODELING

The linear interaction analysis (LIA) of the problem is carried out using ANSYS software (Version 12). The finite element discretization of the problem is shown in Figure-3.

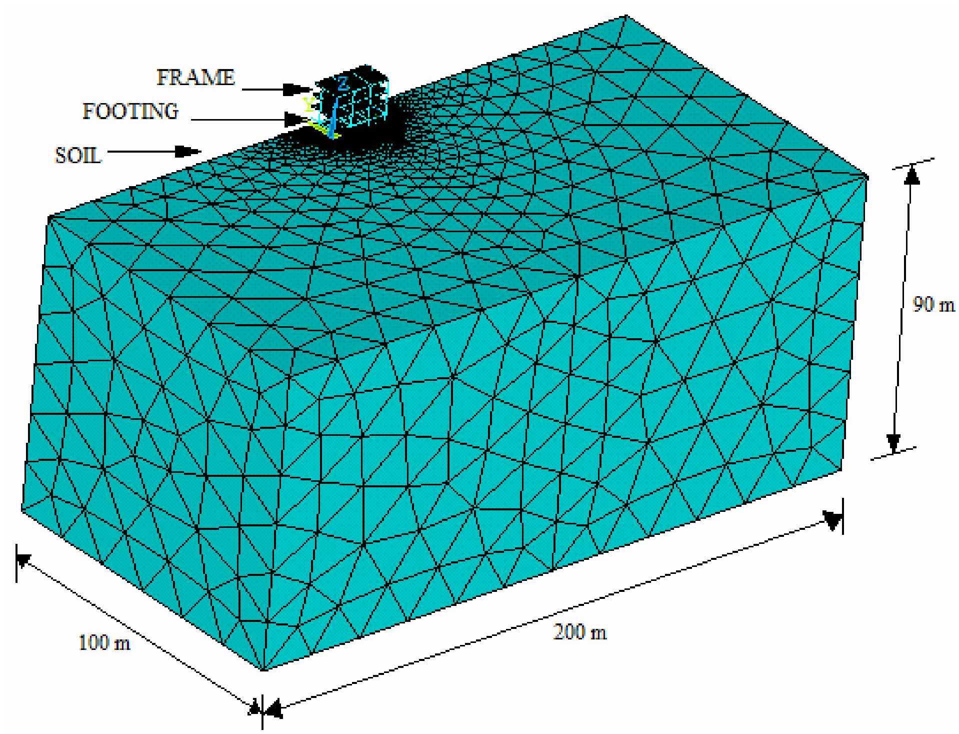

Figure-3. Finite element discretization of frame-footing-soil system (symmetric half model).

The floor beams, plinth beams, strap beams and the columns are discretized with two node beam bending element (BEAM4) with six degrees of freedom per node (Ux, Uy, Uz, Rx, Ry, and Rz). It is assumed that the joints between various members are perfectly rigid. The roof slab is discretized with four node plate bending element (SHELL181) having six degrees of freedom at each node (Ux, Uy, Uz, Rx, Ry and Rz). The footing is discretized with eight node plate bending element (SHELL281) having six degrees of freedom at each node (Ux, Uy, Uz, Rx, Ry and Rz).

The semi-infinite extent of the soil model is considered as 200 m x 100 m x 90 m which is achieved by trial and error. The extent of soil mass is decided where vertical and horizontal stresses are found to be negligible due to loading on the superstructure. The vertical displacements in soil mass are restrained at the bottom boundary whereas horizontal displacements are restrained at vertical boundaries.

The soil mass is idealized as isotropic, homogeneous, half-space model and discretized with ten-node tetrahedral element (SOLID92) having three degrees of freedom at each node (Ux, Uy and Uz). SOLID92 has a quadratic displacement behavior and is well suited to model irregular meshes. The interface characteristics between the raft and soil are represented by TARGE170 and CONTA174 elements. The element size for beams, columns, slabs and footings are taken as 0.25 m. The soil mass is discretized with finer meshes in close vicinity of footing where stresses are of higher order.

5. VALIDATION OF RESULTS

The results obtained by the ANSYS software are validated with the results already available in the literature (Noorzaei *et al*., 1996). They carried out the interaction analysis of a square raft (10 m x 10 m x 0.5 m) resting on soil mass. The raft is subjected to uniform pressure of 100 kN/m^2. The geometry, material properties, loading and element discretization of the square raft is shown in Figure-4.

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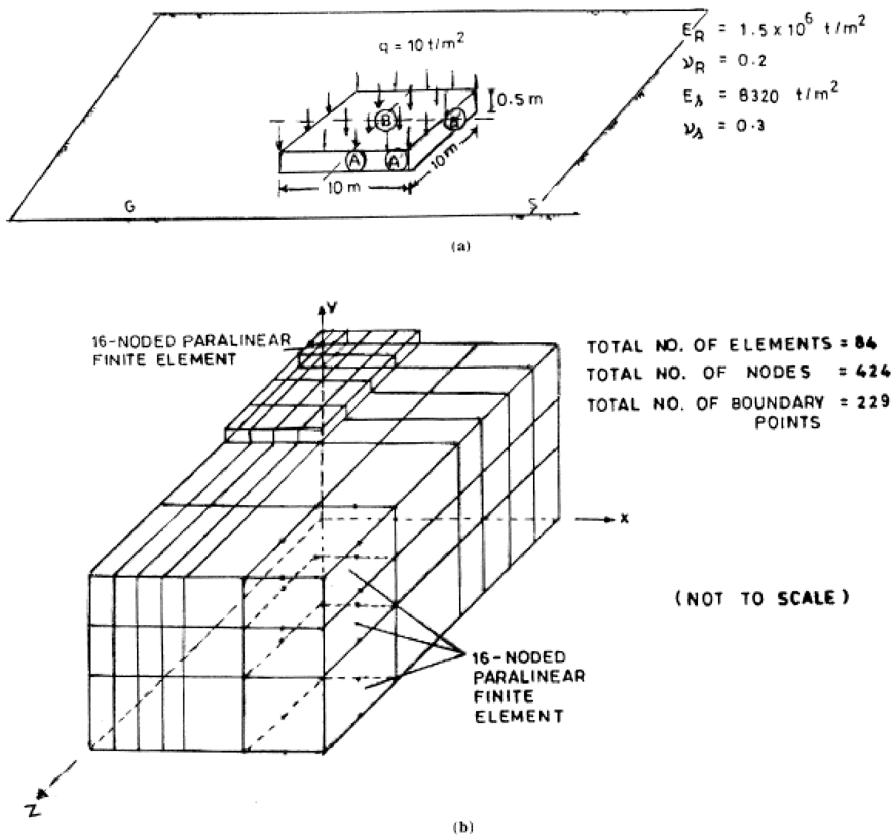

Figure-4 (a). Square raft resting on soil surface. (b) Three dimensional finite element discretization of quarter portion of raft-soil system. (Noorzaei *et al*., 1996).

The comparison of total settlement (mm) of central, mid side and corner of the raft is provided in the Table-3.

Table-3. Comparison of total vertical settlement (mm) of central, mid side and corner of the raft.

Component	**ANSYS results**	**Noorzaei. J.** (1996)
Center of raft	10.492	9.937
Mid-side of raft	7.288	7.389
Corner of raft	4.654	5.486

6. INTERACTION ANALYSIS

The axial force and bending moment in columns and shear force and bending moment in plinth, floor and strap beams are evaluated due to NIA and LIA and discussed subsequently. Because of the symmetrical nature of the problem, the results of only quarter portion are presented.

6.1. Axial force in the columns

Table-4 shows the values of axial force in the columns of frame-footing-soil system due to various analyses.

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Table-4. Comparison of axial force Fz (kN) in columns for various analyses.

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
57	0.0	0.0	0.0	-605.04	-793.47	-715.70	1.31	1.18	0.90
57	0.0	0.0	2.0	605.04	793.47	715.70	1.31	1.18	0.90
58	0.0	0.0	2.0	-528.22	-664.74	-607.68	1.26	1.15	0.91
58	0.0	0.0	5.5	528.22	664.74	607.68	1.26	1.15	0.91
59	0.0	0.0	5.5	-327.95	-416.76	-378.89	1.27	1.16	0.91
59	0.0	0.0	9.0	327.95	416.76	378.89	1.27	1.16	0.91
60	0.0	0.0	9.0	-124.52	-160.76	-145.30	1.29	1.17	0.90
60	0.0	0.0	12.5	124.52	160.76	145.30	1.29	1.17	0.90
61	6.0	0.0	0.0	-1040.60	-1062.40	-1062.60	1.02	1.02	1.00
61	6.0	0.0	2.0	1040.60	1062.40	1062.60	1.02	1.02	1.00
62	6.0	0.0	2.0	-905.98	-924.25	-923.97	1.02	1.02	1.00
62	6.0	0.0	5.5	905.98	924.25	923.97	1.02	1.02	1.00
63	6.0	0.0	5.5	-562.43	-574.46	-573.96	1.02	1.02	1.00
63	6.0	0.0	9.0	562.43	574.46	573.96	1.02	1.02	1.00
64	6.0	0.0	9.0	-218.11	-223.15	-223.02	1.02	1.02	1.00
64	6.0	0.0	12.5	218.11	223.15	223.02	1.02	1.02	1.00
73	0.0	6.0	0.0	-1040.60	-1063.00	-1063.10	1.02	1.02	1.00
73	0.0	6.0	2.0	1040.60	1063.00	1063.10	1.02	1.02	1.00
74	0.0	6.0	2.0	-905.98	-925.01	-924.30	1.02	1.02	1.00
74	0.0	6.0	5.5	905.98	925.01	924.30	1.02	1.02	1.00
75	0.0	6.0	5.5	-562.43	-574.93	-574.18	1.02	1.02	1.00
75	0.0	6.0	9.0	562.43	574.93	574.18	1.02	1.02	1.00
76	0.0	6.0	9.0	-218.11	-223.34	-223.11	1.02	1.02	1.00
76	0.0	6.0	12.5	218.11	223.34	223.11	1.02	1.02	1.00
77	6.0	6.0	0.0	-1687.80	-1455.30	-1532.70	0.86	0.91	1.05
77	6.0	6.0	2.0	1687.80	1455.30	1532.70	0.86	0.91	1.05
78	6.0	6.0	2.0	-1457.80	-1284.20	-1342.10	0.88	0.92	1.05
78	6.0	6.0	5.5	1457.80	1284.20	1342.10	0.88	0.92	1.05
79	6.0	6.0	5.5	-905.18	-791.99	-830.99	0.87	0.92	1.05
79	6.0	6.0	9.0	905.18	791.99	830.99	0.87	0.92	1.05
80	6.0	6.0	9.0	-357.26	-310.80	-326.58	0.87	0.91	1.05
80	6.0	6.0	12.5	357.26	310.80	326.58	0.87	0.91	1.05

Note: Negative sign indicates that axial force acts in downward direction

The comparison of axial force due to NIA and LIA reveals that the interaction effect causes redistribution of the forces in column members. The inner columns are relieved of the forces and corresponding increase is found in the corner columns due to interaction effects. This redistribution of axial forces is more significant in case of LIA-ISO in comparison to LIA-STR. No significant interaction effect is found in axial force of side columns.

LIA-ISO provides variation of -14 to 31% in axial force compared to NIA. The maximum decrease of nearly 14% is found in the inner column below plinth level (member 77) whereas maximum increase of nearly 31% is found in the corner column below plinth level (member 57).

The variation of -9% to 18% is found in the axial force due to LIA-STR compared to NIA. The maximum decrease of nearly 9% is found in the inner column below plinth level (member 77) whereas maximum increase of nearly 18% is found in the corner column below plinth level (member 57).

LIA-STR provides variation of -10 to 5% in axial force compared to LIA-ISO. The maximum decrease of nearly 10% is found in the corner columns (members 57 to 60) whereas maximum increase of nearly 5% is found in the inner columns (members 77 to 80).

6.2. Bending moment in the columns

Table-5 shows the values of bending moment in the columns of frame-footing-soil system due to various analyses.

Table-5. Comparison of bending moment My (kN-m) in columns for various analyses.

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
57	0.0	0.0	0.0	-7.27	256.33	-25.91	-35.26	3.56	-0.10
57	0.0	0.0	2.0	-13.42	-71.08	-37.12	5.30	2.77	0.52
58	0.0	0.0	2.0	-22.87	-44.06	-44.06	1.93	1.93	1.00
58	0.0	0.0	5.5	-35.43	-66.25	-58.58	1.87	1.65	0.88
59	0.0	0.0	5.5	-46.07	-89.20	-68.79	1.94	1.49	0.77
59	0.0	0.0	9.0	-44.08	-82.91	-65.94	1.88	1.50	0.80
60	0.0	0.0	9.0	-44.09	-88.46	-70.46	2.01	1.60	0.80
60	0.0	0.0	12.5	-46.38	-101.14	-78.56	2.18	1.69	0.78
61	6.0	0.0	0.0	-0.45	-16.03	-76.16	35.50	168.71	4.75
61	6.0	0.0	2.0	-0.59	-45.36	-39.05	77.14	66.42	0.86
62	6.0	0.0	2.0	0.97	-24.12	-9.06	-24.99	-9.38	0.38
62	6.0	0.0	5.5	2.10	-26.63	-14.21	-12.71	-6.78	0.53
63	6.0	0.0	5.5	2.21	-31.27	-18.03	-14.18	-8.18	0.58
63	6.0	0.0	9.0	1.22	-31.17	-17.92	-25.50	-14.66	0.57
64	6.0	0.0	9.0	0.84	-35.45	-20.22	-42.12	-24.03	0.57
64	6.0	0.0	12.5	1.37	-40.19	-22.90	-29.27	-16.68	0.57
73	0.0	6.0	0.0	-10.79	350.19	-44.23	-32.44	4.10	-0.13
73	0.0	6.0	2.0	-20.55	-84.65	-52.23	4.12	2.54	0.62
74	0.0	6.0	2.0	-30.60	-53.90	-55.82	1.76	1.82	1.04
74	0.0	6.0	5.5	-44.68	-78.23	-73.39	1.75	1.64	0.94
75	0.0	6.0	5.5	-56.85	-105.57	-85.63	1.86	1.51	0.81
75	0.0	6.0	9.0	-54.86	-98.80	-82.47	1.80	1.50	0.83
76	0.0	6.0	9.0	-55.42	-105.05	-88.21	1.90	1.59	0.84
76	0.0	6.0	12.5	-58.27	-118.84	-97.82	2.04	1.68	0.82
77	6.0	6.0	0.0	-0.35	-22.42	-88.95	64.54	256.08	3.97
77	6.0	6.0	2.0	-0.40	-60.14	-46.51	149.84	115.87	0.77
78	6.0	6.0	2.0	1.02	-22.96	-12.82	-22.57	-12.60	0.56
78	6.0	6.0	5.5	2.06	-29.62	-19.61	-14.35	-9.50	0.66
79	6.0	6.0	5.5	1.89	-38.84	-24.78	-20.54	-13.11	0.64
79	6.0	6.0	9.0	0.70	-38.42	-24.70	-54.55	-35.06	0.64
80	6.0	6.0	9.0	-0.04	-42.84	-27.65	1127.64	727.91	0.65
80	6.0	6.0	12.5	0.33	-47.97	-30.94	-143.85	-92.77	0.64

Note: Negative sign indicates that moment acts in anticlockwise direction about Y axis

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The comparison of bending moments due to NIA and LIA reveals that the interaction effect causes redistribution of the moments in column members. The significantly higher values of bending moments are found due to LIA. A significant increase in the bending moment of outer columns at the column footing junction is found in LIA-ISO as well as reversal in the sign takes place because of the rotation of eccentrically loaded isolated footings. However, LIA-STR suggests that the use of strap beam controls this moment effectively. In LIA-STR bending moment decreases in columns except at inner column bases in comparison to LIA-ISO. The similar results are found for column moments about X axis (Mx).

LIA-STR provides variation of -90 to 375% in bending moment compared to LIA-ISO. The maximum decrease of nearly 90% with reversal in sign is found in the corner column (member 57) whereas the maximum increase of nearly 375% is found in the side column (member 61).

6.3. Shear force in the floor and plinth beams

Table-6 shows the values of shear force in the floor and plinth beams of frame-footing-soil system due to various analyses.

Table-6. Comparison of shear force Fz (kN) in X-direction beams for various analyses.

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
1	0.0	0.0	2.0	-38.41	-64.34	-54.04	1.67	1.41	0.84
1	6.0	0.0	2.0	-39.59	-13.67	-23.96	0.35	0.61	1.75
2	6.0	0.0	2.0	-39.00	-38.96	-39.00	1.00	1.00	1.00
4	0.0	0.0	5.5	-98.99	-122.61	-113.09	1.24	1.14	0.92
4	6.0	0.0	5.5	-108.39	-84.47	-94.03	0.78	0.87	1.11
5	6.0	0.0	5.5	-103.57	-105.60	-104.69	1.02	1.01	0.99
7	0.0	0.0	9.0	-100.55	-126.55	-115.47	1.26	1.15	0.91
7	6.0	0.0	9.0	-106.70	-80.12	-91.41	0.75	0.86	1.14
8	6.0	0.0	9.0	-103.44	-105.42	-104.66	1.02	1.01	0.99
10	0.0	0.0	12.5	-61.56	-79.49	-71.83	1.29	1.17	0.90
10	6.0	0.0	12.5	-69.33	-51.71	-59.27	0.75	0.85	1.15
11	6.0	0.0	12.5	-65.74	-67.25	-66.73	1.02	1.01	0.99
13	0.0	6.0	2.0	-56.01	-85.43	-75.75	1.53	1.35	0.89
13	6.0	6.0	2.0	-57.99	-28.57	-38.26	0.49	0.66	1.34
14	6.0	6.0	2.0	-57.00	-57.00	-57.01	1.00	1.00	1.00
16	0.0	6.0	5.5	-126.30	-154.17	-145.74	1.22	1.15	0.95
16	6.0	6.0	5.5	-137.50	-105.47	-115.75	0.77	0.84	1.10
17	6.0	6.0	5.5	-132.74	-135.22	-134.19	1.02	1.01	0.99
19	0.0	6.0	9.0	-128.86	-160.11	-149.28	1.24	1.16	0.93
19	6.0	6.0	9.0	-135.27	-99.64	-112.20	0.74	0.83	1.13
20	6.0	6.0	9.0	-132.67	-135.67	-134.46	1.02	1.01	0.99
22	0.0	6.0	12.5	-79.69	-100.63	-93.50	1.26	1.17	0.93
22	6.0	6.0	12.5	-88.85	-65.04	-73.32	0.73	0.83	1.13
23	6.0	6.0	12.5	-85.86	-86.95	-86.38	1.01	1.01	0.99

Note: Negative sign indicates that shear force acts in downward direction

The comparison of shear force due to NIA and LIA reveals that the interaction effect causes redistribution of the shear forces in beam members. The inner end of the outer beams is relieved of the forces and corresponding increase is found in the outer end of the beams. This redistribution of shear forces is more significant in LIA-ISO in comparison to LIA-STR. The inclusion of strap beam causes decreases in the higher values of shear force

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in outer beams whereas insignificant interaction effect is found in the inner beams. Similar results are found for shear force in Y direction beams.

LIA-ISO provides variation of -65 to 67% in shear force compared to NIA. The maximum decrease of nearly 65% is found in the inner end of plinth beam (member 1) whereas the maximum increase of nearly 67% is found in the outer end of plinth beam (member 1).

The variation of -39% to 41% is found in the shear force due to LIA-STR compared to NIA. The maximum decrease of nearly 39% is found in the inner end of plinth beam (member 1) whereas the maximum increase of nearly 41% is found in the outer end of plinth beam (member 1).

LIA-STR provides variation of -16 to 75% in shear force compared to LIA-ISO. The maximum decrease of nearly 16% is found in the outer end of plinth beam (member 1) whereas the maximum increase of nearly 75% is found in the inner end of plinth beam (member 1).

6.4. Bending moment in the floor and plinth beams

Table-7 shows the values of bending moment in the floor and plinth beams of frame-footing-soil system due to various analyses.

Table-7. Comparison of bending moment My (kN-m) in X-direction beams for various analyses.

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
1	0.0	0.0	2.0	35.77	114.26	80.50	3.19	2.25	0.70
1	6.0	0.0	2.0	-39.30	37.75	9.74	-0.96	-0.25	0.26
2	6.0	0.0	2.0	38.93	32.11	38.22	0.82	0.98	1.19
4	0.0	0.0	5.5	77.52	138.78	115.09	1.79	1.48	0.83
4	6.0	0.0	5.5	-102.51	-41.10	-66.59	0.40	0.65	1.62
5	6.0	0.0	5.5	98.36	91.94	94.48	0.93	0.96	1.03
7	0.0	0.0	9.0	83.00	152.02	122.63	1.83	1.48	0.81
7	6.0	0.0	9.0	-99.79	-33.61	-61.64	0.34	0.62	1.83
8	6.0	0.0	9.0	97.60	92.29	94.79	0.95	0.97	1.03
10	0.0	0.0	12.5	44.33	89.56	70.44	2.02	1.59	0.79
10	6.0	0.0	12.5	-63.79	-16.31	-36.56	0.26	0.57	2.24
11	6.0	0.0	12.5	62.17	51.34	56.02	0.83	0.90	1.09
13	0.0	6.0	2.0	51.66	139.42	108.73	2.70	2.10	0.78
13	6.0	6.0	2.0	-57.60	31.18	3.74	-0.54	-0.07	0.12
14	6.0	6.0	2.0	56.97	51.55	55.73	0.90	0.98	1.08
16	0.0	6.0	5.5	93.34	156.57	137.70	1.68	1.48	0.88
16	6.0	6.0	5.5	-121.60	-50.36	-73.80	0.41	0.61	1.47
17	6.0	6.0	5.5	118.26	106.61	110.35	0.90	0.93	1.04
19	0.0	6.0	9.0	100.02	171.76	146.55	1.72	1.47	0.85
19	6.0	6.0	9.0	-117.70	-40.32	-67.37	0.34	0.57	1.67
20	6.0	6.0	9.0	117.09	107.05	110.47	0.91	0.94	1.03
22	0.0	6.0	12.5	54.87	101.65	85.65	1.85	1.56	0.84
22	6.0	6.0	12.5	-76.37	-20.95	-40.14	0.27	0.53	1.92
23	6.0	6.0	12.5	76.04	60.45	65.72	0.79	0.86	1.09

Note: Negative sign indicates that moment acts in anticlockwise direction about Y axis

The comparison of bending moment due to NIA and LIA reveals that the interaction effect causes redistribution of the moments in beam members. The inner ends of the outer beams are relieved of the moments and corresponding increase is found in the outer ends of the beams due to interaction effects. This redistribution of bending moments is more significant in LIA-ISO analysis in comparison to LIA-STR analysis. The strap beam causes decrease in the higher values of bending moment in outer beams. The reversal in the sign of bending moment is found at inner ends of outer plinth beams. The insignificant interaction effect is found in bending moment of inner beams. The similar results are found for bending moment in Y direction beams.

LIA-ISO provides variation of -74 to 219% in bending moment compared to NIA. The maximum decrease of nearly 74% is found in the inner end of floor beam of III storey (member 10) whereas the maximum increase of nearly 219% is found in the outer end of plinth beam (member 1). The reversal in the sign of bending moment is found at inner ends of outer plinth beams (member 1 and member 13).

The variation of -47% to 125% is found in the bending moment due to LIA-STR compared to NIA. The maximum decrease of nearly 47% is found in the inner end of floor beam of III storey (member 22) whereas maximum increase of nearly 125% is found in the outer end of plinth beam (member 1). The reversal in the sign of bending moment is found at inner ends of outer plinth beams (member 1 and member 13).

LIA-STR provides variation of -88 to 124% in bending moment compared to LIA-ISO. The maximum decrease of nearly 88% is found in the inner end of plinth beam (member 13) whereas the maximum increase of nearly 124% is found in the inner end of floor beam of III storey (member 10).

Figures 5 to 10 show the values of bending moment in the frame members of frame-footing-soil system due to various analyses.

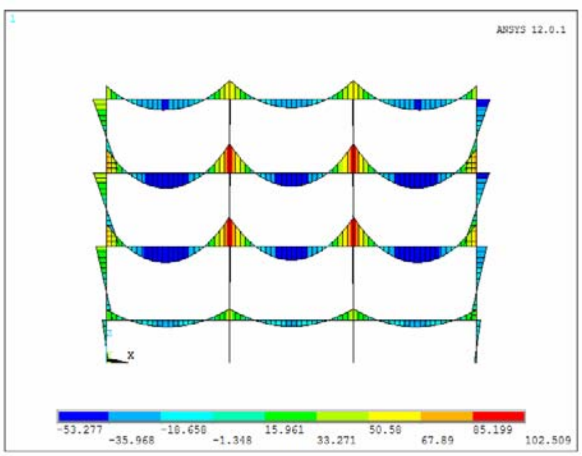

Figure-5. Bending moment diagram of frame members at section-AA for NIA.

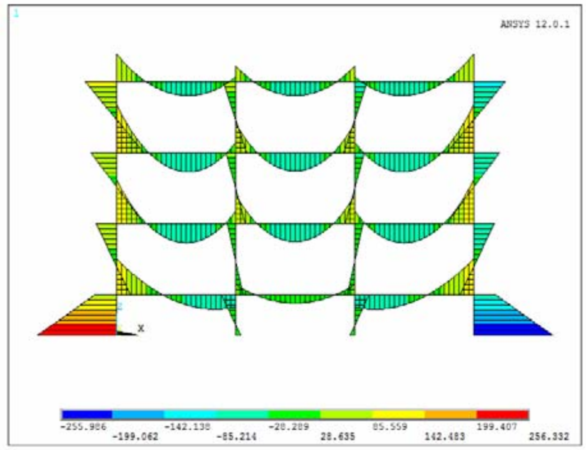

Figure-6. Bending moment diagram of frame members at section-AA for LIA-ISO.

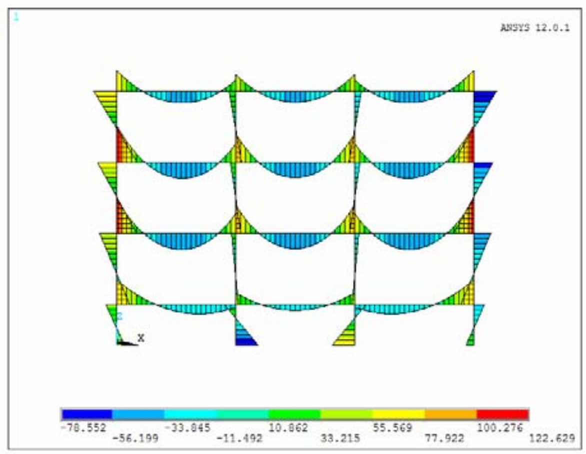

Figure-7. Bending moment diagram of frame members at section-AA for LIA-STR.

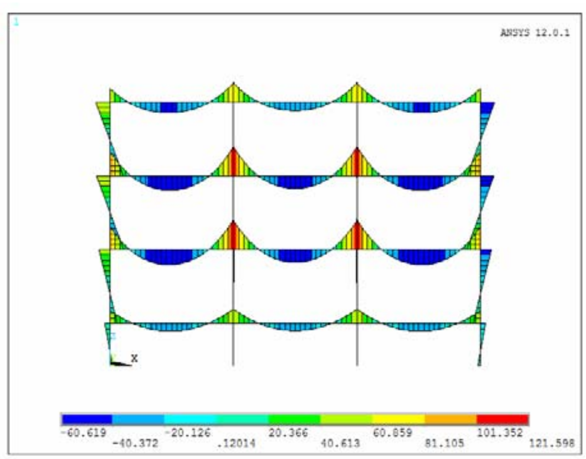

Figure-8. Bending moment diagram of frame members at section-BB for NIA.

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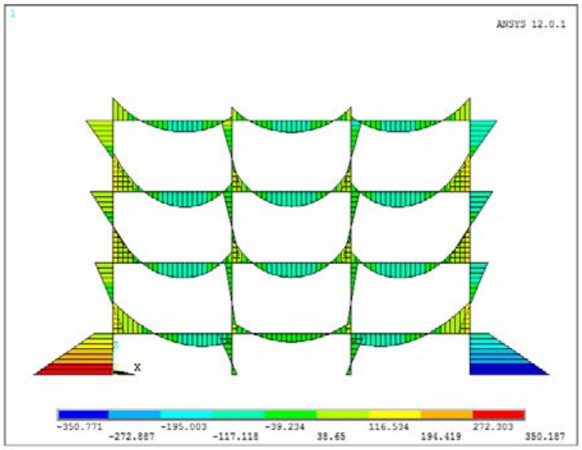

Figure-9. Bending moment diagram of frame members at section-BB for LIA-ISO.

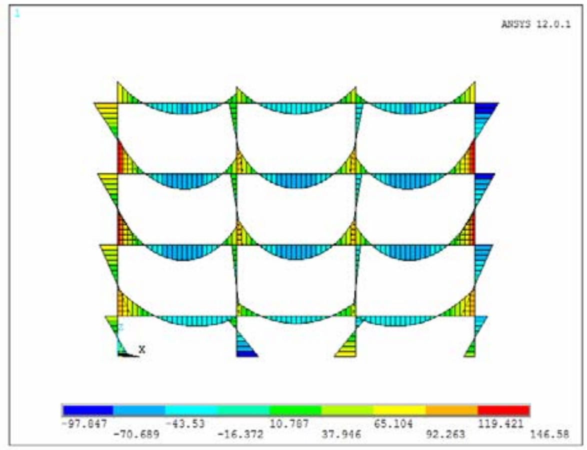

Figure-10. Bending moment diagram of frame members at section-BB for LIA-STR.

6.5. Forces in the strap beams

Table-8 shows the values of forces in the strap beams for space frame-strap footing-soil system (LIA-STR).

Table-8. Forces in strap beams.

Member No.	Co-ordinates			Case-3 LIA-STR		
	X	Y	Z	Fz	Mx	My
89	0.0	0.0	0.0	321.09	39.82	59.13
89	6.0	0.0	0.0	385.91	12.89	432.93
90	6.0	0.0	0.0	220.53	-7.31	-362.93
92	0.0	6.0	0.0	403.99	-5.25	46.17
92	6.0	6.0	0.0	454.94	6.33	510.79
93	6.0	6.0	0.0	283.36	-2.47	-419.94
95	0.0	0.0	0.0	322.66	-58.78	-39.28
95	0.0	6.0	0.0	388.53	-432.76	-12.40
96	0.0	6.0	0.0	221.01	362.89	7.05
97	6.0	0.0	0.0	405.01	-46.12	4.77
97	6.0	6.0	0.0	454.68	-510.33	-6.58
98	6.0	6.0	0.0	281.33	419.19	3.00

Note: Positive sign indicates that forces Fz (kN) acts in upward direction
Negative sign indicates that moments act in anticlockwise direction about respective axes

7. CONCLUSIONS

a) The interaction effect causes significant redistribution of the forces and moments in frame members.
b) The interaction effect causes redistribution of the axial forces in column members. The inner columns are relieved of the axial forces and corresponding increase is found in the corner columns. This causes more uniform distribution of axial forces in the columns.
c) The interaction analyses provide higher bending moments in columns as compared to non-interaction analysis.
d) The use of strap beam causes decrease in the bending moments in columns except at base of the inner columns.
e) The bending moments of very high magnitude are found at column bases resting on eccentric footing of space frame-isolated footing-soil interaction system. However,

use of strap beams control these moments quite effectively.

f) The shear forces are relieved from the inner ends of the outer beams and corresponding increase is found in the outer ends of the beams due to interaction effects. The strap beam decreases the higher values of shear force in outer beams. The insignificant interaction effect is found in the shear force of inner beams.

g) The bending moments are relieved from the inner ends of the outer beams and corresponding increase is found in the outer ends of the beams due to interaction effects. The strap beam decreases the higher values of bending moment in outer beams. The reversal in the sign of bending moment is found at inner ends of outer plinth beams. The insignificant interaction effect is found in bending moment of inner beams.

The interaction analysis results reveals the necessity of strap footing to control the excessive moments induced at the column bases of a framed structure when eccentrically loaded isolated footings are used.

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