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In-Plane Internal Forces in Reinforced Concrete Diaphragms Subjected to Seismic Forces

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***Abstract* – This paper focuses on internal membrane forces in reinforced concrete slabs that form diaphragms to transmit horizontal forces like seismic loads to vertical elements like columns and walls. It is found that considerable axial forces exist in the slab near columns in flat plate systems supported by columns and larger axial forces exist in slabs and their beams along walls lines in slabs supported by walls, where horizontal forces are resisted by the walls. These internal forces especially tension must be considered in the design of the slabs and the beams. This issue should be taken into account in using computer softwares which do not design slabs and beams for axial forces.**

***Keywords* – Diaphragms, Collectors, Slabs, Beams, SAP2000.**

I. Introduction

Slabs of reinforced concrete buildings are subjected to out-of-plane internal forces due to vertical applied gravity loads of dead and live loads. These internal forces are moments and shears which are varied along the slab whetherit's one way or two way. The moments and shears are concentrated along column lines which are known as column strips in two way slab systems. Also, the slabs are subjected to in-plane moments, shears and axial forces due to the seismic horizontal forces within the slab. The slab which forms a diaphragm transmits the seismic loads in equivalent static method or dynamic seismic loads to the vertical structural elements like walls and columns. The walls and columns restrict the movement of the slab or diaphragm, so internal forces develop in these slabs. This study will concentrate on in-plane internal forces in the slabs or diaphragms.

The solid reinforced concrete slabs are with or without beams. The slabs without beams transmit the horizontal forces to the columns and walls directly, so internal axial forces tension and compression will be developed in the slabs and concentrated in zones around or near the columns and along lines parallel to the walls at their extensions. The zones in the slab at extension of walls are named collectors in design codes. The collector extends along the line that has the wall. The collectors are subjected to high axial tension and compression forces. The tension force requires high area of steel in some slabs. The slabs that have beams are also subjected to axial tension and compression in zones around the columns or in zones along walls extension. The following sections will illustrate many cases that show large axial forces in slabs and beams and show their distribution.

The reinforced concrete slabs (diaphragms) form deep beam which is subjected to horizontal uniform load. The column lines and the walls form supports to these deep beams. So, the diaphragms will deflect and then shear and bending moment will develop. The diaphragms must be checked for the internal shear forces and must be designed for the internal moment. So, reinforcing bars shall be used in tension and compression end zones (chords) of the diaphragm. The area of steel is equal to the force in the chord divided by tension strength reduction factor times the yield strength of steel.

Most of the structural analysis and design softwares do not design beams for axial compression or tension. So, one should take care of the axial forces in beams in diaphragms that are subjected to horizontal forces as the case of seismic forces.

In general, the slab diaphragm and its beams are subjected to axial tension and compression forces. The following sections will illustrate the formation of these internal forces.

II. Modeling of The Structural Systems

Membrane forces in the slab and its beams will be developed as the slab is subjected to horizontal seismic forces whether the equivalent static method or the response spectrum analysis are used.

The structural analysis and design software Sap2000 will be used to analyze a typical three by three panels slab system (two way) one floor.Fig. 1 shows the plan.

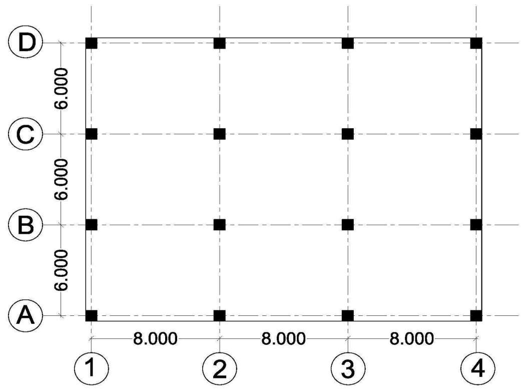

Fig. 1. Slab (diaphragm) layout- structural system 1

The slab is composed of three spans of 8m in x-direction and three spans of 6m in y-direction. The floor height is 4m. The columns are 0.4x0.4m square cross section and the walls are 0.4m thick. The slab is solid and has a thickness of 0.25m. The concrete compressive strength, f'c is equal to 28MPa with modulus of elasticity, E equals to 24870MPa. The end restraints to the columns and meshed walls are pins. The slab is subjected to horizontal force of $10kN/m^2$ in the y-direction to represent the horizontal seismic force. Also, a gravity load of $10kN/m^2$ is applied

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to the slab to compare the membrane forces in case of horizontal and gravity loads.

Eight structural systems are considered in this study. System 1 is formed of flat plate resisted by columns as shown in Fig. 1. System 2 is formed of two way slab with beams between all columns and supported by columns as shown in Fig. 2. Systems 3, 4 and 5 are flat plate supported by walls and columns as shown in Figures3, 4 and 5. Systems 6, 7 and 8 are two way slabs with beams between all columns and supported by walls and columns as shown in Figures 6, 7 and 8.

The beams of the frames are 0.30m width and 0.7m thickness. The columns and beams are modeled as line elements and the slab and walls are modeled as area elements.

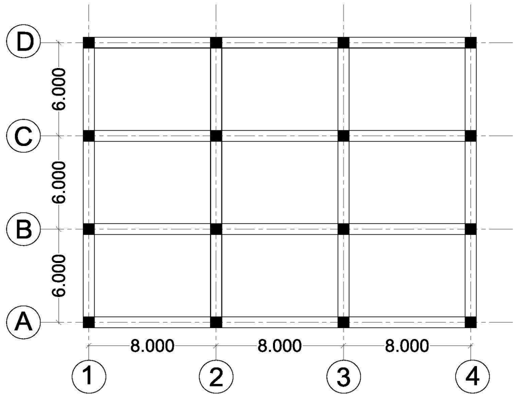

Fig. 2. Structural system 2

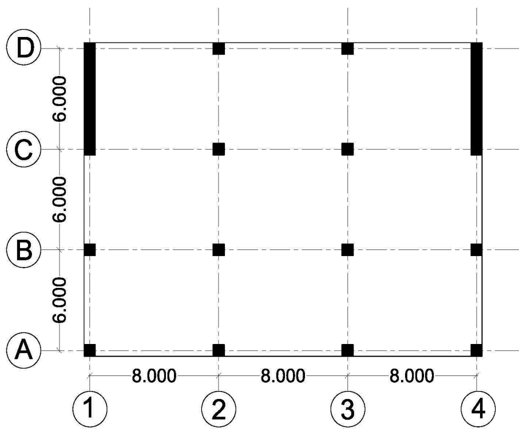

Fig. 3. Structural system 3

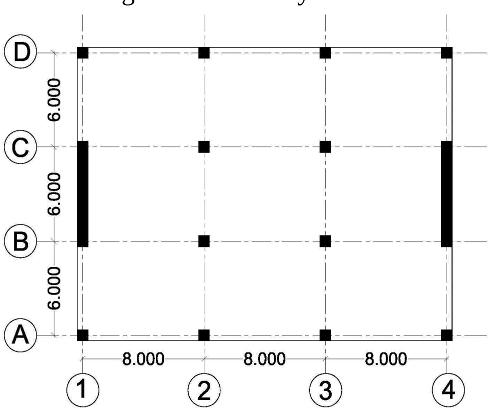

Fig. 4. Structural system 4

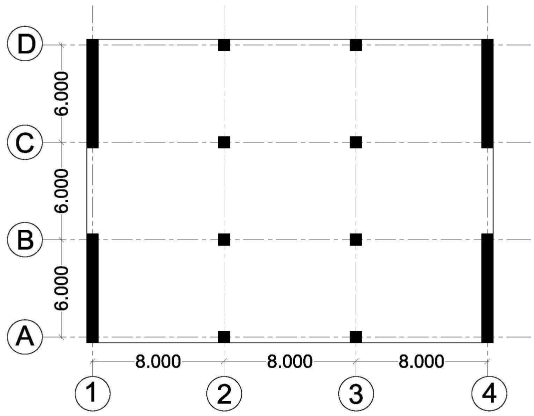

Fig. 5. Structural system 5

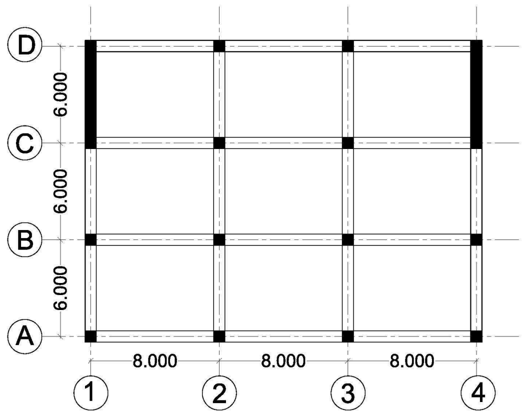

Fig. 6. Structural system 6

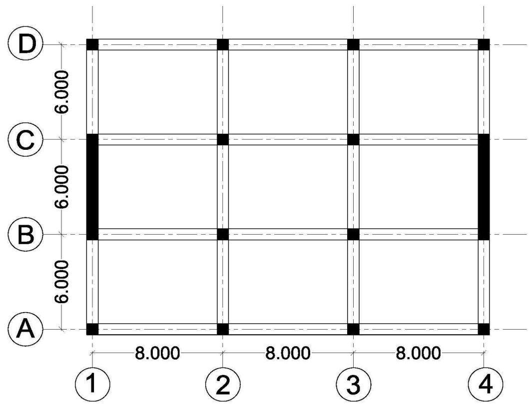

Fig. 7. Structural system 7

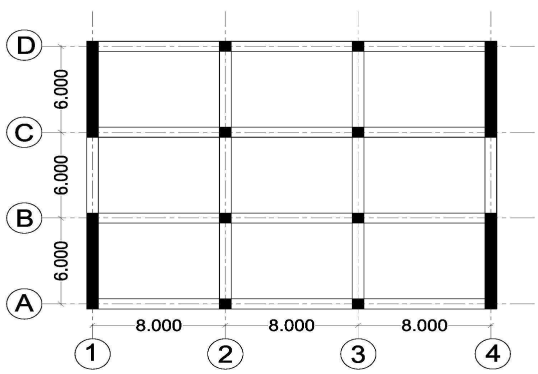

Fig. 8. Structural system 8

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III. Analysis of Structural Systems and Results

The eight models are analyzed by Sap2000 software. A deep investigation of internal forces especially axial tension and compression is done.

System 1*:*

The system is composed of flat slab which is supported by columns as shown in Fig. 1. The maximum membrane forces in the slab due to gravity loads are 19.2kN compression and 4.1kN tension, refer to Fig. 9. The maximum membrane forces in the slab due to horizontal loads are 593.76kN tension and 593.76kN compression close to the corner columns as shown in Fig.10.

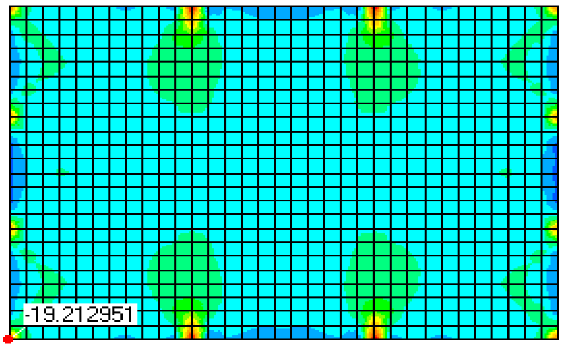

Fig. 9. Membrane forces in slab in system 1 due to gravity loads

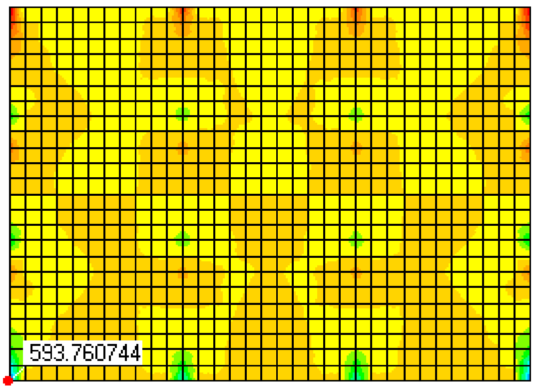

Fig. 10. Membrane forces in slab in system 1 due to horizontal loads

System 2**:**

The system is composed of slab with beams between all columns which is supported by columns as shown in Fig. 2. The maximum membrane forces in the slab due to gravity loads are 4.98kN compression and 0.58kN tension, refer to Fig.11. Also, the axial force in the beam corresponding to the slab is equal to 2.05kN. The maximum membrane forces in the slab due to horizontal loads are 200.46kN tension and 200.46kN compression close to the columns as shown in Fig.12 and the axial force in the corresponding beam is equal to 166.58kN as shown in Fig. 13.

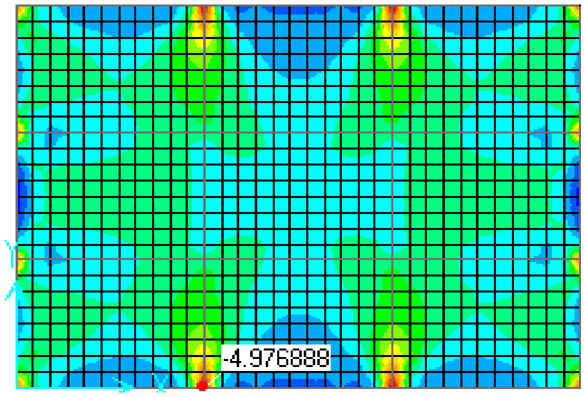

Fig. 11. Membrane forces in slab in system 2 due to gravity loads

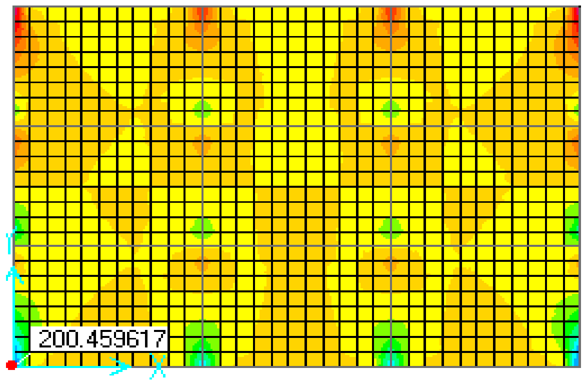

Fig. 12. Membrane forces in slab in system 2 due to horizontal loads

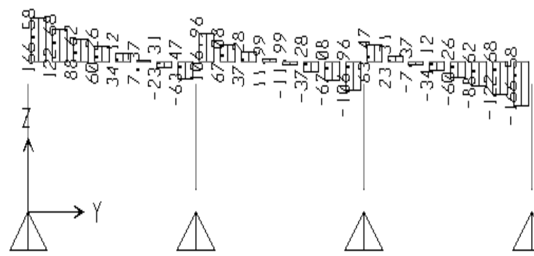

Fig. 13. Axial forces in beam in system 2 due to horizontal loads at gridline 1

System 3:

The system is composed of flat slab which is supported by columns and walls as shown in Fig. 3. The maximum membrane force in the slab due to gravity loads is 40.83kN tension as shown inFig. 14 which is located in the slab very close to the wall.The maximum membrane forces in the slab due to horizontal loads is1030.55kN compressionas shown in Fig. 15 which is located in the slab very close to the wall. This value will be changed to tension if the applied horizontal force is reversed.

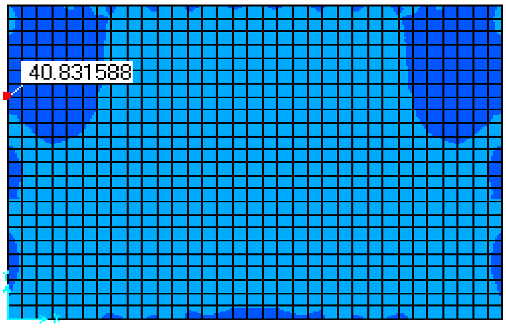

Fig. 14. Membrane forces in slab in system 3 due to gravity loads

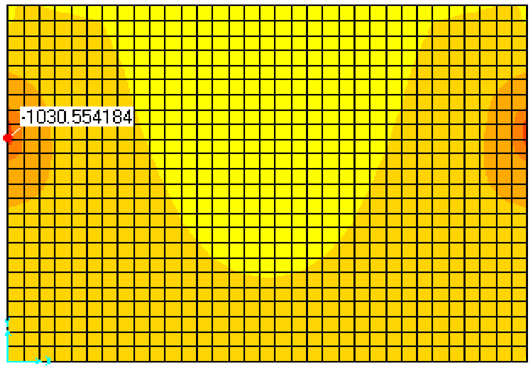

Fig. 15. Membrane forces in slab in system 3 due to horizontal loads

It is found that the variation of axial compression force along grid line 1 due to horizontal forces is linear. It starts from zero at gridline A, reaches maximum of 1030.55kN at gridline C (edge of wall) and then decreased to zero at gridline D as shown in Fig. 16.

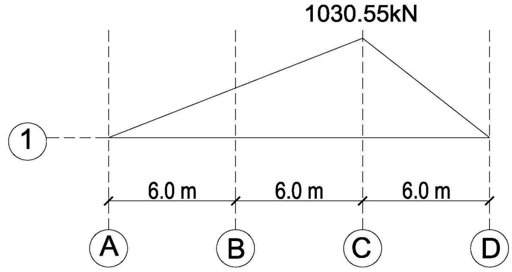

Fig. 16. Variation of membrane forces in slab in system 3 due to horizontal loads at gridline 1

System 4:

The system is composed of flat slab which is supported by columns and walls as shown in Fig. 4. The maximum membrane force in the slab due to gravity loads is 45.42kN tension as shown in Fig. 17 which is located in the slab very close to the wall along gridline 1 at the intersections of gridlines B and C. The maximum membrane forces in the slab due to horizontal loads is 520.26kN compression and tension as shown in Fig. 18 which is located in the slab very close to the wall at gridlines B and C.

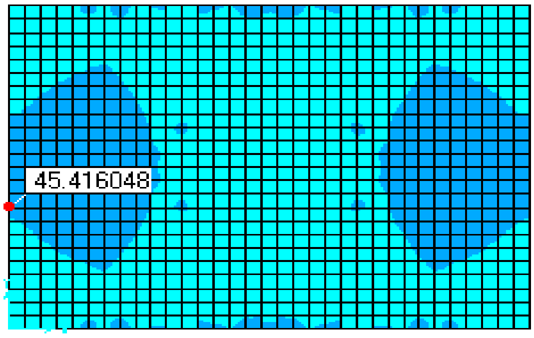

Fig. 17. Membrane forces in slab in system 4 due to gravity loads

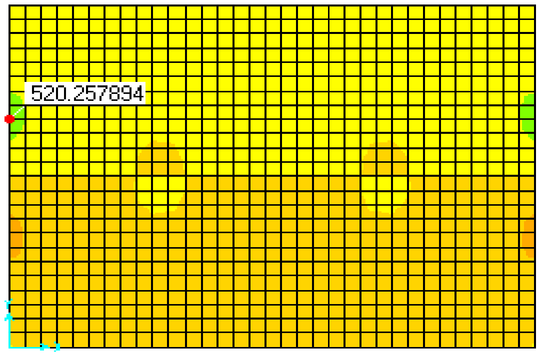

Fig. 18. Membrane forces in slab in system 4 due to horizontal loads

It is found that the variation of axial compression and tension forces along gridline 1 due to horizontal forces is linear. It starts from zero at gridline A, reaches maximum compression of 520.26kN at gridline B (edge of wall), reaches maximum tension force of 520.26kN at gridline C (edge of wall) and then decreased to zero at gridline D as shown in Fig. 19.

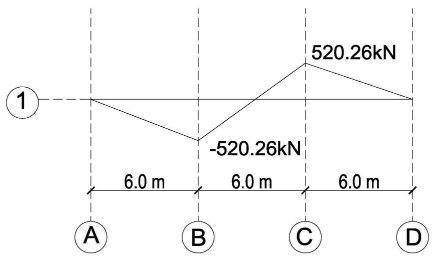

Fig. 19. Variation of membrane forces in slab in system 4 due to horizontal loads at gridline 1

System 5:

The system is composed of flat slab which is supported by columns and walls as shown in Fig. 5. The maximum membrane force in the slab due to gravity loads is 33.19kN tension and compression as shown in Fig.20 which is located in the slab very close to the wall along gridline 1 at the intersections of gridlines B and C. The maximum membrane forces in the slab due to horizontal loads is 408.88kN compression and tension as shown in Fig.21which is located in the slab very close to the wall at gridlines B and C.

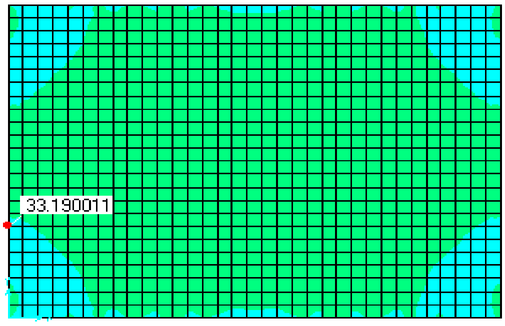

Fig. 20. Membrane forces in slab in system 5 due to gravity loads

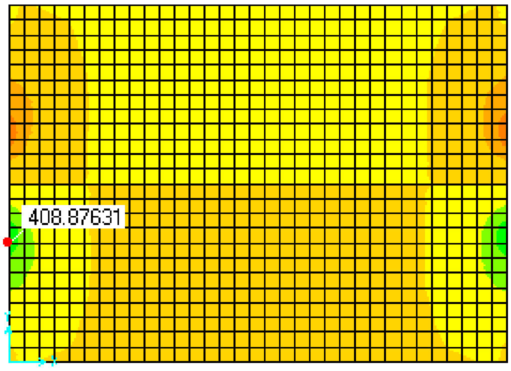

Fig. 21. Membrane forces in slab in system 5 due to horizontal loads

It is found that the variation of axial compression and tension forces along gridline 1 due to horizontal forces is linear. It starts from zero at gridline A, reaches maximum tension of 408.88kN at gridline B (edge of wall), reaches maximum compression force of 408.88kN at gridline C (edge of wall) and then decreased to zero at gridline D as shown in Fig. 22.

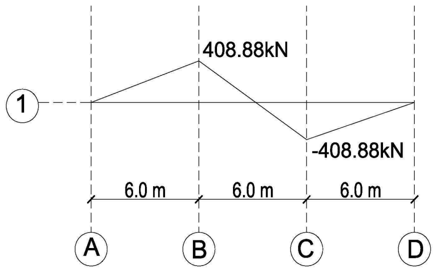

Fig. 22. Variation of membrane forces in slab in system 5 due to horizontal loads at gridline 1

In general, it is seen that the membrane forces due to gravity loads are very small and can be neglected in the design of the slab and its beams. The following paragraphs will concentrate on membrane forces due to horizontal forces only.

System 6:

The system is composed of slab with beams between all columns which is supported by columns and walls as shown in Fig. 6. The maximum membrane forces in the slab due to horizontal loads is 541.8kN compression as shown in Fig.23which is located in the slab very close to the wall along gridline 1 at gridlines C and the maximum axial force in the corresponding beam along gridline 1 is 493.44kN as shown in Fig. 24.

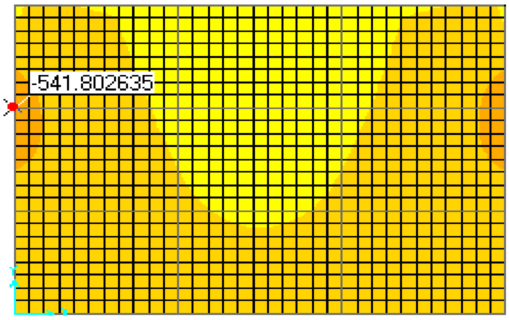

Fig. 23. Membrane forces in slab in system 6 due to horizontal loads

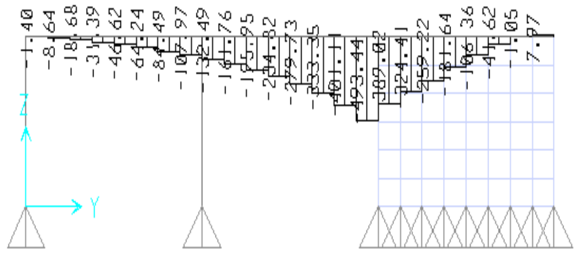

Fig. 24. Axial forces in beam in system 6 due to horizontal loads at gridline 1

It is found that the membrane forces in the slab varies linearly along gridline 1 from zero at gridline A to maximum of 541.8kN at gridline C, then to zero at gridline D as shown in Fig. 25.

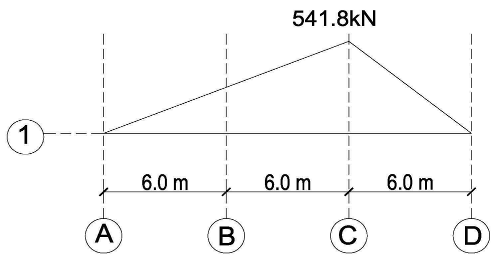

Fig. 25. Variation of membrane forces in slab in system 6 due to horizontal loads at gridline 1

System 7:

The system is composed of slab with beams between all columns which is supported by columns and walls as shown in Fig. 7. The maximum membrane forces in the slab due to horizontal loads is 277.68kN compression and tension as shown in Fig. 26 which is located in the slab very close to the wall along gridline 1 at gridlines B and C and the maximum axial force in the corresponding beam along gridline 1 is 244.93kN as shown in Fig. 27.

It is found that the membrane forces in the slab varies linearly along gridline 1 from zero at grid line A to maximum of 277.68kN compression at gridline B then to 277.68kN tension at gridline C, then to zero at gridline D as shown in Fig. 28.

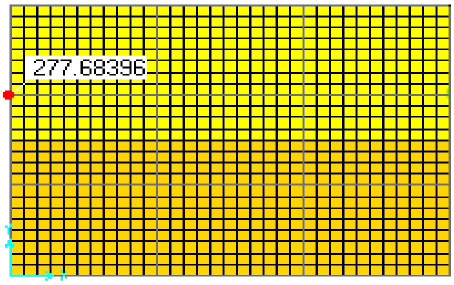

Fig. 26. Membrane forces in slab in system 7 due to horizontal loads

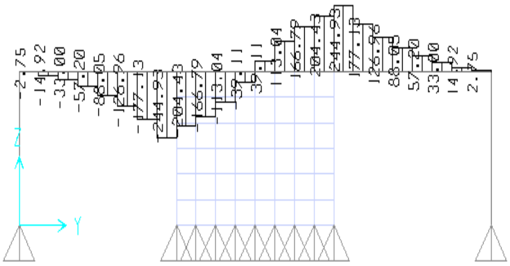

Fig. 27. Axial forces in beam in system 7 due to horizontal loads at gridline 1

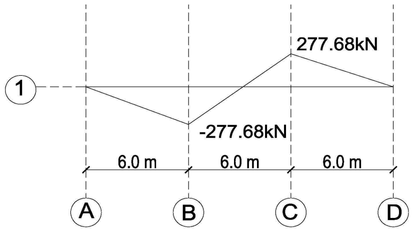

Fig. 28. Variation of membrane forces in slab in system 7 due to horizontal loads at gridline 1

System 8:

The system is composed of slab with beams between all columns which is supported by columns and walls as shown in Fig. 8. The maximum membrane forces in the slab due to horizontal loads is 201.62kN compression and tension as shown in Fig. 29 which is located in the slab very close to the wall along gridline 1 at gridlines B and C and the maximum axial force in the corresponding beam along gridline 1 is 176.97kN as shown in Fig.30.

It is found that the membrane forces in the slab varies linearly along gridline 1 from zero at grid line A to maximum of 201.62kN tension at gridline B then to 201.62kN compression at gridline C, then to zero at gridline D as shown in Fig. 31.

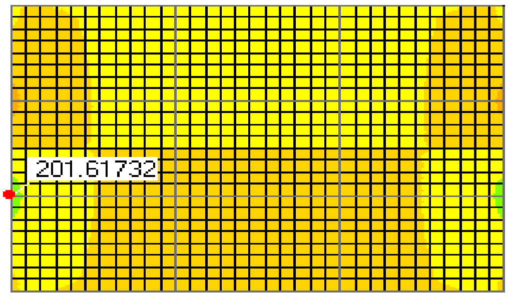

Fig. 29. Membrane forces in slab in system 7 due to horizontal loads

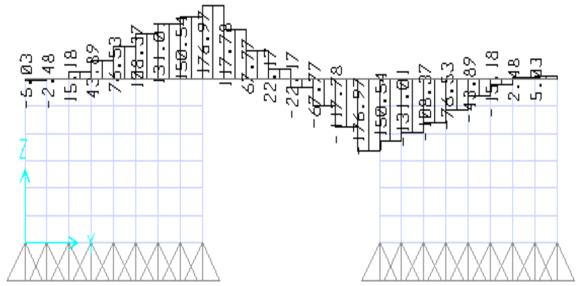

Fig. 30. Axial forces in beam in system 8 due to horizontal loads at gridline 1

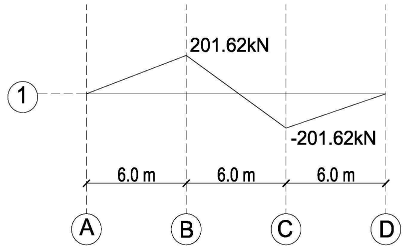

Fig. 31. Variation of membrane forces in slab in system 8 due to horizontal loads at gridline 1

IV. Discussion

It is clear that membrane forces exist in the slab (diaphragm) due to horizontal forces such as seismic loads. The membrane forces are found near the columns in flat plate slab at small areas. Also, it is found that the membrane forces with larger values exist in the slab close to wall edges in flat plate systems. In slabs with beams between all columns which is supported by columns, membrane forces exist in the slab near columns at small areas, but less than the values in flat plate and axial forces exist in the beams. In slabs between all columns which are supported by walls and beams, larger membrane forces exist in the slab at edges of walls and axial forces exist in the beams. In general the maximum membrane forces in the slab exist in flat slabs supported by walls and the smaller values exist in slab with beams supported by columns. The axial forces in the beams depend on their stiffnesses relative to the slab.

V. Conclusion

The slabs and beams that form the diaphragm are subjected to membrane forces; axial tension and compression; due to horizontal loads like seismic loads. The maximum values exist along wall lines in the slab and in the beam which form collectors. The design codes put some specifications dealing with the details of the diaphragms and collectors, but they did not indicate the variation of membrane forces in these diaphragms; the slab and the beams.

The structural designer should take into account these axial forces in the design and must be aware of the results of structural analysis and design softwares, as most of softwares do not consider axial forces in concrete slab and beam elements.

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AUTHOR'S PROFILE

Ibrahim Mohammad Arman: Lecturer at civil engineering department at An-Najah National University in Palestine. He was born in 1969 in Palestine. He received the bachelor degree in civil engineering from An-Najah National University in Palestine in the years 1994 and he received the master degree in structural engineering from the same university in the year 2004. He worked in many engineering companies in Palestine and Jordan. His work and research experience includes analysis and design of steel and concrete structures, finite element applications and earthquake engineering.