NUMERICAL STUDY OF THE DIAPHRAGM BEHAVIOR OF THE COMPOSITE FLOOR SYSTEMS SUBJECTED TO LATERAL LOAD

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ABSTRACT
The influence of the in-plane flexibility of composite floor systems on the seismic response of the structures may become significant, particularly when considerable floor slab cracking and yielding are expected. As in recent years the use of composite floor systems is increasing, in this study the lateral in-plane behavior of composite floor diaphragms in steel structures is investigated through numerical simulations. The structures considered in the study were two models of the prototype buildings, where the elastic and inelastic response of the diaphragms under lateral load is analyzed using 3-D finite element models and FEM linear and nonlinear structural analysis. It was found that under the seismic load specified in the code, the criterion of diaphragm rigidity is too small, so the composite floor systems can be assumed as rigid body, however under lateral loads with higher amplitudes, by developing the cracks in the concrete slabs, nonlinear behavior and stiffness degradation of the diaphragms might occur. The results showed that for both single story structures the ultimate strength of the diaphragms was very high about 20 to 33 times of the seismic load specified in Iran's seismic code, however the ultimate strength of the second diaphragm was considerable showing an increment about 50–60 percent compared to the ultimate strength of the first diaphragm. The comparisons between the numerical and previously obtained experimental results showed that FEM overestimates the diaphragm response in terms of stiffness and deformability; however conservatively estimates the diaphragms strength.

Keywords: composite floor system, numerical simulation, finite element method, nonlinear analysis, diaphragm, seismic load, crack pattern, ultimate strength, in-plane stiffness

1. INTRODUCTION
The contribution of the floor systems in transferring the lateral loads (seismic actions, wind pressures, etc.) to the vertical structural elements and subsequently to the foundation of the building structures is well known and indisputable. The floor systems in building structures, are usually designed to carry the gravity loads to the vertical structural elements, however they should be also designed to resist the
lateral forces and be able to transfer them to the resisting systems by a diaphragm action. If the floor elements act together in resisting the horizontal action and have the same deflection and show high in-plane lateral stiffness, the floor performance is known as rigid diaphragm behavior. In current design practice of building structures the floors sub assemble, according to the specifications of many building codes are usually considered as a rigid diaphragm. Even this assumption is often used to reduce the degrees of freedom of the structure and simplifies seismic response analysis of many types of buildings, however for some classes of structural systems, the effect of diaphragm deformability cannot be disregarded, especially in the case of rectangular buildings with large aspect ratios where considerable inelastic floor slab behavior is expected [6]. Since the diaphragm behavior is one of the most important factors in the seismic response of the structures, researchers have conducted studies on this subject, but the studies have not a long precedent and they are mostly performed in the last two decades.

An extended numerical parametric study was carried out to study the diaphragm behavior of RC floor systems (slabs and beams). The results show that the influence of aspect ratio on the criterion of the diaphragms rigidity ($\Delta_s/\Delta_c$) is considerable, although there is no clear correlation between these two structural characteristics [10]. The seismic behavior of wood diaphragms in unreinforced masonry buildings has been studied through the tests on three test specimens, using different rehabilitation methods. The results indicate that FEMA 273 tended to overpredict the stiffness and significantly underpredict yield displacement and ultimate deformation levels, while FEMA 356 tended to underpredict stiffness and overpredict yield displacement [7]. The studies on the low rise steel buildings with metal roof deck have shown that the lateral period is influenced by the diaphragm in-plane flexibility and the forces in the resistant elements can be amplified due to dynamics of the flexible diaphragm, also the shaking table results have indicated that the diaphragm in-plane deformations are twice of the values obtained from static analysis [11].

The diaphragm behavior of different types of floor systems usually differs substantially and depends on the details of the floor system, so as the use of composite floors is increasing, due to their low weight and economic benefits, in this paper the behavior of composite floor systems (CFS) (steel beams with upper concrete slab) in typical steel structures under lateral load with the influence of the gravity load, and also the in-plane characteristics of the diaphragm such as the deformability, stiffness, ultimate strength, yield point and crack pattern was investigated.

2. ANALYTICAL MODELS OF THE FLOOR DIAPHRAGMS WITH LINEAR BEHAVIOR

2.1. Design and Description of Prototype Buildings

The structures considered in this study are 3-D single-story typical steel buildings consisting of composite floor and X bracings, common in many countries. The 10.8m×7.2m×3m prototype buildings considered in the study are illustrated in
Figure 1. The girders and floor joists are I shapes supported on box columns braced by X bracings having box sections. The overall geometry of the structures presented in Figure 1 is the same and the main difference is the direction of the floor joists.

![Figure 1](image)

**Figure 1.** The steel buildings prototype: (a) The floor joists parallel to the lateral load. (b) The floor joists perpendicular to the lateral load.

The composite floors were designed with the AISC code specifications and composite structures design handbook [12]. Thickness of the floor slab was obtained as 8cm and the spacing between the floor joists in the structures shown in Figure 1, were set to 108cm and 90cm respectively. The seismic design of the structure was performed according to the seismic code of Iran [2], where the specified seismic lateral load for the structure, $V$, is given by:

$$ V = CW, \quad C = \frac{ABI}{R} $$

Where $C$ is the seismic shear force coefficient, $A$ is zonal acceleration, $B$ is the seismic response factor, $I$ is the importance factor, $R$ is the force modification factor and $W$ is the seismic weight of the structure.

For these administrative building structures in Tehran we have:

$A=0.35$, $B=2.5$, $R=6$, $I=1$

So we have $C=0.146$ and the total seismic load calculated for both of the structures, obtained from Eq.(1) is 54.1 kN.

2.2. Linear Analysis

The linear analysis of the structures was performed using SAP2000 computer program. For each structure two finite element models were developed, in the first models the floors were modeled by SHELL element having four nodes in each element to consider in-plane flexibility of the diaphragm. The beams, columns and bracings were modeled by FRAME element and the connection between these elements was modeled by the coincident nodes. The scaled structures with flexible diaphragm were analyzed under lateral load specified in the seismic code [2], with
the influence of gravity load. The FEM model and deformed shape of the structure with flexible diaphragm is presented in Figure 2(a) and (b). Due to flexibility of the diaphragm the displacement of mid point of the diaphragm is more than the side points as shown in Figure 2(b). In the second models rigid diaphragm hypothesis was used and the floors were modeled by rigid diaphragms. Figure 2(c) and (d) shows the FEM model and deformed shape of the structure with rigid diaphragm. In this model the displacements of all points of the diaphragm are the same as shown in Figure 2 (d).

![Figure 2. (a) Meshing of the FE Model with Flexible Diaphragm. (b) Deformed Shape. (c) Model of Structure with Rigid Diaphragm. (d) Deformed Shape](image)

2.3. Results of Linear Analysis
The results of analysis of the FEM models for both structures and also the results of the rotating tests are presented in Table 1. In this table RD1 and RD2 are the FE models with rigid diaphragm and FD1 and FD2 are the FE models with flexible diaphragm. Also E1 and E2 are the specimens tested under lateral and gravity loads.
The results show that both of the composite floor diaphragms were rather rigid under the lateral load specified in the seismic code. The difference between the calculated tensile and compressive bracing forces were obtained using Table 1 where for the first specimen were about 17% and 1% respectively, while in the second specimen were 3% and 10.5%.

The net displacement of the diaphragm is the relative displacement of the mid frame to the side frames, which is given by:

\[ \Delta_d = \Delta_m - \Delta_s \]  

(2)

Where \( \Delta_d \) is the diaphragm displacement, \( \Delta_m \) is the displacement of the mid frame and \( \Delta_s \) is the displacement of the side frames or the story drift. The proportion of \( \frac{\Delta_d}{\Delta_s} \) is a criterion to evaluate diaphragms rigidity in some building codes, for example with respect to the specification of Iran's seismic code[2], if \( \frac{\Delta_d}{\Delta_s} \leq 0.5 \), the diaphragm can be assumed rigid. As in these structures proportion of \( \frac{\Delta_d}{\Delta_s} \) was small (0.063 to 0.083), these composite floors under lateral load behave as rigid diaphragms. One of the effective parameters in the diaphragm behavior of floor systems is aspect ratio of the floor plan, so that for high plan aspect ratios, in-plane flexibility of the diaphragms increases significantly, but there is no clear relation between aspect ratio and \( \frac{\Delta_d}{\Delta_s} \) [3]. Therefore in these structures with low aspect ratio\(^1\) (L/D=1.5), the behavior of floor system as a rigid diaphragm, is somehow expectable.

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**Table 1: Results Obtained from Three Models for the Structures**

<table>
<thead>
<tr>
<th>Compressive force (kg)</th>
<th>Tensile force (kg)</th>
<th>( \frac{\Delta_d}{\Delta_s} )</th>
<th>( \Delta_d ) disp. (mm)</th>
<th>( \Delta_s ) disp. (mm)</th>
<th>Lateral load (kg)</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>429.5</td>
<td>433.1</td>
<td>–</td>
<td>0</td>
<td>0.30498</td>
<td>0.30498</td>
<td>1380</td>
</tr>
<tr>
<td>433.1</td>
<td>426.4</td>
<td>0.97</td>
<td>0.2689</td>
<td>0.29835</td>
<td>0.31924</td>
<td>1380</td>
</tr>
<tr>
<td>519</td>
<td>429</td>
<td>0.082</td>
<td>0.026</td>
<td>0.119</td>
<td>0.345</td>
<td>1380</td>
</tr>
<tr>
<td>429.5</td>
<td>433.1</td>
<td>–</td>
<td>0</td>
<td>0.39498</td>
<td>0.30498</td>
<td>1380</td>
</tr>
<tr>
<td>422.8</td>
<td>426.8</td>
<td>0.068</td>
<td>0.02046</td>
<td>0.29869</td>
<td>0.11915</td>
<td>1380</td>
</tr>
<tr>
<td>440.8</td>
<td>483.1</td>
<td>0.063</td>
<td>0.020</td>
<td>0.32</td>
<td>0.34</td>
<td>1380</td>
</tr>
</tbody>
</table>
3. ANALYTICAL MODELS FOR THE FLOOR DIAPHRAGMS WITH NONLINEAR BEHAVIOR

3.1. Description of Prototype Buildings

In some cases, floor diaphragm may undergo lateral loads more than the seismic lateral load of a single story building specified in the building codes. For example, the seismic lateral force on a floor diaphragm in lower stories of a multistory building is much more than the seismic lateral load of a single story building with a similar plan. So in the second part of the study, the nonlinear behavior of diaphragms of composite floor systems is studied. In order to ascertain nonlinear behavior of composite diaphragms and study the nonlinear characteristics of diaphragms (such as in-plane deformations, stiffness, ultimate strength, etc.) the stiffness of lateral load-resisting system of the structures were increased by doubling the number of X bracings. It was to give priority to the failure of diaphragms compared to the failure of structures. Structures considered in this part of study and meshing of the FEM models are presented in Figure 3. Connections of the columns to the foundation are rigid connections, while the connection of beams and bracings to the columns are hinge connections.

![Figure 3. Meshing of the FEM Models](image)

3.2. Theoretical Nonlinear Analysis

The seismic load was simulated by lateral cyclic load applied at the roof level distributed on the floor thickness and the pattern of the amplitudes of lateral cyclic load was the same as the previously conducted experiments. The nonlinear analysis of the structures was performed using ANSYS [8]. The elements used in modeling the structures are described as follows.

3.2.1. Used Elements [1]

-SOLID65:

In this study the concrete slab of composite floor system is modeled by SOLID65 element and the temperature reinforcement is considered by the volume ratio. The connectivity between the concrete and the steel beams is modeled by common joints within a distance same as the spacing of the shear keys.
- **BEAM24**: BEAM24 is a uniaxial element of arbitrary cross-section (open or single-celled closed section) with tension-compression, bending and St.Venant torsional capabilities. The element has plastic, creep, and swelling capabilities in the axial direction as well as a user-defined cross section. In this study BEAM24 element were used to mesh the steel elements of the structural steelwork, such as girders, joists of the composite floors, columns and bracings.

- **BEAM44**: BEAM44 is a uniaxial element with tension, compression, torsion and bending capabilities. This element allows a different unsymmetrical geometry at each end and permits the end nodes to be offset from the centroidal axis of the beam. Since in this element the properties of each end of beam (such as stiffness) may differ, in this study BEAM44 element were used to develop hinge connections of beams and bracings to the columns, so that all steel elements were meshed by BEAM24 element, except the end elements of the beams and braces which were meshed by BEAM44 element, then by releasing the moment of the node located at the connections, hinge connections were created. The application of BEAM24 and BEAM44 elements in developing the FEM model is presented in Figure 4.

![Figure 4. Application of the Beam Elements in Modeling the Structures](image)

### 3.2.2. Loading

#### 3.2.2.1. Gravity Load

The gravity load includes dead and live loads and a load related to scaling and simulation requirements. Because as the scale factor is 0.5 the materials used in the scaled structure must be twice of the prototype ones, so to cover the lack of weight, $Q_\rho$, a load equal to the weight of concrete slab is considered in total gravity load. The total gravity load applied on the diaphragms is given by:

$$Q_{tot} = Q_{DL} + Q_{LL} + Q_\rho = 372 \text{ kg/m}^2 = 3650 \text{ Pa}$$  \hspace{1cm} (3)

The total gravity load was applied on SOLID65 element as uniform pressure of 3650 Pa with Load key=6. Also the weight of structural elements was included using base acceleration of $g=9.8 \text{ m/s}^2$ upward which is equivalent to acceleration of structural elements.
3.2.2.2. Lateral Load
The lateral load was applied as uniform compressive pressure on the elements located at the edge of the floor slab. Since lateral cyclic load was applied in reverse directions, in the southern edge elements Load key=2 and in the northern edge elements Load key=4 were used. Amplitudes of lateral cyclic load in each cycle (which are the same as the previously conducted tests) [9] for both structures are shown in Figure 6. The end points of the curves are the failure points of diaphragms of the structures.

3.3. Results of Nonlinear Analysis
3.3.1. Ultimate Strength
After loading and unloading in each cycle, the lateral loads of the next cycle were applied with larger amplitude as shown in Figure 7. The composite diaphragms concrete failed when the solutions of nonlinear analysis were not converging, because despite the time steps were too small and decreased automatically, and also the number of iterations were too large, after a large number of iterations the nonlinear analysis diverged. The criterion of concrete failure is the criterion of William and Warnke, which represents a surface of failure, using the properties of the concrete, such as uniaxial tensile and compressive stresses and the coefficients of shear transfer in open and close cracks [8]. The displacement solution of side frame (story drift) is presented in Figure 7. The end points of the graphs shown in Figure 7 relates to the divergence of solutions. According to Figure 11 the ultimate strength of the diaphragms are 27 tons and 40.8 tons, respectively. The results
show that the ultimate strength of the second diaphragm is greater than the first one with a factor of 1.511.

3.3.2. Crack Pattern
In both diaphragms some cracks developed under the gravity load which were the same in both models, however cracking under the gravity load were nominal and the main cracks developed under the lateral load. In the first model the first cracks appeared when the lateral load was about 6 tons, then by increasing the lateral load, most of the cracks developed parallel to the joists or the direction of lateral load, but under the loads about the ultimate strength (26 tons), a few cracks developed near the braced frames, which inclined about 45º to the joists. In the second model the first cracks appeared when the lateral load was about 31 tons, then by increasing the lateral load, most of the cracks developed near the braced frames, which inclined about 45º to the joists. Crack patterns of the diaphragms of two models are illustrated in Figure 12 [8].
Performance of diaphragms is generally controlled by a combination of shear and flexural actions. In this study, performance of the composite diaphragms can be perceived from the crack patterns of the diaphragms, so that if the diaphragms are considered as beams on the braced frames as their support, in the first model the crack pattern indicates that the flexural action is dominate, but in the second model the crack pattern shows that the shear action is dominant.

3.3.3. Diaphragms' Deformation and Stiffness
Deformed shapes of the diaphragms were extracted using a path through axis 2-2 (shown in Figure 4). For example deformed shape of the diaphragm of the first model under lateral load of 6 tons is illustrated in Figure 9. The horizontal axis is calibrated as diaphragm width, which is 5.4 m, and the vertical axis presents displacement of all points of the diaphragm. Net displacement of the diaphragm can be found from deformed shapes of diaphragm, which is difference of mid and side frames of the diaphragm.

![Figure 9. Deformed shape of the first diaphragm](image)

The analytically obtained load-displacement curves of the diaphragms are shown in Figure 10. The horizontal axis is the net displacement of the diaphragms and the vertical axis is total lateral load applied on the diaphragm [12].

![Figure 10: Load-displacement curves of the diaphragms. (a) First model. (b) Second model](image)

In order to compare in-plane flexibility of the diaphragms, the displacement of two diaphragms versus lateral load is traced in one coordinate system (Figure 11a)). As
shown in Figure 11(a) the displacement of the diaphragms under lateral loads less than 20 tons is almost the same, but under lateral loads more than 20 tons the displacement of the first diaphragm compared to the second one increases significantly. For example under ultimate load of the first diaphragm, the displacement of the first diaphragm is about 2.2 times of the second one. The comparison was made in the joint region, since the ultimate strength of the diaphragms was not the same.

![Figure 11(a)](image1)

*(a) The displacement of two diaphragms. (b) and (c) Variation of the diaphragms stiffness of First and Second model.*

One of the most important characteristics of the diaphragms which affect their behavior is their in-plane lateral stiffness. As the stiffness is the load required for unit displacement in a specific point, slope of the load-displacement curves (shown in Figure 10) represents the in-plane stiffness of the diaphragms. Variation of stiffness of two diaphragms versus lateral load is presented in Figure 11(b) and (c). As shown, in the first model the diaphragm stiffness is rather constant until lateral load is 18 tons (about 60% of the ultimate strength), then decreases about 70% until failure. However in the second model the diaphragm stiffness is constant until 34 tons (about 85% of the ultimate strength), then decreases about 50% until failure [8].

### 3.3.5. Stress Contours of Diaphragms

Since the structures have low plan aspect ratios, the distribution of shearing stress in the diaphragms is more important. The contours of shearing stress ($S_{xy}$) in the diaphragms are presented in Figure 12. Due to the symmetry of the models, the absolute values of shearing stress in two sides of the axis of symmetry are the
same, but have different signs. As shown in Figure 18 in both diaphragms the maximum shearing stress is observed near the braced frames. Maximum of the shearing stress for the first diaphragm is about 2.04 MPa ($0.452\sqrt{f'c}$), and for the second diaphragm is about 2.73 MPa ($0.618\sqrt{f'c}$), which shows an increase about 36% comparing to the first one.

![Figure 12](image1.png)  
(a) (b)  
Figure 12. Contours of Shearing Stress in the Diaphragms. (a) First Model. (b) Second Model

### 3.4. Analysis of Results

The results of nonlinear structural analysis by ANSYS are compared with the results previously obtained from quasi-static cyclic lateral loading test as follows. The ultimate strengths of the diaphragms, obtained from nonlinear FEM analysis were 27 tons and 40.8 tons respectively, while the ultimate strengths obtained from the tests were 29 tons and 47 tons, which show errors about 7% and 13% comparing to the values obtained from the tests. The difference between the results can be described as follows; ANSYS computer program can predict failure of the concrete using the criterion of William and Warnke [1], which represents a surface of failure, by means of properties of the concrete. However after failure of the concrete, some other structural elements, such as the columns, braces and the joists, and also the interlocking of the temperature reinforcement with the concrete and the joists, resist the lateral load until overall failure of the structure; so the ultimate strength of both diaphragms obtained from the tests are slightly higher than the analytical ones.

The crack pattern of both diaphragms, obtained from numerical analysis using ANSYS illustrated in Figure 8, are in good agreement with the crack pattern of concrete observed in the previous tests ([4] and [9]). As shown in the diaphragm of the first specimen most cracks are parallel to the direction of lateral load, but in the diaphragm of the second specimen most cracks inclined about 45° to the joists, showing that the test results confirm the results of FEM nonlinear analysis. According to the results obtained in the previous experiments ([4] and [9]), it is obvious that for both diaphragms the finite element method generally underpredicts
the diaphragms displacements under lateral load and overpredicts the diaphragms stiffness compared to the ones obtained from tests. The difference between the results of two methods can be described as follows; in FEM analysis of diaphragms, size of the elements affect the displacement values of the response, and if the discretisation mesh is not fine enough the stresses of the lateral resisting elements may be determined with a good approximation, but the response displacements may be determined with some errors [3]. In modeling of the structures, with respect to the hardware abilities, the diaphragms were meshed by 11.25 cm x 13.5 cm elements as shown in Figure 3, so by using finer elements in meshing of the diaphragms, the analytical displacement responses of the diaphragms may be closer to the experimental ones. Also concrete is not a homogeneous material and has rather complicated behavior, so modeling the concrete by simplified material models may result in inaccurate results in the nonlinear analysis of concrete elements.

The results analysis show that if two individual diaphragms are designed under gravity load with the same conditions, the diaphragm with joists perpendicular to the lateral load, exhibits a better performance under lateral loads, so it is recommended that in a building with low plan aspect ratio, composite floor systems are so constructed that the direction of the joists in the vicinity of braced frames or shear walls, is perpendicular to the direction that the main lateral load resisting elements act, or the joists are set in a staggered manner all over the plan. If a building has a high plan aspect ratio, directing the joists in the long direction would lead to better performance of the composite diaphragm, however in some cases directing the joists to be perpendicular to the lateral load would be with some penalties, because if the joists are in the long direction of the diaphragm, they are less efficient under gravity load and it would be more costly.

4. CONCLUSIONS

In this paper the behavior of composite diaphragms was studied in two parts, in the first part the diaphragms were subjected to the lateral seismic load specified in the seismic code and distribution of the lateral load among the resistant elements was studied using FEM analysis with rigid diaphragm and flexible diaphragm hypothesizes and verified with the results of the tests on the half scale specimens. The results show that under the seismic load specified in Iran's seismic code [2], the criterion of diaphragm rigidity (\( \frac{\Delta_s}{\Delta_y} \)) is too low and the diaphragms can be assumed rigid. Also the forces of bracings calculated from the methods have errors less than 17%, which indicates that using the rigid floor diaphragm model provides adequate results for the stresses of the laterally resisting vertical structural elements and the story drift. The models considered in the first part after increasing the stiffness of the side braced frames, were subjected to the quasi-static reverse cyclic lateral load up to failure. The results show that the second diaphragm (where the joists direction was perpendicular to the lateral load direction) has higher lateral in-plane stiffness and there were no significant stiffness degradation until 85% of the ultimate load, but the first diaphragm (where the joists direction was parallel to the
lateral load direction) had lower stiffness and the stiffness degradation started at a load of 48% of the ultimate load. The ultimate strength of the second diaphragm was considerable showing an increment about 50–60 percent compared to the ultimate strength of the first diaphragm, also for both of the single story structures the ultimate strength of the diaphragms was very high and was about 20 and 33 times of the seismic load specified in Iran's seismic code, respectively. The comparisons between the numerical and experimental results previously obtained by the authors showed that FEM overestimates the diaphragm response in terms of stiffness and deformability; however FEM conservatively estimates the diaphragms strength. Generally it seems that one of the most important parameters in the diaphragm behavior of the composite floor systems is the direction of the joists relative to the lateral load and it is recommended that the composite floor systems are so constructed that the joists direction is perpendicular to the direction toward which the main lateral load resisting elements act.

5. ACKNOWLEDGMENTS

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