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In this paper a review of the provisions of some modern seismic codes for the analytical modeling of the floor diaphragm action is made and a methodology using finite elements models, taking into consideration the in-plane flexibility, for monolithic floor is suggested. Using this method with comparative response-spectrum dynamic analyses, some reinforced concrete structures with different plan shapes like T-shape, L-shape, U-shape and rectangular according to 2800 (Iranian seismic code) are analyzed. Then, the efficiency of codes provisions is investigated.

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Abstract- All the seismic codes generally accept that in most cases the floor diaphragms may be modeled as fully rigid without in-plane deformability. Even though a rigid floor diaphragm is a good assumption for seismic analysis of the most buildings, several building configurations may exhibit significant flexibility in floor diaphragms. In these configurations, some codes like (EC8, NZS4203, GSC-2000) set certain qualitative criteria related to the shape of the diaphragm, while some others (2800, UBC-97, SEAOC-90, FEMA-273) set quantitative criteria relating the in-plane deformation of the diaphragm with the average drift of the associated storey.

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Keywords: *rigid floor diaphragm, flexible floor diaphragms, average drift, in-plan deformation, floor diaphragm action, response-spectrum analysis.*

I. Introduction

In the analysis of multistory buildings subjected to lateral loads, a common assumption is that the floor system undergoes no deformation in its own plan [1, 2]. Building structures are typically designed using the assumption that the floor systems serve as a rigid diaphragm between the vertical elements of the lateral load-resisting system. For the majority of buildings, floor diaphragms offer the most economical and rational method of resisting the lateral forces, since they are ordinarily included in the buildings to support the vertical workloads. It is thus, of the utmost importance, that they must be provided with sufficient in-plane stiffness and strength, together with efficient connections to the vertical structural elements. Muto (1974) used a beam with bending and shear deformation effects to simulate the behavior of flexible floors in buildings. Jain (1984) also used this beam including flexible and shear deformation effects to generate a solution to find the flexible-floor effect under the dynamic analysis. Saffarini and Qudaimat (1992) analyzed 37 reinforced concrete buildings to compare the difference between static rigid-floor and flexible-floor analyses. They found that the rigid-floor assumption is accurate for buildings without shear walls, but it can cause errors for building systems with shear walls. The quantitative investigation of the difference between the flexible-floor and rigid-floor analyses of buildings with shear walls was not found in their study and appears to be absent in the literature. Ju and Lin (1999) investigated the difference between rigid-floor and flexible-floors. They found that the rigid-floor assumption can cause errors for building system with shear walls. A quantitative investigation is made and an error formula is generated using the regression analysis of the rigid-floor and flexible-floor analyses from 520 rectangular, U-shaped, and T-shaped buildings. The effect of opening in slab was not found in their study and appears to be absent in the literature. Busu and Jain (2004) investigate the influence of floor diaphragm flexibility in asymmetric buildings. They investigate the effect of torsional code provisions in asymmetric buildings. They concluded that torsional effects may be quite significant in buildings with a flexible floor diaphragm (in semi-rigid structures specially). In such buildings, neither the floor diaphragm flexibility nor the torsional response can be ignored. Moreover, ignoring either accidental torsion or torsional amplification may cause significant differences in design forces. However, when the floor diaphragm is completely or significantly flexible (Tena-Colunga and Abrams 1996), each individual frame responds almost independently without any interference from the others and the torsional contribution may be significantly diminished.

In this paper a review of the provisions of some modern seismic codes for the analytical modeling of the floor diaphragm action is made and a methodology using finite elements models, taking into consideration the in-plane flexibility, for monolithic floor is suggested. Using this method with comparative response-spectrum dynamic analyses, some reinforced concrete structures with different plan shapes like T-shape, L-shape, U-shape and rectangular according to 2800 (Iranian seismic code) are analyzed. Then, the efficiency of codes provisions is investigated. This article has 3 sections, in first section the results of building

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analyses is investigated, in second section, codes provisions is investigated via the results of building analyzes and in third section, the quantitative criteria of codes provision is investigated via an error formula.

II. Code Provisions

In this section a review of the provisions of some modern seismic codes for the analytical modeling of the floor diaphragm action is made. All the seismic codes generally accept that in most cases the floor diaphragms may be modeled as fully rigid without in-plane deformability. Even though a rigid floor diaphragm is a good assumption for seismic analysis of the most buildings, several building configurations may exhibit significant flexibility in floor diaphragms. In these configurations, some codes like (EC8, NZS4203, GSC-2000) set certain qualitative criteria related to the shape of the diaphragm, while some others (2800, UBC-97, SEAOC-90, FEMA-273) set quantitative criteria relating the in-plane deformation of the diaphragm with the average drift of the associated storey.

III. Uniform Building Code [UBC, 1994]

Diaphragms shall be considered flexible for the purposes of distribution of storey shear and torsional moment when the maximum lateral deformation of the diaphragm ($\Delta_{flexible}$) is more than twice the average storey drift of the associated storey (Δ_{story}) (Fig. 1). The deflection in the plane of the diaphragm shall not exceed the permissible deflection of the attached elements. Permissible deflection shall be that deflection which permits the attached element to maintain its structural integrity under the individual loading and continue to support the permissible loads [12]. Floor and roof diaphragms shall be designed to resist the forces determined in accordance with given formulas [12].
In the other word diaphragm is rigid when:

$$\beta = \frac{\Delta_{flexible}}{\Delta_{Story}} < 2 \tag{1}$$

And it is flexible when:

$$\beta = \frac{\Delta_{flexible}}{\Delta_{Story}} \geq 2 \tag{2}$$

IV. Structural Engineers Association of California [SEAOC, 1990]

Diaphragms shall be considered flexible when the maximum lateral deformation of the diaphragm is more than twice the average drift of the associated storey ($\beta \geq 2)$ [9]. The term "flexible" implies that the diaphragm may be modelled as a simple beam (horizontal girder) between vertical resisting elements, whose cross section is composed of connected web and flange elements. The web (shear resisting element) is provided by the floor or roof deck, while chord or boundary members serve as flanges to resist the axial tension or compression resulting from flexural action [9]. This girder analogy should not be regarded as complete and should only be considered as an approximation, usually having the special properties of deep beams (shear deformations etc.) [9].

In most cases the diaphragm may be modelled as "fully rigid" without in-plane deformability. However there are structural configurations such as vertical resisting elements having large differences in stiffness or offsets between stories, and diaphragms with irregular shapes and/or openings, where the Engineer should investigate the effects of diaphragm deformability. The use of the most critical results obtained from the "fully rigid" and the "flexible" models would be acceptable [9].

IRAN SESMIC CODE-THIRD EDITION (2800)

Floor diaphragms shall be classified as either "flexible" or "rigid". "Flexible" when the maximum lateral deformation of the diaphragm along its length is more than half the average inter-storey drift of the storey immediately below, "rigid" when this lateral deformation of the diaphragm is less than half the average inter-storey drift of the associated storey. The inter-storey drift and diaphragm deformations shall be estimated using the seismic lateral forces. The term "flexible" implies that the diaphragm may be modelled as a simple beam (horizontal girder) between vertical resisting elements, whose cross section is composed of connected web and flange elements. The web (shear resisting element) is provided by the floor or roof deck, while chord or boundary members serve as flanges to resist the axial tension or compression resulting from flexural action. This girder analogy should not be regarded as complete and should only be considered as an approximation, usually having the special properties of deep beams (shear deformations etc.) [15].
In the other word diaphragm is rigid when:

$$\lambda = \frac{\Delta_{diaph}}{\Delta_{Story}} < 0.5 \tag{3}$$

And it is flexible when:

$$\lambda = \frac{\Delta_{diaph}}{\Delta_{Story}} \geq 0.5 \tag{4}$$

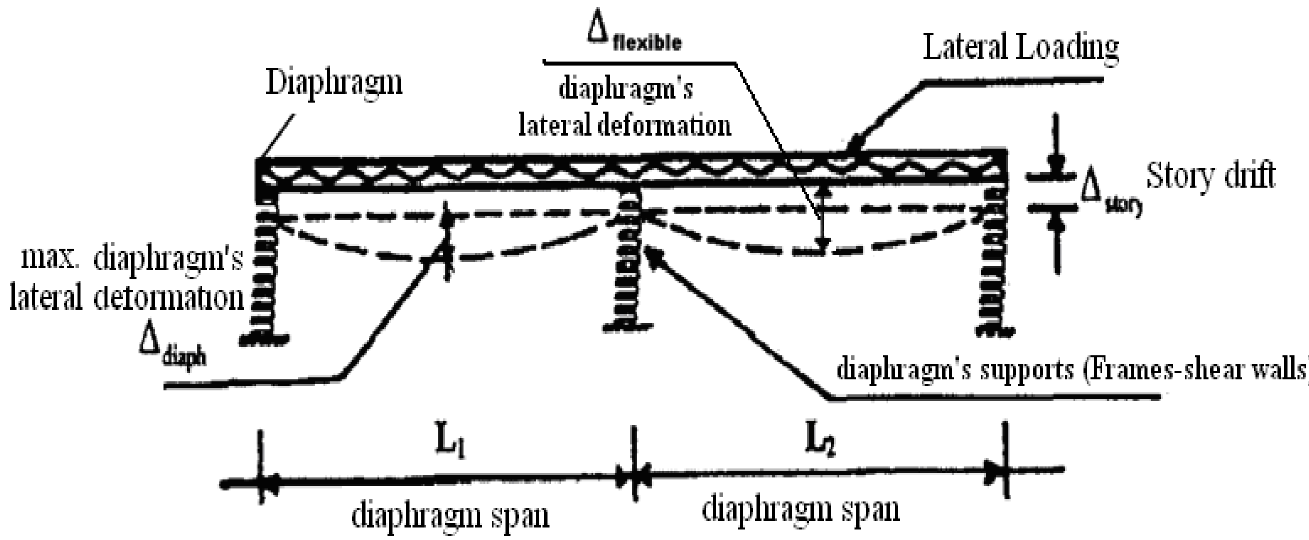

FIG. 1. Simulation of diaphragm with a simple deep beam [15]

V. Federal Emergency Management Agency [FEMA 1997]

Floor diaphragms shall be classified as either "flexible", "stiff", or "rigid". "Flexible" when the maximum lateral deformation of the diaphragm along its length is more than twice the average inter-storey drift of the storey immediately below ($\lambda \geq 2$), "rigid" when this lateral deformation of the diaphragm is less than half the average inter-storey drift of the associated storey ($\lambda < 0.5$) and "stiff" when the diaphragm it is neither flexible nor rigid ($0.5 \leq \lambda < 2$). The inter-storey drift and diaphragm deformations shall be estimated using the seismic lateral forces. The in-plane deflection of the floor diaphragm shall be calculated for an in-plane distribution of lateral force consistent with the distribution of mass, as well as all in-plane lateral forces associated with offsets in the vertical seismic framing at that floor [13].

Mathematical models of buildings with stiff or flexible diaphragms should be developed considering the effects of diaphragm flexibility. Floor diaphragms shall be designed to resist the effects of the inertia forces developed at the level under consideration and the horizontal forces resulting from offsets or changing in stiffness of the vertical seismic framing elements above and below the diaphragm. For concrete diaphragms, the analytical model can typically be taken as a continuous or simple span horizontal elastic beam that is supported by elements of varying stiffness. The beam may be rigid or semi-rigid. When the length-to-width ratio of the diaphragm exceeds 2.0, the effects of diaphragm deflection shall be considered when assigning lateral forces to the resisting vertical elements [13].

Eurocode 8 [EC8, 1994]

When the floor diaphragms are sufficiently rigid in their plane, the masses and the moments of inertia of each floor may be lumped at its centre of gravity. The seismic design shall cover the verification of reinforced concrete (RC) diaphragms in the following cases of Ductility Class "H" structures [11]:

- Irregular geometries or divided shapes in plan, recesses, re-entrances
- Irregular and large openings in the slabs
- Irregular distribution of masses and or stiffness
- Basements with walls located only in part of their perimeter, or only in part of the ground floor area.

In these cases, action effects in RC diaphragms may be estimated by modeling them as deep beams on yielding supports or plane trusses. In steel buildings, concrete floor diaphragms may be considered as rigid for the dynamic analysis without further verification, if the openings in them do not significantly affect the overall in-plane rigidity of the floor and they are constructed according to Chap. 2 [11].

When the floor diaphragms of the building may be taken as being rigid in their planes, the masses and the moments of inertia of each floor may be lumped at the centre of gravity [11].

- The diaphragm is taken as being rigid, if, when it is modelled with its actual in-plane flexibility, its horizontal displacements nowhere exceed those resulting from the rigid diaphragm assumption by more than 10% of the corresponding absolute horizontal displacements in the seismic design situation [11].

VI. Greek Seismic Code [GSC, 2000]

In buildings subjected to horizontal seismic actions, if the in-plane stiffness of the diaphragms is assured to be large ("rigid floors"), then the mass properties of each diaphragm may be lumped at its centre of mass (reducing the independent in-plane degrees of freedom to three per floor), else additional degrees of freedom must be considered [14].

The shape of the floors in plan must guarantee the "rigid floor" diaphragm action in point of stiffness and strength. For this reason, long shapes in plan (length to width ratio ≥ 4) must be avoided, as well as plan shapes composed of long parts (L, Π, etc.) or with large re-entrances. When this is not possible, the effects of the in-plane floor flexibility to the distribution of the lateral forces at the vertical resisting elements must be taken into consideration and the strength capacity at the weak areas of the diaphragm must be checked [14].

VII. Standards Association of New Zealand [NZS 4203, 1992]

When there are abrupt discontinuities, major variations in in-plane stiffness or major re-entrant corners in diaphragms, the assumption of a rigid diaphragm may not be valid. In some cases, investigation of the effects may be require the stiffness of the diaphragm to be modelled in the analysis to ensure that a realistic distribution of lateral force has been obtained [10].

VIII. Structural Modelling and Analysis Framework

The total number of degrees of freedom is equal to three times the total number of slaved nodes and master nodes in the mesh for a three-dimensional (3D) building analysis. For building analyses under the flexible-floor assumption, each node contains six degrees of freedom — three translations and three rotations. Thus, the number of degrees of freedom for the flexible-floor mesh is about twice as large as that for the rigid-floor mesh.

For the equivalent static lateral force method, the horizontal forces are often applied to the master nodes of a rigid-floor analysis. However, it is difficult to add these horizontal forces to the nodes of a building with the flexible-floor assumption. For example, adding these horizontal forces only to the node at the mass center of each floor will cause stress concentration near the mass center. Thus, to compare the results of the rigid-and flexible-floor analyses, dynamic analysis is probably a better choice since the earthquake loading can be applied to the building base without any differentiation between the rigid and flexible-floor analyses. Forced dynamic analyses include time-history and response-spectrum analyses. For time-history analysis, it is not easy to compare the complex analysis results between the rigid- and flexible-floor analyses. For example, the two results may differ due to a significant time shift, so comparing them at a certain time will cause error. The response-spectrum analysis does not have this problem, since only the maximum responses are calculated in this method. Thus this method with the response spectrum of the 2800 code (Fig. 2) is used to perform the two types of building analyses. In the dynamic analysis, the mode superposition method is used, and the first 30 modes are calculated to perform the response to perform the response-spectrum analysis. The effective masses of the x-translation, y-translation and z-rotation for these 30 modes are always larger than 95% of their total masses in our building analyses.

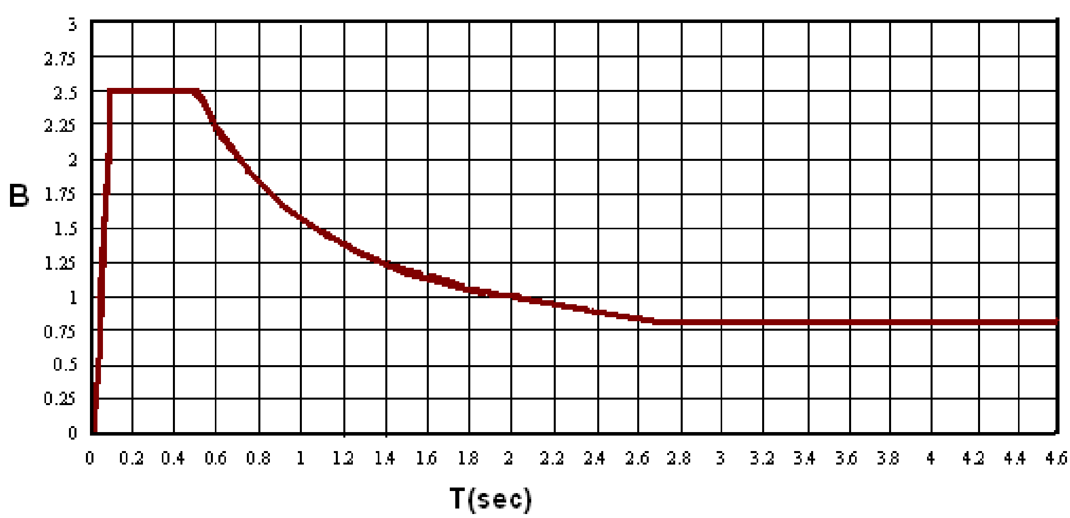

FIG.2- Response Spectrum of 2800 Code [15]

For the analytical modeling and dynamic analyses of the structures considered, the computer program SAP2000 was used. The floor diaphragms and shear walls are modeled with shell elements.

IX. Characteristics of Buildings

For the investigation of codes provisions, some reinforcement concrete buildings with T-shaped, L-shaped, U-shaped and rectangular plan shape are considered. Fig 3 shows the plans shape and position of shear walls. These buildings are analyzed with shear wall and without shear walls. 3-story T-shaped building consists of two long rectangular interconnected parts, with aspects ratio ≈ 1:4 and 1:5. 4-story L-shaped building consists of two long rectangular interconnected parts, with aspects ratio ≈ 1:4.5 for each of them. 6-story U-shaped building consists of three long rectangular interconnected parts, with aspects ratio ≈ 1:3.75 and 1:5.2. The floor plan in rectangular building has a rectangular shape with aspect ratio 1:4.

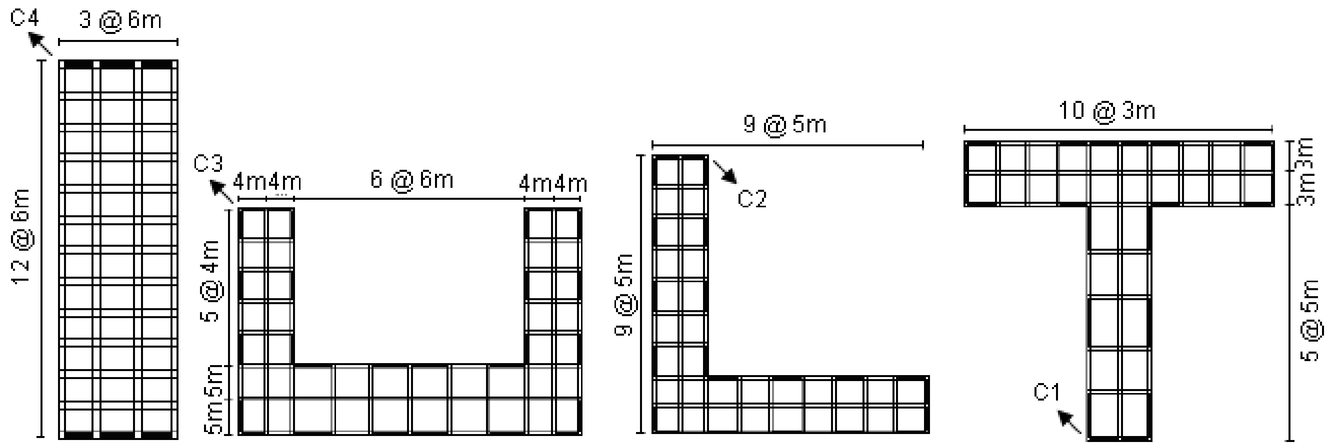

FIG. 3 Plan shape and position of shear walls

Member sizes and other properties of the structures are shown in the table 1. In T-shaped building, the beams with 3m length have 30X70cm section, and beams with 5m length, have 50X70cm section. In U-shaped building, the beams with 3m length have 30X80cm section, beams with 4m length have 40X80cm section, and beams with 5m length have 50X80cm section.

Table1- Member Sizes and other properties of buildings

Shape of buildings	Beam section (cm)	Column section (cm)	Slab thickness (cm)	Shear wall thickness (cm)	Number of stories	Story height (m)
T-shape	30X70 50X70	50X50	12	12	3	4
L-shape	40X80	50X50	12	15	4	4
	30X80					
U-shape	40X80 50X80	80X80	15	30	6	4
Rectangular	50X80	80X80	15	15	5	4

X. First Section, Results of Analyses

The buildings with and without shear walls, and with rigid and flexible diaphragm assumption are analyzed. From the results obtained of a number of response-spectrum analyses, the rigid floor model was found to be accurate enough for buildings without shear walls. However, the difference between the rigid-floor and flexible-floor analyses can be large for the buildings with shear walls. In each building a diagram indicates the difference between two types of analyses. In mentiond diagrams, the axial force (in selected column in fig 3) is used as X-direction and story level is used as Y-direction.

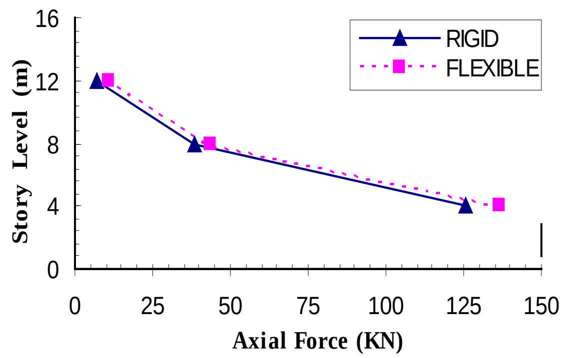

FIG. 4. Axial forces of C1 in T-shaped building without shear walls under Y-Y direction earthquake

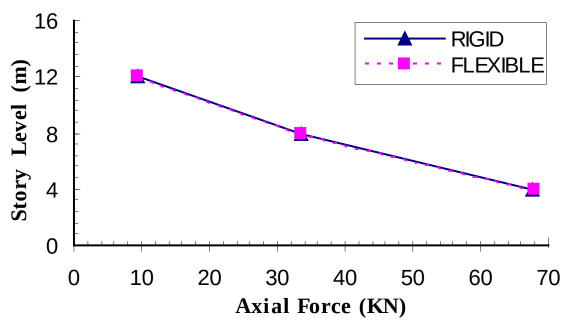

FIG 5- Axial forces of C1 in T-shaped building with shear walls under Y-Y direction earthquake

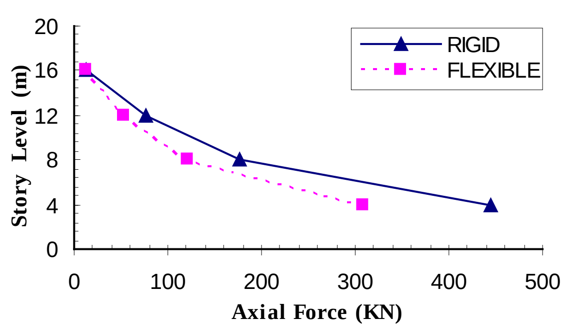

FIG 6-Axial forces of C2 in L-shaped building without shear walls under Y-Y direction earthquake

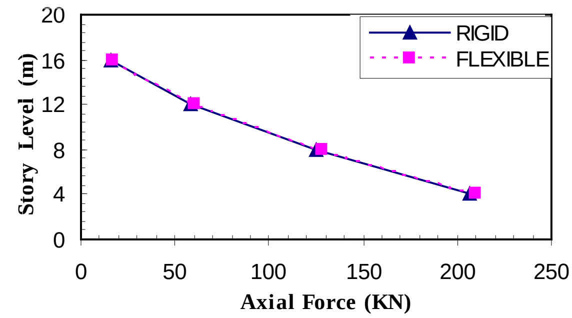

FIG. 7. Axial forces of C2 in L-shaped building with shear walls under Y-Y direction earthquake

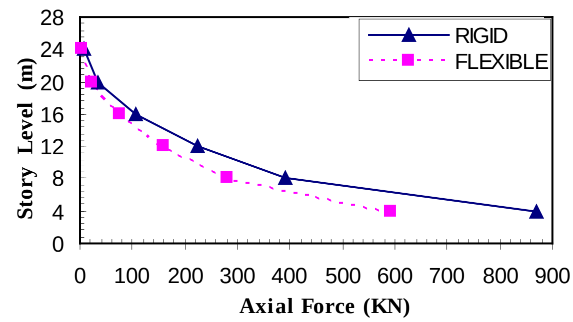

FIG. 7. Axial forces of C3 in U-shaped building without shear walls under Y-Y direction earthquake

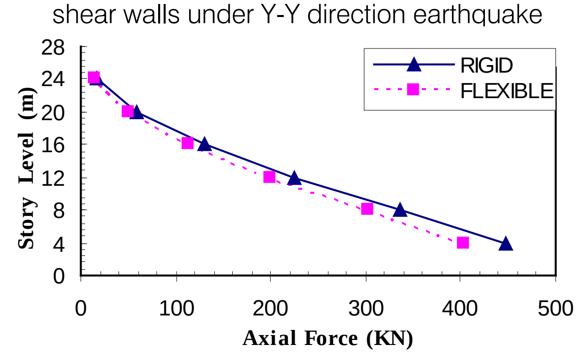

FIG. 8. Axial forces of C3 in U-shaped building with shear walls under Y-Y direction earthquake

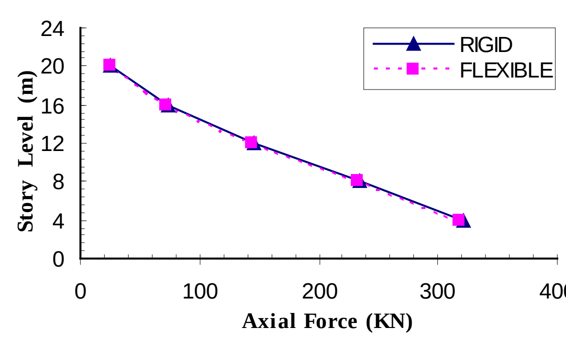

FIG.9- Axial forces of C4 in Rectangular building without shear walls under X-X direction earthquake

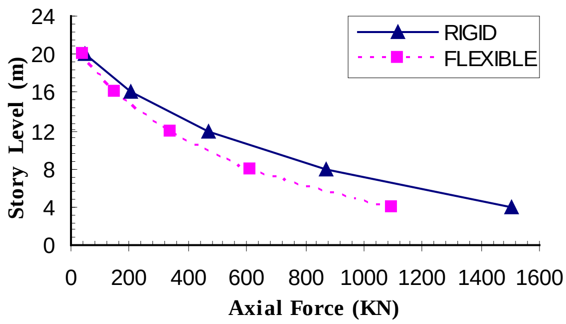

FIG10- Axial forces of C4 in Rectangular building with shear walls under X-X direction earthquake

Above figures illustrate the analysis differences. These figures indicate that the maximum difference between the rigid floor and flexible floor building analyses for T-shaped building with shear walls is approximately 32%. This difference, for T-shaped building without shear walls is less than 1%, for L-shaped building with and without shear walls respectively is about 46% and 4%, for U-shaped building with and without shear walls respectively is about 75 and 25, for rectangular building with and without shear walls respectively is about 42% and 1%. It is concluded in the most building with shear walls, difference between two types of analysis is low. Since in the buildings without shear walls, the in-plan floor deformation is more than lateral deformation, the rigid floor assumption is accurate for these buildings.

XI. Second Section, Investigation of Codes Provisions via the Results of Analyses

In this section codes provisions are investigated by use the results of building analyses. In order to set the conditions under which the in-plane deformability must be taken into consideration, some codes (EC8, NZS4203, GSC) set certain qualitative criteria related to the shape of the diaphragm, while some others (UBC, SEAOC, FEMA) set quantitative criteria relating the in-plane deformation of the diaphragm with the average drift of the associated storey, as mentioned above.

1. UBC-97 and SEAOC-90 quantitative criteria

The provisions of these codes for about the diaphragm, is similar and diaphragms shall be considered flexible when the maximum lateral deformation of the diaphragm is more than twice the average drift of the associated storey ($\beta \geq 2$) and diaphragms shall be considered flexible when ($\beta < 2$). The values of β are shown in tables 2 and in accordance with that in buildings with shear walls, only the rectangular building is flexible and other T-shaped, L-shaped and U-shaped buildings are rigid. All of the buildings without shear walls are rigid.

TABLE 2. The values of $\boldsymbol{\beta}$

Building type		Max of β	Associated story
Buildings with shear walls	T-shaped	1.22	Rigid
	L-shaped	1.68	Rigid
	U-shaped	1.51	Rigid
	Rectangular	2.00	Flexible
Buildings without shear walls	T-shaped	1.02	Rigid
	L-shaped	1.02	Rigid
	U-shaped	1.03	Rigid
	Rectangular	1.02	Rigid

2. 2800 quantitative criteria

Diaphragms shall be considered flexible when the maximum lateral deformation of the diaphragm along its length is more than half the average inter-storey drift of the storey immediately below ($\lambda > 0.5$), and diaphragms shall be considered flexible when ($\lambda < 0.5$). The values of λ are shown in tables 3 and in accordance with that in buildings with shear walls, only the T-shaped building is rigid and other L-shaped, U-shaped and rectangular buildings are flexible. All of the buildings without shear walls are rigid.

TABLE 3. The values of λ

Building type		Max of λ	Associated story
Buildings with shear walls	T-shaped	*0.22*	*Rigid*
	L-shaped	*0.68*	*Flexible*
	U-shaped	*0.51*	*Flexible*
	Rectangular	*1.00*	*Flexible*
Buildings without shear walls	T-shaped	*0.019*	*Rigid*
	L-shaped	*0.018*	*Rigid*
	U-shaped	*0.03*	*Rigid*
	Rectangular	*0.015*	*Rigid*

3. FEMA-273 quantitative criteria

Floor diaphragms shall be classified as either “flexible”, “stiff”, or “rigid”. “Flexible” when the maximum lateral deformation of the diaphragm along its length is more than twice the average inter-storey drift of the storey immediately below ($\lambda \geq 2$), “rigid” when this lateral deformation of the diaphragm is less than half the average inter-storey drift of the associated storey (

$\lambda < 0.5$) and "stiff" when the diaphragm it is neither flexible nor rigid ($0.5 \leq \lambda < 2$). In accordance with table 3 in buildings with shear walls, the T-shaped building is rigid, the L-shaped, U-shaped and rectangular buildings are semi-rigid (stiff). All of the buildings without shear walls are rigid.

4. *EUROCODE 8 [EC8] qualitative criteria*

Since all of the buildings in fig 3 have irregular geometries or divided shapes in plan, recesses, re-entrances, are classified in Class "H" structures. The diaphragm is considerd rigid, if, when it is modelled with its actual in-plane flexibility, its horizontal displacements nowhere exceed those resulting from the rigid diaphragm assumption by more than 10% of the corresponding absolute horizontal displacements in the seismic design situation, and accordance with this observation, all of the buildings with shear walls are flexible and all of the buildings without shear walls are rigid.

5. *Greek Seismic Code [GSC, 2000] qualitative criteria*

The shape of the floors in plan must guarantee the "rigid floor" diaphragm action in point of stiffness and strength. For this reason, long shapes in plan (length to width ratio ≥ 4) must be avoided, as well as plan shapes composed of long parts (L, Π, etc.) or with large re-entrances. When this is not possible, the effects of the in-plane floor flexibility to the distribution of the lateral forces at the vertical resisting elements must be taken into consideration. Since all of the structures have long rectangular interconnected parts, with aspects ratio ≥ 4, then all of the buildings with and without shear walls are flexible.

6. *Standards Association of New Zealand [NZS 4203, 1992] qualitative criteria*

When there are abrupt discontinuities, major variations in in-plane stiffness or major re-entrant corners in diaphragms, the assumption of a rigid diaphragm may not be valid. In some cases, investigation of the effects may be requiring the stiffness of the diaphragm to be modelled in the analysis to ensure that a realistic distribution of lateral force has been obtained. The qualitative criteria of this code is rather ambiguous and non-objective, because the criteria has not determinate the limit of itself. So, if the large rectangular interconnected parts suppose that are abrupt discontinuities, then all of the buildings with and without shear walls are flexible.

Table 4 indicates the classification of buildings diaphragms behavior

Building type		2800	SEAOC-90	UBC-97	FEMA-273	EC8	NZS4203	GSC-2000
Buildings with shear walls	T-shaped	Rigid	Rigid	Rigid	Rigid	Flexible	Flexible	Flexible
	L-shaped	Flexible	Rigid	Rigid	Stiff	Flexible	Flexible	Flexible
	U-shaped	Flexible	Rigid	Rigid	Stiff	Flexible	Flexible	Flexible
	Rectangular	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible	Flexible
Buildings without shear walls	T-shaped	Rigid	Rigid	Rigid	Rigid	Rigid	Flexible	Flexible
	L-shaped	Rigid	Rigid	Rigid	Rigid	Rigid	Flexible	Flexible
	U-shaped	Rigid	Rigid	Rigid	Rigid	Rigid	Flexible	Flexible
	Rectangular	Rigid	Rigid	Rigid	Rigid	Rigid	Flexible	Flexible

XII. Third Section, Investigation of the Quantitative Criteria via the Error Formula

In this section the quantitative criteria in UBC-97, SEAOC-90, 2800 and FEMA-273 via an error formula that has presented in Ju and Lin (1999) study (equation (6)). Codes quantitative criteria only differ in the limit of rigidity. The aim of this section is to answer two following questions:

1- Has the limit of quantitative criteria in the mentioned codes enough accuracy?
2- If the first question's answer is negative, what is the accurate limit?

In accordance with Ju and Lin (1999) study as mentioned, they found that the rigid-floor assumption can cause errors for building system with shear walls. A quantitative investigation is made and an error formula is presented by them (6):

$$R = \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{flexible}} \tag{5}$$

$$Error\% = 81.53R + 3.8 \tag{6}$$

They concluded that if R<0.2, then the rigid floor assumption is accurate and if R>0.4, then the flexible-floor analysis should be used to replace the rigid-floor analysis. If 0.2<R<0.4 then the structures behavior is semi-rigid.

Each code has the special criteria that are mentioned in the above sections, some use Δ_{diaph} (2800 and FEMA-273) and some use $\Delta_{flexible}$ (UBC-97 and SEAOC-90) as shown in fig. 1. In this section in first the criteria become uniform and then its efficiency is tested with (6).

UBC-97 and SEAOC-90

Diaphragm is rigid when: $\frac{\Delta_{flexible}}{\Delta_{Story}} < 2$

Diaphragm is flexible when: $\frac{\Delta_{flexible}}{\Delta_{Story}} \geq 2$

2800

Diaphragm is rigid when: $\frac{\Delta_{diaph}}{\Delta_{Story}} < 0.5 \Rightarrow \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{rigid}} = \frac{\Delta_{flexible}}{\Delta_{rigid}} - 1 < 0.5 \Rightarrow \frac{\Delta_{flexible}}{\Delta_{rigid}} < 1.5$

Diaphragm is flexible when: $\frac{\Delta_{diaph}}{\Delta_{Story}} > 0.5 \Rightarrow \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{rigid}} = \frac{\Delta_{flexible}}{\Delta_{rigid}} - 1 > 0.5 \Rightarrow \frac{\Delta_{flexible}}{\Delta_{rigid}} > 1.5$

FEMA-273

Diaphragm is rigid when: $\frac{\Delta_{diaph}}{\Delta_{Story}} < 0.5 \Rightarrow \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{rigid}} = \frac{\Delta_{flexible}}{\Delta_{rigid}} - 1 < 0.5 \Rightarrow \frac{\Delta_{flexible}}{\Delta_{rigid}} < 1.5$

Diaphragm is flexible when: $\frac{\Delta_{diaph}}{\Delta_{Story}} > 2 \Rightarrow \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{rigid}} = \frac{\Delta_{flexible}}{\Delta_{rigid}} - 1 > 2 \Rightarrow \frac{\Delta_{flexible}}{\Delta_{rigid}} > 3$

Diaphragm is stiff when: $0.5 < \frac{\Delta_{diaph}}{\Delta_{Story}} < 2 \Rightarrow 0.5 < \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{rigid}} = \frac{\Delta_{flexible}}{\Delta_{rigid}} - 1 < 2 \Rightarrow 1.5 < \frac{\Delta_{flexible}}{\Delta_{rigid}} < 3$

1. Comparison of the quantitative criteria

By comparison of the quantitative criteria in UBC-97, SEAOC-90, 2800 and FEMA-273, it is concluded that the criteria in 2800 and FEMA-273 is more conservative than UBC-97 and SEAOC-90. After the making criteria uniform, it is concluded the quantitative criteria for being rigid:

In FEMA-273 and 2800 is $\longrightarrow \frac{\Delta_{flexible}}{\Delta_{rigid}} < 1.5$

In UBC-97 and SEAOC-90 is $\longrightarrow \frac{\Delta_{flexible}}{\Delta_{rigid}} < 2$

2. Investigation of quantitative criteria accuracy

In this section we are going to answer the first mentioned question, R is obtained from (5), in accordance with 2800 and FEMA-273 codes the value of R is:

$$R = \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{flexible}} = \frac{\Delta_{flexible} / \Delta_{rigid} - 1}{\Delta_{flexible} / \Delta_{rigid}} = \frac{1.5 - 1}{1.5} = \frac{1}{3} = 0.33$$

And, in accordance with Ju and Lin (1999) study, in buildings with continuous symmetric shear walls, when R<0.2, the behavior of diaphragm is rigid, but in according to the 2800 and FEMA-273 quantitative criteria when R<0.33, the behavior of diaphragm is rigid. Thus, the quantitative criteria in building codes have not enough accuracy and they need to reform.

XIII. Reformation of Quantitative Critrria

In this section we are going to answer the second mentioned question and present an appropriate limit. If the limit of quantitative criteria for being rigid in more conservative codes (2800 and FEMA-273) is decreased to half of the former limit and then calculated the value of R, it is concluded that this suggestive limit is appropriate, because:

$$\frac{\Delta_{diaph}}{\Delta_{Story}} < 0.25 \Rightarrow \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{rigid}} = \frac{\Delta_{flexible}}{\Delta_{rigid}} - 1 < 0.25 \Rightarrow \frac{\Delta_{flexible}}{\Delta_{rigid}} < 1.25 \Rightarrow$$

$$\Rightarrow R = \frac{\Delta_{flexible} - \Delta_{rigid}}{\Delta_{flexible}} = \frac{\Delta_{flexible} / \Delta_{rigid} - 1}{\Delta_{flexible} / \Delta_{rigid}} = \frac{1.25 - 1}{1.25} = \frac{1}{5} = 0.2$$

Thus, if $\frac{\Delta_{flexible}}{\Delta_{rigid}} < 1.25$, the behavior of diaphragm in according to the codes and error formula is fully rigid and so the rigid-floor analysis is sufficiently accurate.

It should be say that in according to the study of the Busu and Jain (2004), the torsional effects may be quite significant in buildings with a flexible-floor diaphragm (in semi-rigid structures specially). Specifying of the limit for the classification of buildings to the flexible and semi-rigid diaphragm is difficult and requires to another study, thus in this study buildings are classified in rigid-floor and non-rigid-floor (include flexible and semi-rigid floor) diaphragm.

1. Reformation of UBC-97 and SEAOC-90 quantitative criteria

Diaphragms shall be considered flexible for the purposes of distribution of storey shear and torsional moment when the maximum lateral deformation of the diaphragm is more than 1.25 times the average storey drift of the associated storey. In the other word:

- Diaphragm is rigid when: $\frac{\Delta_{flexible}}{\Delta_{Story}} < 1.25$
- Diaphragm is flexible (non-rigid) when:

$$\frac{\Delta_{flexible}}{\Delta_{Story}} \geq 1.25$$

2. Reformation of 2800 and FEMA-273 quantitative criteria

Floor diaphragms shall be classified as "Flexible" when the maximum lateral deformation of the diaphragm along its length is more than quarter the average inter-storey drift of the storey immediately below, "rigid" when this lateral deformation of the diaphragm is less than quarter the average inter-storey drift of the associated storey. In the other word:

- Diaphragm is rigid when:

$$\frac{\Delta_{flexible}}{\Delta_{Story}} < 1.25 \quad \text{or} \quad \frac{\Delta_{diaph}}{\Delta_{story}} < 0.5$$

- Diaphragm is flexible (non- rigid) when:

$$\frac{\Delta_{flexible}}{\Delta_{Story}} \geq 1.25 \quad \text{or} \quad \frac{\Delta_{diaph}}{\Delta_{story}} \geq 0.5$$

XIV. Summary and Conclusions

1. All the codes generally accept that in most cases the floor diaphragms may be modelled as fully rigid without in-plane deformability. Furthermore, in order to set the conditions under which the in-plane deformability must be taken into consideration, some codes (EC8, NZS4203, GSC) set certain qualitative criteria related to the shape of the diaphragm, while some others (UBC-97, SEAOC-90, FEMA-273, 2800) set quantitative criteria relating the in-plane deformation of the diaphragm with the average drift of the associated storey.
2. The quantitative and qualitative criteria must be use with together.The quantitative criteria for classification of a floor diaphragm as "flexible", "stiff" or "rigid" (UBC-97, SEAOC-90, FEMA-273, 2800) are rather ambiguous and non-objective, because the determination of the in-plane deformations of the diaphragm depends on the forces acting on it, while these forces depend on the deformations to be determined.
3. The proposed deep-beam (EC8, SEAOC-90, FEMA-273, 2800) or plane-truss (EC8) models for the diaphragms generally contain many approximations and limitations regarding the shape, connectivity and stiffness properties of the floor diaphragms to be modelled, thus is recommended that it is better the diaphragm is analyzed in a 3D finit elements model.
4. The quantitative criteria in building codes have not enough accuracy and they need to reform.
5. The shape of the floors in plan must guarantee the "rigid floor" diaphragm action in point of stiffness and strength. For this reason, long shapes in plan (length to width ratio ≥ 3) must be avoided, as well as plan shapes composed of long parts (L, Π, etc.) or with large re-entrances, especially when the opening area is large than 50%. When this is not possible, the effects of the in-plane floor flexibility to the distribution of the lateral forces at the vertical resisting elements must be taken into consideration and the strength capacity at the weak areas of the diaphragm must be checked.

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