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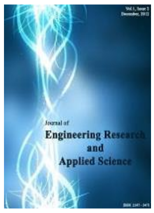

Representation of roof diaphragm in industrial buildings by hinged elastic brace pairs

M.Uzun

Karamanoglu Mehmetbey University, Civil Engineering, Karaman, Turkey.

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Abstract

Industrial buildings are generally produced as precast. During assembly, the lower end of the columns are connected to the foundation as a fixed support. However, the upper ends of the columns connecting with the roof truss are hinged joints. Therefore, large displacements occur in the building during an earthquake. In order to prevent story drifts, column sections are taken large. However, it has been observed that the roof diaphragm of the building reduces the damages in the types of damage seen in the earthquakes experienced in recent years. The issue of including the roof diaphragm in the structure during the projecting phase has gained importance. A lot of studies have been conducted on this subject in recent years. The roof diaphragm provides the horizontal structural elements to move together in the structure. In this way, excessive displacements are prevented and it is possible to reduce the internal forces acting on the structure. Due to the relative drift limits given in TBEC-2018, larger column sections are chosen in prefabricated buildings. The rigidity of the building is increased with large column sections. However, if the rigid diaphragm behavior is applied to the building, the relative drifts are already reduced in the building.

The TBEC-2018 code provides a method for transferring seismic loads from the roof diaphragm to the vertical bearing elements. In this method, the roof covering is represented by elastic brace pairs. In this study, analysis models in which a roof diaphragm is formed with rigid diaphragm, semi-rigid diaphragm and elastic brace pairs are created. The models created were compared with parameters such as natural vibration period, base shear force, and relative drift. As a result, it has been understood that the diaphragm behavior of the structures formed by elastic brace pairs is not exactly similar a rigid diaphragm. It has been observed that the diaphragm formed by the elastic brace pairs shows similarities with the semi-rigid diaphragm.

Keywords: Industrial buildings, rigid diaphragm, semi-rigid diaphragm, elastic brace pairs.

1. Introduction

In buildings, the lateral load effect such as earthquake and wind are mainly met by vertical bearing elements [1]. Slabs, which carry vertical loads in buildings and transfer them to beams and columns, also provide the transfer of lateral loads to vertical bearing elements [2]. The slabs transfer the loads that they are exposed to in-plane to the vertical carrier elements by the diaphragm behavior [3]. In-plane loads acting on the slabs force the slab like a thin beam with a very large section depth. In-plane loads are transferred to the vertical elements as shear forces without any damage due to the excessive depth of the section [4]. This shear force and seismic load must be balanced at all levels [5]. If the slabs can transfer the seismic load acting parallel to their planes to the vertical bearing elements without any deformation, they are considered as rigid diaphragms. If the slab changes shape with rigid translation, it is considered as a flexible diaphragm [6]. It is accepted that each point on the floor makes the same displacement in the rigid diaphragm assumption. In order for a slab to be accepted as a rigid diaphragm, the slab must make very small deflections under the effect of seismic load and the in-plane bending stiffness must be very large [5].

Most of the prefabricated industrial buildings in Turkey are constructed with fixed column-foundation connection, and the column top connection is hinged [7]. Therefore, rigid diaphragm formation becomes difficult in prefabricated industrial structures. It was observed that industrial buildings were damaged in the 1999 Marmara and 2011 Van earthquakes [8–10]. The seismic load acting on the building cannot be transferred to the vertical bearing elements in the hinged column connections at the upper end [11]. In

[a] Corresponding author; mehmetuzun@kmu.edu.tr

industrial buildings, in the absence of a diaphragm on the roof, the separate behavior of the frames arises [12]. However, in the examinations made after the 2011 Van Earthquake, it was observed that the roof covering in industrial buildings exhibited a rigid diaphragm-like behavior. For this reason, a proposal regarding the acceptance of diaphragm in roofing in industrial buildings is presented in the Turkish Building Earthquake Code - 2018 (TBEC - 2018) [13]. It is accepted that the roof covering is represented as pairs of hinged elastic braces at both ends. According to the acceptance, the roof diaphragm is given in Figure 1.

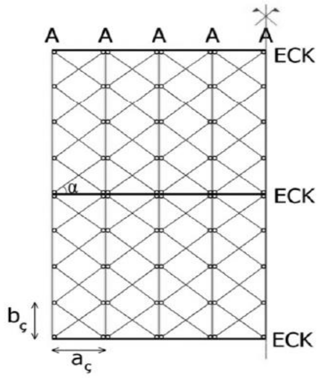


Figure 1. Representation of the roof covering by pairs of hinged elastic braces [13]

Here, ECK, A and $a_ç$ represent the roof truss, purlin and purlin spacing, respectively.
The equivalent axial stiffness of the braces representing the roof covering is calculated according to Equation 1 [13]:

$$(EA)_e = 3.5t \tag{1}$$

Here E, A and t represent the elastic modulus of the elastic brace bar, the area of the elastic brace bar and the thickness of the sheet forming the covering material, respectively.

In this study, the contribution of the diaphragm acceptance defined in TBEC - 2018 to the behavior under the influence of earthquakes in industrial buildings was examined. The behavior of the industrial building modeled in SAP 2000 program under seismic loads was compared in case of rigid diaphragm, semi-rigid diaphragm and diaphragm formation according to the method determined in TBEC-2018. [14].

2. Material and method

An industrial structure with a frame spacing of 8 m and a frame span of 21.2 m in an area of soil class ZC in Konya was investigated. The plan of the building is given in Figure 2. C30 concrete and S420 steel were used in the construction. The seismic load that will affect the building was determined by the equivalent seismic load method determined in TBEC-2018. Sandwich panel was used as roof covering in the building. The sandwich panel used was produced with painted galvanized sheet metal. Upper sheet thickness was 0.50 mm, lower sheet thickness was 0.40 mm. Coating weight was 0.1 kN/m^2. The snow load that will affect the building was taken as 0.115 kN/m^2. Columns were taken as 50x50 cm. The columns were modeled in such a way that they were fixed from the bottom and their upper ends were hinged. The roof truss and purlin beams connections of the building were accepted as hinged connections.

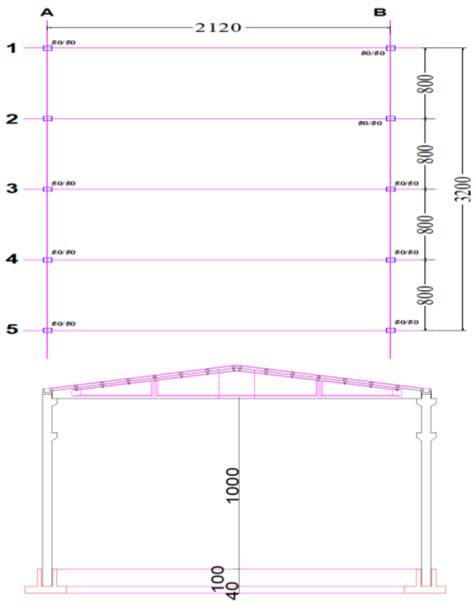


Figure 2. The plan and frame section of the industrial building (dimensions are in cm.)

Equivalent seismic load parameters used to depend on the location of the structure were given in Table 1.

Table 1. Equivalent seismic load method parameters

Parameters	Value
Ground Seismic Motion Level	DD-2
Soil Classification	ZC
Latitude	37.883887°
Longitude	32.462966°
S_S	0.312
S_1	0.074
S_{DS}	0.406
S_{D1}	0.111
PGA	0.135
PGV	6.800

The construction model was created separately for three different diaphragm states. Roof diaphragm was formed by rigid diaphragm, semi-rigid diaphragm and elastic brace pairs. In order to calculate the equivalent axial stiffness of the elastic brace pairs with Equation 1, 0.90 mm, which is the sum of the upper and lower sheet thicknesses, is taken as the coating thickness. The area of the bars was accepted as 1 mm^2 and the modulus of elasticity was found to be 3150 MPa. The building models and their features are given in Table 2.

Table 2. Building models and features

Model	Diaphragm type
M1	Rigid diaphragm
M2	Semi-rigid diaphragm
M3	Elastic brace pairs

The 3D model of the building created in the SAP 2000 program is given in Figure 3. The placement of elastic brace pairs on the roof plan is given in Figure 4.

Figure 3. Three-dimensional model of the building

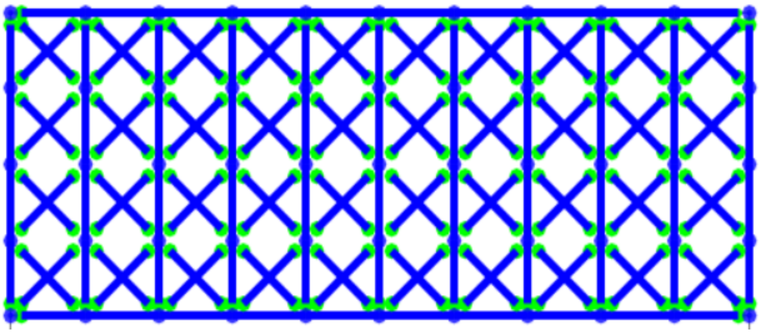


Figure 4. Elastic brace pairs defined on the roof

3. Results and discussions

In this study, analysis models were created according to different roof diaphragm formations. The natural vibration periods and mass participation rates in the x and y directions of the industrial building are given in Table 3 according to different modeling types.

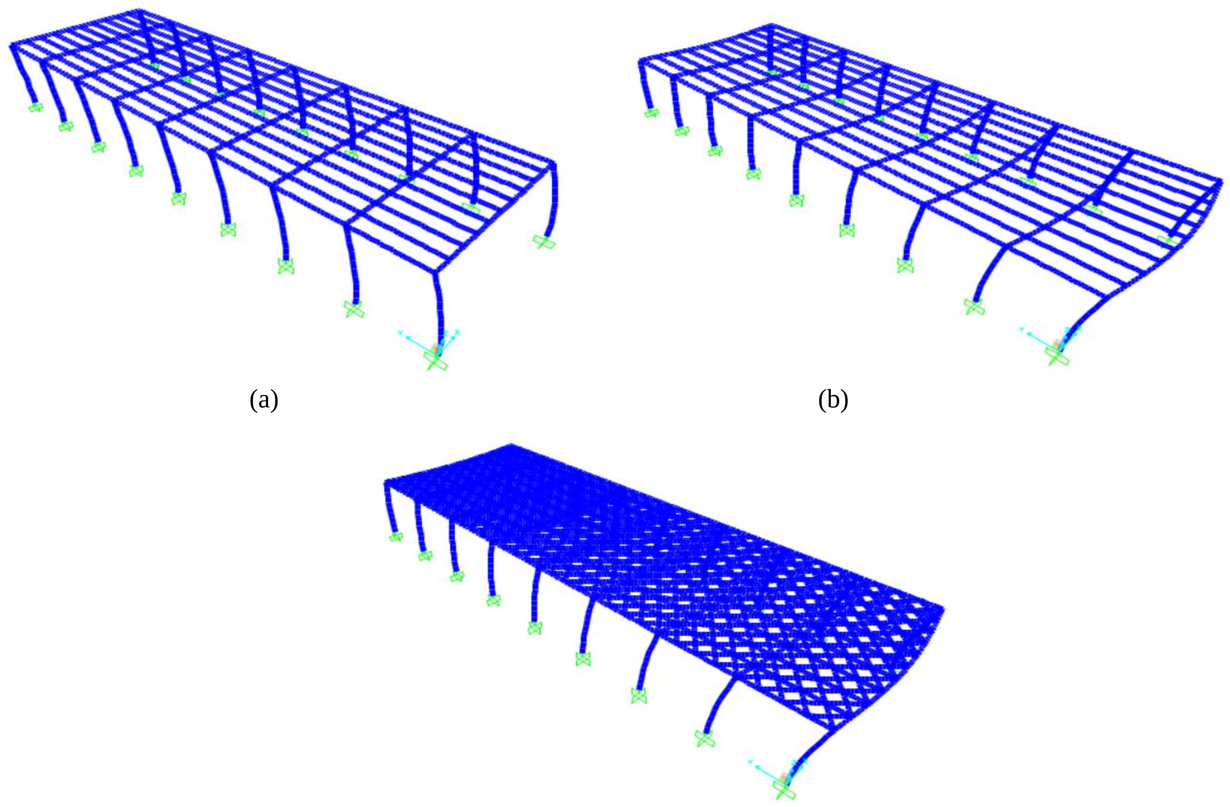
Table 3. Natural vibration periods

Model	T(s)		Mass participation ratio (%)	
	X	Y	X	Y
M1	1.80	1.81	0.99	1
M2	2.20	1.88	0.92	0.97
M3	1.86	2.10	0.95	0.98

The modal analysis results in the Y direction of the M1, M2 and M3 is given in Figure 5. The base shear reaction in the X and Y directions of the models are given in Table 4.

Table 4. Base shear reaction

Model	Base shear reaction (kN)	
	X	Y
M1	155.8	156.7
M2	150	128.2
M3	151.6	134.3

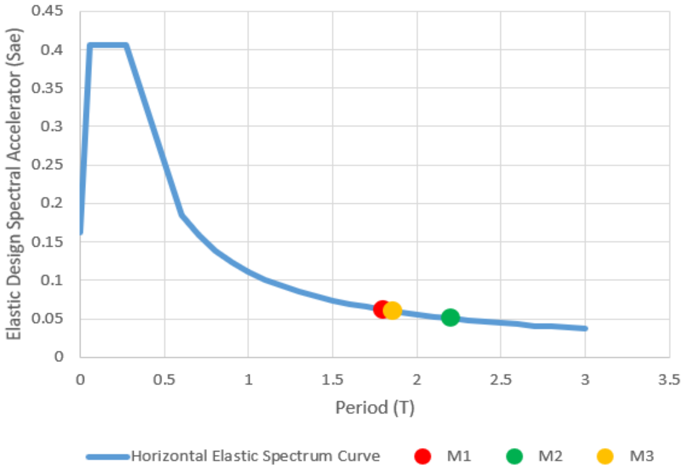


(a) (b)

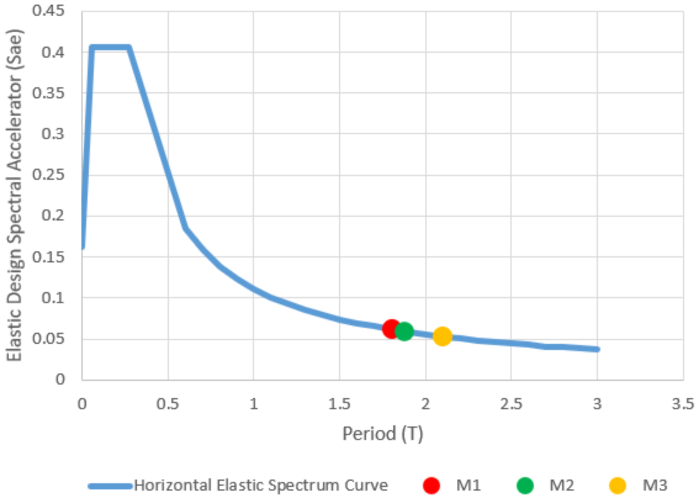
(c)

Figure 5. Mode shapes; (a) M1, (b) M2, (c) M3

As seen in Table 3, the highest natural vibration period in the X direction was obtained at the semi-rigid diaphragm. In the Y direction, the highest natural vibration period was obtained with elastic brace pairs. The fact that the building has a single span in the x direction reduces its rigidity in the x direction. Reducing the diaphragm stiffness increased the natural vibration period of the building in the x direction. In the Y direction, the natural vibration period change was small due to the large number of frames. However, the natural vibration period obtained with elastic brace pairs in the y direction was the largest. The mode shapes given in Figure 5 show the diaphragm behavior in the y direction. In the rigid diaphragm, each point on the roof slab moves together, while in the semi-rigid diaphragm and elastic brace pairs, the displacement is maximum at the middle point of the slab. Elastic brace pairs are a method closer to the actual behavior of the structure. The midpoint of the roof plane of the building under the effect of earthquake may cause more displacement and cause the roof truss to fall over. The overturning of the roof truss means that the structure collapses without any damage to the vertical bearing elements. In the earthquakes experienced in the past years, similar collapse events have occurred in industrial structures. Therefore, it is necessary to take the necessary precautions on the roof plane. When the mass participation rates given in Table 5 are examined, it is seen that the high mass participation rates are in Mode 1 and 2. In this case, it can be said that the building has a regular shape. In a structure without irregularities, the mode mass participation rates increase in Mode 1 and 2. The fact that the mass participation ratios of the building are high in 1 and 2 Modes show that the equivalent seismic load method is applicable. When the base shear forces acting on the building are examined, it is seen that less base shear forces act on the model created with elastic brace pairs. Due to the high natural vibration period of the building, the design spectral acceleration decreases as the period increases. As seen in Figure 6, the design spectral acceleration affecting the building is in the tail region of the graph. Therefore, as the natural vibration period increases, the design spectral acceleration decreases.



(a)



(b)

Figure 6. Elastic design spectral acceleration curves; (a) x direction, (b) y direction

Table 5. Modal analysis results (mass participation ratios)

Mode	M1				M2				M3			
	Period (s)	UX	UY	UZ	Period (s)	UX	UY	UZ	Period (s)	UX	UY	UZ
1	1.81	0.99	0	0	2.20	0	0.97	0	2.10	0.00	0.98	0
2	1.80	0	1	0	1.88	0.91	0	0	1.86	0.95	0	0
3	1.40	0	0	0.75	1.71	0.004	0	0	1.64	0.01	0	0
4	1.38	0.01	0	0	1.52	0.05	0	0	1.40	0.00	0	0.8
5	1.20	0	0	0.007	1.40	0.000	0	0.75	1.38	0.04	0	0
6	0.97	0	0	0.020	1.36	0.002	0	0	1.20	0.00	0	0.1
7	0.80	0	0	0.001	1.24	0.02	0	0	1.18	0.002	0	0
8	0.68	0	0	0.003	1.20	0.000	0	0.007	1.03	0.01	0	0
9	0.60	0	0	0.001	1.16	0.002	0	0	0.97	0.00	0	0.1
10	0.55	0	0	0.001	1.11	0.004	0	0	0.94	0.00	0	0
11	0.52	0	0	0.001	1.06	0.004	0	0	0.87	0.00	0	0
12	0.44	0	0	0.001	0.97	0.00	0	0.020	0.86	0.001	0	0

The most important problem is that the displacements are excessive in the industrial buildings built with top-hinged and bottom-fixed columns. Therefore, in TBEC-2018, conditions regarding the limitation of relative storey drifts have been introduced. In Equation 2 and Equation 3, the relative storey drift limit in TBEC-2018 is given.

$$\delta_i = \frac{R}{I}\Delta_i \quad (2)$$

$$\lambda\frac{\delta_i}{h_i} \leq 0.008\kappa \quad (3)$$

Here, δ_i, R, I, Δ_i, λ, h_i and κ represent effective relative storey drift, structural behavior coefficient, building importance coefficient, relative story drift, the ratio of the elastic design spectral acceleration calculated for DD-3 to the elastic design spectral acceleration calculated for DD-2, building height and a coefficient taken as 1 for reinforced concrete buildings, respectively. The required values for the relative storey drift controls are given in Table 5.

Table 5. Required parameters for relative storey drift controls

Model	Δ_i (mm)		R	I	h_i (m)	δ_i(mm)		$(S_{ae})_{DD-2}$		$(S_{ae})_{DD-3}$	
	X	Y				X	Y	X	Y	X	Y
M1	17.8	16.9	3	1	10	53.4	50.7	0.0617	0.0613	0.0233	0.0232
M2	18.1	23.3	3	1	10	54.3	69.9	0.0505	0.0590	0.0191	0.0223
M3	18.2	21.9	3	1	10	54.6	65.7	0.0597	0.0529	0.0226	0.0200

As seen in Table 6, the relative storey drift values are below the limit value in all models. This indicates that the second-order effects are negligible. The displacement behavior and mode shapes of the diaphragm formed by the elastic brace pairs are similar to the semi-rigid diaphragm.

Table 6. Relative storey drift controls

Model	λ		$\lambda\frac{\delta_i}{h_i}$		Control
	X	Y	X	Y	
M1	0.378	0.378	0.002019	0.001917	≤ 0.008
M2	0.378	0.378	0.002053	0.002642	≤ 0.008
M3	0.378	0.378	0.002064	0.002484	≤ 0.008

4. Conclusions

In this study, seismic analysis of an industrial building with fixed lower end and hinged upper end of column was carried out. Three different diaphragm types were selected for the roof diaphragm. The results obtained with the analyzes for each model are given below:

- The definition of a rigid diaphragm in the roof plane reduces the natural vibration period of the building. However, since there are large spans in industrial buildings and the upper ends of columns are hinged, the natural vibration periods are very large. Since the period values remain in the tail region in the elastic design spectral acceleration curve of the building, an increase in the period value increases the elastic design spectral acceleration value.
- Parameters such as natural vibration period, mode shapes and base shear force show similar behavior with semi-rigid diaphragm in the model with elastic braces pairs on roof diaphragm. However, it will be possible to obtain more unfavorable results in the case of torsion or any irregularity in the building behavior.
- The absence of irregularities in the building model used contributed positively to the behavior of the building. However, the differences between the results obtained in buildings with irregularities will increase.

Creating a roof diaphragm with elastic brace pairs seems to be a applicable method to obtain realistic results.

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