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Investigation into diaphragm flexibility using shear wall

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Professional paper

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The diaphragm stiffness has a significant influence on the structural responses. Typically engineers assume those diaphragm are rigid. This assumption decreases the degree of freedom and provides easier analysis. But diaphragm damages in past earthquakes, due to its flexibility, have attracted researchers toward the diaphragm behaviour. In order to investigate this behaviour, in this study single storey RC structure was considered (four frame models using ETABS2000 and LUSAS) to calculate optimum ratio between diaphragm deflection and storey displacement. The diaphragm ratio with lower 0.5 should be considered as rigid.

Key words:
Diaphragm, flexibility, optimum ratio, storey displacement, diaphragm deflection

Stručni rad

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Utjecaj poprečnih zidova na popustljivost stropne ploče

Krutost stropne ploče ima značajan utjecaj na odgovor konstrukcije. Uobičajena je pretpostavka da se radi o krutom elementu. Ovakva pretpostavka smanjuje stupanj slobode i osigurava lakšu analizu. No, tijekom posljednjih potresa, popustljivost stropne ploče privukla je znatiželju znanstvenika. Kako bi se istražilo njeno ponašanje, u ovom radu analizirana je jednokatna armiranobetonska konstrukcija. Analiza je provedena na četiri okvirne konstrukcije, a primjenom računalnih programa ETABS2000 i LUSAS je izračunat optimalni omjer između popustljivosti stropne ploče i pomaka konstrukcije. Analiza je pokazala da se kod omjera manjeg od 0,5 stropne ploče mogu razmatrati kao kruti element.

Ključne riječi:
stropna ploča, popustljivost, optimalni odnos, pomak kata, progib ploče

Fachbericht

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Einfluss von Querwänden auf die Flexibilität von Deckenplatten

Die Steifigkeit von Deckenplatten hat einen bedeutenden Einfluss auf das Verhalten des Tragwerks. Normalerweise wird ein steifes Element vorausgesetzt; diese Annahme vermindert die Anzahl der Freiheitsgrade und ermöglicht einfachere Analysen. Aufgrund von Beschädigungen im Laufe der letzten Erdbeben, hat die Flexibilität von Deckenplatten jedoch die Aufmerksamkeit der Forschung auf sich gezogen. Um das entsprechende Verhalten zu untersuchen, wird in dieser Arbeit eine einstöckige Stahlbetonkonstruktion analysiert. Dazu sind mittels der Programme ETABS und LUSAS vier verschiedene Rahmenkonstruktionen betrachtet und optimale Verhältnisse zwischen der Flexibilität der Deckenplatte und der Stockwerksverschiebung berechnet worden. Die Analysen haben gezeigt, dass bei einem Verhältnis unter 0,5 die Deckenplatten als steife Elemente betrachtet werden können.

Schlüsselwörter:
Deckenplatte, Flexibilität, optimales Verhältnis, Stockwerksverschiebung, Deckendurchbiegung

1. Introduction

A ratio between diaphragm deflection and storey displacement is investigated in this paper. This ratio is very important in civil engineering calculation, and especially in frame structure modelling. The diaphragm stiffness consists of the out-of-plane and in-plane stiffnesses. Based on the in-plane stiffness criterion, the diaphragm can be modelled as a rigid body or flexible body. Engineers commonly assume that these diaphragm floors are rigid bodies because this assumption decreases the degree of freedom and enables easier analysis. The calculation of structural mode shapes with the rigid diaphragm assumption in seismic codes is yet another evidence pointing to the importance of this criterion [1].
However, the diaphragm damage incurred during past earthquakes has attracted researchers to investigate the in-plane diaphragm behaviour. Saffarini and Qudaimat [2] established that the rigid-diaphragm assumption in bare systems (buildings without shear wall) is acceptable, but that it can cause problems and errors within dual systems (buildings with shear wall). Ju and Lin [3] also confirmed this statement. Moeini et al. [4] demonstrated that the rigid-diaphragm assumption is sufficient in buildings without shear walls (regular and irregular).
Bhuiyan and Leon [5] evaluated the effect of diaphragm flexibility on the response of tall buildings and established that tall buildings with flexible diaphragms absorb higher accelerations (displacements) and that, consequently, their natural periods are also longer. In this regard, Fleischman et al. [6] found that the plasticity of flexible diaphragms is generated at lower storey level diaphragms due to their deformation demands.
Hadianfard and Sedaghat [7,] studied nonlinear responses of braced steel buildings with flexible diaphragms (concrete block-joist floor) and demonstrated that the span ratio is an important parameter for diaphragm flexibility (if the ratio exceeds three, the flexibility assumption cannot be ignored).
Through establishment of simple relationships, Sadashiva et al. [8] demonstrated that displacement of structures is significantly affected by diaphragm flexibility. Using the proposed formulas, designers can estimate the in-plane displacement with regard to diaphragm flexibility condition.

All methods for studying the in-plane diaphragm behaviour can be classified into two groups: qualitative criteria, e.g. EN 1998-1 [9], and quantitative criteria, e.g. FEMA 273 [10]. According to EN 1998-1, the diaphragm should be modelled according to the actual in-plane flexibility. In other words, if the horizontal displacement of the rigid diaphragm exceeds 10 % of the allowed horizontal displacement, then the diaphragm is considered to be rigid. On the other side, FEMA 273 divides diaphragms into three groups; flexible, stiff, and rigid, as shown in Table 1 (Figure 1).

Table 1. FEMA 273 Diaphragm flexibility classification

Diaphragm flexibility	Limitations
Rigid	$\frac{D_{Diaphragm}}{D_{Story}} < 0,5$
Stiff	$0,5 \leq \frac{D_{Diaphragm}}{D_{Story}} \leq 2$
Flexible	$2,0 < \frac{D_{Diaphragm}}{D_{Story}}$

The above introduction shows that the flexibility of diaphragms is one of the most important structural criteria that should not be neglected by designers. Although they are used in some design standards, limits above 0.5 and 2 have still not been established, and so further research is needed in this area.

1.1. Modelling features

A single storey RC structure with four columns is considered in this study in order to investigate the in-plan deflection of diaphragm, and a relative optimum ratio (OR) between the diaphragm displacement ($D_{Diaphragm}$) and the maximum storey displacement (D_{Storey}). The study involves the modelling and analysis of four models (3D frame with diaphragm): 3 by 3 meter span, 3 by 6 meter span, 3 by 6 meter span, associated with the partial shear wall, and 3 by 6 meter span

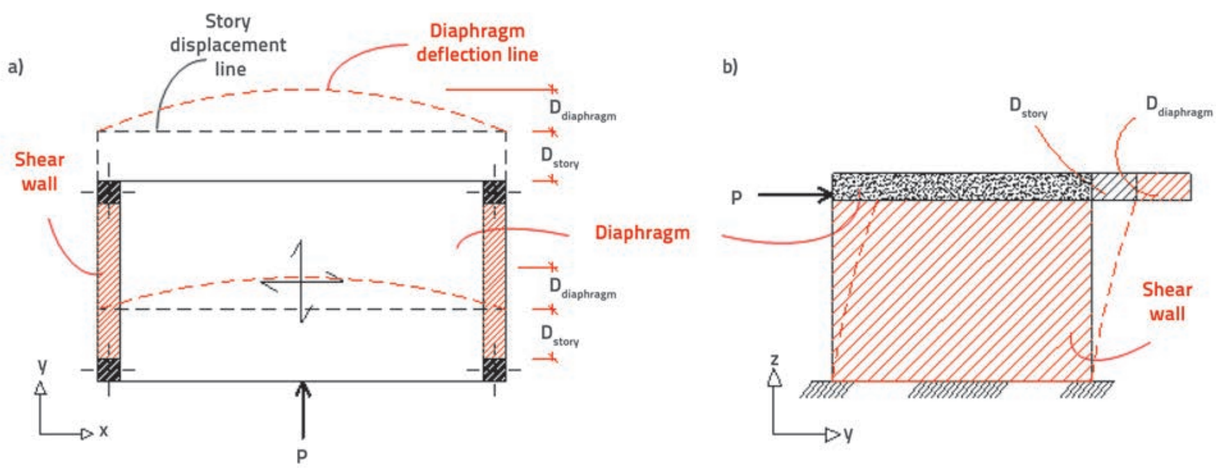

Figure 1. Exaggerated in-plane deflection of diaphragm: a) structure in plan view; b) elevation view

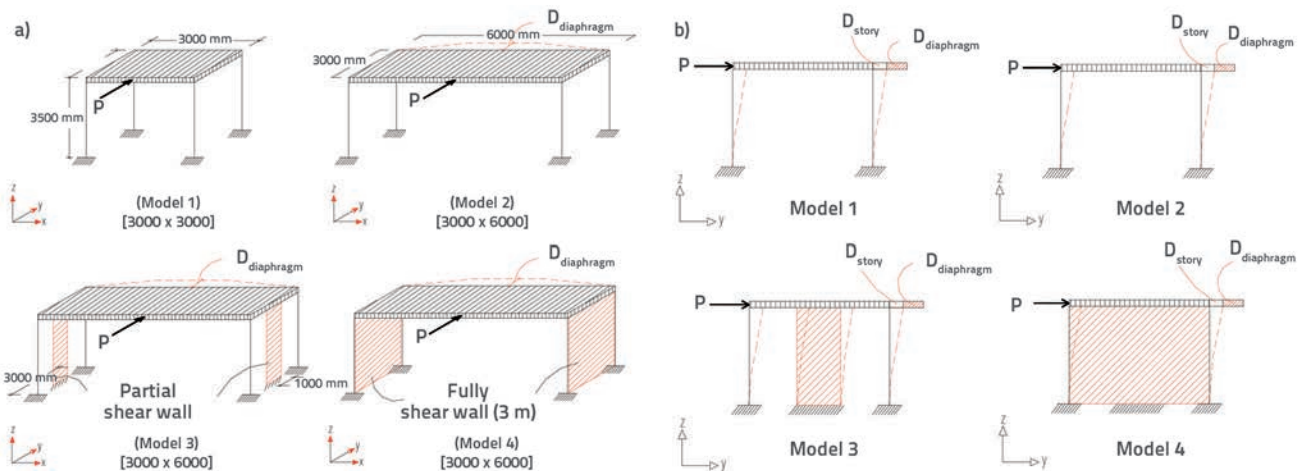

Figure 2. Models without shear walls, with partial shear walls, and with full shear wall: a) 3D view of models; b) lateral view of models

Table 2. Seismic base shear coefficient

Code	Items	Parameters	Amount of items	
			Bare system	Dual system
Earthquake load EN 1998-1:2004	Ground acceleration	a_{gr} = 3,45 m/s^2	a_g = 3,45	a_g = 3,45
	Importance factor	γ_τ = 1,0 (table 4.3)		
	Soil factors (Type 1)	Ground type = B		
		S = 1,2		
		T_B = 0,15		
		T_C = 0,5		
		T_D = 2,0		
	Fundamental period of vibration	H = 3,50 m	**T_1 = 0,192 s**	**T_1 = 0,127 s**
		C_t = 0,075 (concrete moment frame)		
		C_t = 0,05 (dual system)		
		T_1 = Ct,H3/4		
	Behavior factor	a_u/a_1 = 1,1 (5.2.2.2)	q = 3,3	q = 3,3
		q = 3 a_u/a_1 (table 5.1)		
	Design spectrum	$T_B < T_1 < T_C$	$S_d(T_1)$ = 3,13	$S_d(T_1)$ = 3,08
		$S_d(T) = a_g S(2,5/q)$ (bare system)		
		$S_d(T) = a_g S\,[2/3 + T_1/T_B(2,5/q - 2/3)]$ (dual system)		
		β = 0,2		
	Correction factor	$T_1 < 2T_C$	λ = 0,85	λ = 0,85
	Seismic base shear factor	$C = S_d(T1)\lambda$	**c = 0,0521**	**c = 0,0339**
		C = 0,51		
		c = C/9,81 (ETABS)		

associated with the full shear wall. The thickness of the slab and shear wall is 150 mm, and the beam and column measure 250 x 300 mm and 350 x 350 mm, respectively. The beam bars and column bars are 6ϕ16 (6 bars 16 mm in diameter) and 8ϕ16, respectively.

The numerical analysis was conducted to measure the optimum ratio between the maximum diaphragm deflection and the maximum storey displacement. The ETABS2000 software was used to calculate the maximum storey displacement, and the LUSAS software was used to calculate the maximum diaphragm deflection. The models (frames) were subjected to horizontal seismic load according to EN 1998-1. It was assumed that all models are located in an earthquake prone area (Figure 2). Table 2 shows procedures that are needed to calculate the seismic base shear factor for RC bare frames and dual systems (for all models) according to EN 1998-1. Material specifications are as follows:

f_c = 30 N/mm^2 (B-300), f_y = 400 N/mm^2 (A-III), f_{ys} = 400 N/mm^2 (A-II)

1.2. Modelling strategy

It is important to emphasize once again that diaphragms transmit inertial forces from the floor system to vertical elements up to the limit of their strength [11], and that they link vertical elements together [12] thus providing the strength and stiffness to the in-plane floor (diaphragm action) [13]. In previous studies, various methods were used for diaphragm modelling. These methods can be categorised into two groups: three-dimensional modelling (using shells and plate elements) [14], and beam element modelling [12]. The second method seems to be much simpler for modelling and use. Diaphragms can be modelled as deep beams in horizontal direction [12, 15]. The deep beam modelling (Figure 3) was implemented in this paper. This is a simplification from Figure 1.a.

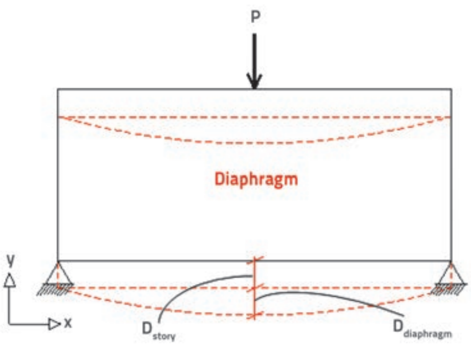

Figure 3. Deep beam modeling (simplified Figure 1.a)

2. Methodology

As indicated in the introduction, the current study involves modelling and analysis of four models, the purpose being to determine the relationship between $D_{Diaphragm}$ and D_{Storey}. According to Figure 4, two important structural factors (geometry and system) were mixed in order to achieve the objective of this study: different diaphragm sizes (Models 1 and 2) and shear wall effect (Models 3 and 4).

When one storey of the building is subjected to lateral load, such as in Model 1 (Figure 4.a), then it can be moved in the y direction. In this paper, the stiffness of columns and shear walls serves as a protection against horizontal structural displacements. The proposed numerical method assumes that the diaphragm deflection ($D_{Diaphragm}$) will start once the maximum storey displacement (D_{Storey}) is reached. Consequently, it can be simplified and divided into two deflection parts, which can be calculated separately. One is the maximum value of storey displacement (before slab deflection), and the other one is the diaphragm deflection. This means that the storey deflection is calculated in the first stage, while two pined supports are assumed for diaphragm in the second stage. Thus, the behaviour of diaphragm is regarded as behaviour of a deep beam (Figure 4.b) and, in this way, the beam deflection is obtained. The ETABS2000 was used to calculate and show the amount of earthquake load (P in the Figures) and lateral displacement (D_{Storey}), whereas the LUSAS software was utilised to analyse the diaphragm so as to obtain diaphragm deflection ($D_{Diaphragm}$). For this purpose, the ETABS uses the seismic base shear factor as illustrated in Table 2. According to the modelling strategy section, the deep

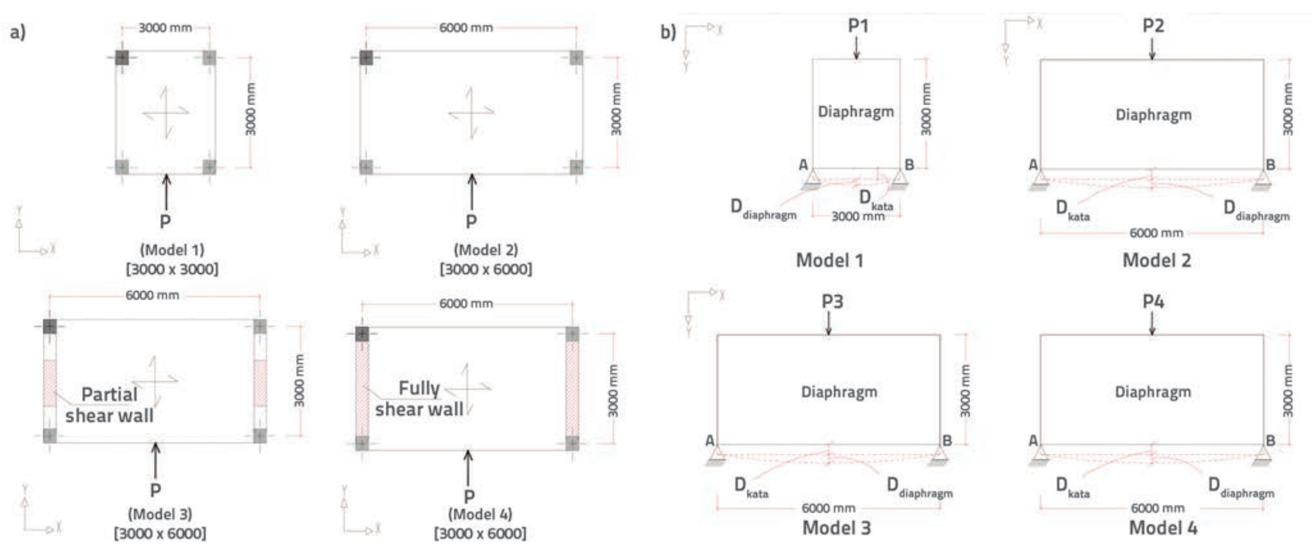

Figure 4. Deep beam modelling strategy justification: a) plan view of the models; b) conversion of diaphragm to deep beam diaphragm

beam modelling was used for each model (Figure 4). So first the loads (P1, P2, P3 and P4) were obtained from the ETABS2000, and then the obtained values were applied to each relevant deep beam model in order to calculate $D_{Diaphragm}$. Every deep beam gives its own deflection in terms of meshing method used. D_{Storey} and $D_{Diaphragm}$ were tabulated in order to calculate the absolute ratio ($D_{Diaphragm}$/D_{Storey}). After that, the results were presented in form of a line chart and, finally, this diagram was used to calculate the OR.

3. Results and discussion

Every earthquake load (P_i) was obtained by the ETABS 2000 as follows and as shown in Figure 5.

model 1: P_1 = 9,71 kN, model 3: P_3 = 12,02 kN,
model 2: P_2 = 16,32 kN, model 4: P_4 = 14,81 kN.

Storey displacements $\mathbf{D}_{Storey}$ are summarized in Table 3.

Table 3. Maximum storey displacement according to ETABS

Models	Model 1	Model 2	Model 3	Model 4
$\mathbf{D}_{storey}$ [mm]	0,47600	0,74200	0,03800	0,00600

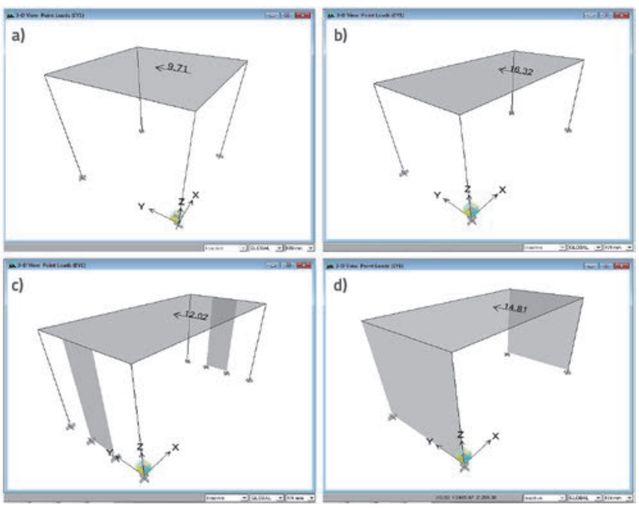

Figure 5. Earthquake point load (EY) of one storey structure in ETABS2000; a) Model 1; b) Model 2; c) Model 3; d) Model 4

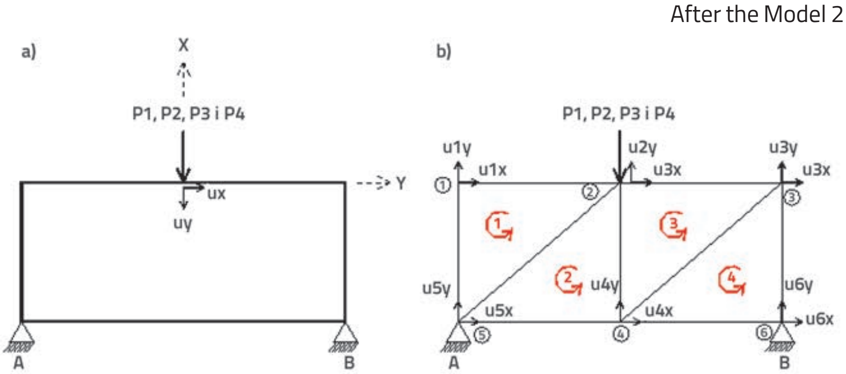

Figure 6. Finite element specification: a) load position and displacement convention; b) linear triangle meshing method

According to Figure 6, when the diaphragm (as a deep beam) is subjected to the obtained loads P_1, P_2, P_3 and P_4 (from the ETABS results), the maximum displacement values are calculated using the Finite Element Software (LUSAS). These values are listed in Table 4 with respect to the Finite Element Meshing Method (real diaphragm behaviour is obtained through a finer mesh). Figure 5.b shows an example of discretisation via linear triangular elements (discretisation with 4 linear triangular elements).

Table 4. Maximum diaphragm displacement ($D_{Diaphragm}$) at load position according to LUSAS

Models		Model 1	Model 2	Model 3	Model 4
$\mathbf{D}_{Diapragm}$ [mm]	Linear Quad with 112 elements	0,01236			
	Linear Quad with 128 elements		0,04891	0,03601	0,04438

All ratios are calculated in Table 5, and the corresponding data are shown in Figure 7 (OR between diaphragm deflection and storey displacement), which fulfils the objective of this paper.

Table 5. $D_{Diaphragm}$ and D_{Storey} ratio

Models	$D_{Diapragm}$	D_{Storey}	$D_{Diapragm}/D_{Storey}$
Model 1	0,01236	0,47600	**0,03**
Model 2	0,04891	0,74200	**0,07**
Model 3	0,03601	0,03800	**0,95**
Model 4	0,04438	0,00600	**7,40**

The OR ratio for each model is shown in Figure 7. It can be seen from this figure that the ratio increases only marginally (from 2.6 % to 6.59 %) from Model 1 to Model 2 (without the shear wall). After the Model 2 the curve steepens dramatically from Model 2 to Model 3 with a partial shear wall (from 6.59 % to 94.76 %). It is assumed that such significant change is due to the flexibility factor and use of shear wall (as a robust support for diaphragm), which is why the diaphragm is more flexible than the bare frames. It can therefore be concluded that the criterion OR is the limit between these two models (Model 2 and Model 3). This OR value is an average between the Model 2 ratio and the Model 3 ratio, as shown below:

$$OR = \frac{6,59\%+94,76\%}{2} = 50,67\% \cong \mathbf{50\%}$$

The amount of 50 % or 0.5 is taken as an optimum ratio between the diaphragm deflection and storey displacement using the shear wall. The diaphragm with a lower ratio should be considered as rigid, while diaphragms with the ratios of more than 50 % are considered as flexible. Although this investigation has been extended with respect to FEMA 273, which is summarized in Table 1 (first raw), further study is needed to identify other classifications in the table (stiffness and flexibility).

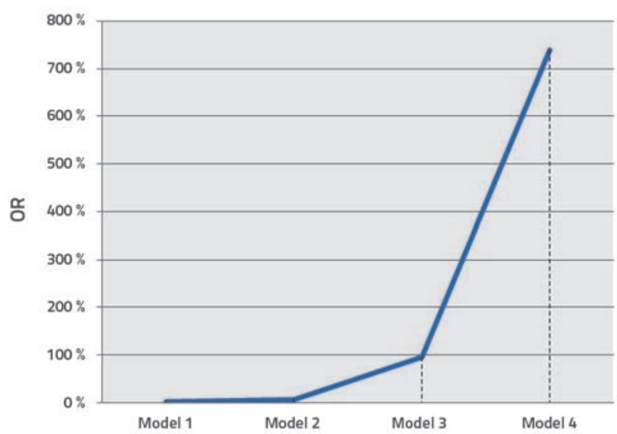

Figure 7. $D_{Diaphragm}$ and D_{Storey} ratio (OR)

4. Conclusion

Prior work documents the influence of flexibility on diaphragm behaviour and, as outlined in the introduction, there are even some significant classifications in seismic codes. However, these studies have either been prescriptive guidance documents, or are not focused on measurement of these limits. In this study, this problem is addressed by means of a simple procedure using four different models (different bays, i.e. 3by3 and 3by6) and systems (with and without shear wall).

It is assumed in this study that a frame is subjected to lateral load while, virtually, columns and shear walls are considered as diaphragm supports. The diaphragm deflection $D_{Diaphragm}$ starts after the maximum storey displacement D_{Storey}. Consequently, the D_{Storey} and $D_{Diaphragm}$ can be calculated separately, and the $D_{Diaphragm}$ is assumed to be a deep beam with two supports. The ETABS2000 is used to calculate earthquake loads and D_{Storey}, and the LUSAS software is used to analyse the diaphragm so as to obtain $D_{Diaphragm}$. Once all deflections are summarized in a table, the (OR = $D_{Diaphragm}/D_{Storey}$) ratio can easily be calculated for each frame.

The main conclusion obtained by numerical analysis presented in this paper is that the optimum ratio between the diaphragm deflection and storey displacement using shear wall can be taken as 0,5. A diaphragm with a lower ratio should be considered as rigid. Although our hypotheses were supported by four different frame configurations, maybe the statistical analysis results would be different under different conditions. Future work should therefore include studies under different conditions (spans and stories) and with different limits (stiffness and flexibility).

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