Bracing/Unbracing Classification of RC Frame Buildings via First Order Analysis

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© Umm Al-Qura University Journal for E & A, Vol.10 Issue No.1, pp.1-20 April 2019

Under Legal Deposit No. ***p- ISSN:*** *1658-4635 /* ***e- ISSN:*** *1658-8150*

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تصنيف المنشآت الخرسانية ذات الإطارات من حيث مقيدة/ غير مقيدة باستخدام التحليل المرن من الدرجة الأولى

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الملخص:

المنشآت ذات الإزاحة هي التي تتعرض لإزاحة جانبية مؤثرة. يتم تعريف الإزاحة الجانبية المؤثرة وفقًا للكود الأمريكي ACI 318-14، على أنها الإزاحة التي تتسبب في زيادة العزوم الناتجة من إزاحة نهايات الأعمدة بنسبة ٥٪ أكبر من عزوم الانحناء المقدرة على هذه الأعمدة في حالة تجاهل هذه الإزاحة. يعتبر التحليل المرن من الدرجة الثانية هو الأداة الواضحة المستخدمة لتحديد ما إذا كان المبنى مقيداً أو غير مقيد. في بعض الحالات يمكن تصنيف المبنى على أنه مقيد أو غير مقيد بفحص إذا كان هيكل المبنى به عناصر داعمة واضحة مثل حوائط القص، أو جمالونات القص، أو أنواع أخرى من الدعامات الجانبية.

في هذه الورقة البحثية تم تطوير إجراء تقريبي موضوعي يستخدم تحليل المرونة من الدرجة الأولى لتحديد ما إذا كان الدور، داخل مبنى هيكلي ذو إطار، مقيداً أو غير مقيد. تم تقديم العديد من الأمثلة للتحقق من النهج المقترح وإظهار بساطته في تصنيف الإطارات ذات الإزاحة كإطارات مقيدة أو غير مقيدة. حيث بينت نتائج البحث على أن النهج المقترح دائمًا ما يكون في الجانب الآمن وفي بعض الحالات يكون متحفظاً.

الكلمات المفتاحية: خرسانة مسلحة، منشآت هيكلية ذات إطارات، حوائط خرسانية، مباني مقيدة وغير مقيدة، تحليل من الدرجة الأولى، تحليل من الدرجة الثانية.

Abstract:

A sway structure is one where side sway is likely to be significant. According to the ACI 318-14, the significance is defined as a situation where lateral displacement at the ends of the columns increases the critical bending moments by more than 5% above the moment calculated ignoring these displacements. A second order elastic analysis is an obvious tool to determine if a structure is braced or unbraced. In some cases, a structure can be classified as braced/unbraced by inspection if the structure has obvious bracing elements such as shear walls, shear trusses, or other types of lateral bracing.

In this paper, an objective approximate procedure utilizing first order elastic analysis has been developed to determine if a story, within a framed structure, is braced or unbraced. Several examples are presented to verify the proposed approach and to show its simplicity in classifying sway frames as braced/unbraced. The results from the proposed approach are always on the safe side.

Keywords: Reinforced concrete, Frame buildings, Shear walls, Bracing/unbracing, First order elastic analysis, Second order analysis.

1. INTRODUCTION:

A structure may be considered braced against side sway if the lateral loads in the direction under consideration are resisted by a lateral load-carrying member or members (such as shear walls, elevator shafts, or other types of lateral bracing) extending from the foundation to the upper end of the structure. In such a structure, the lateral drift of the columns is very small and its effect can be neglected. A frame structure is considered unbraced if the frame itself resists the lateral load effects (Pillai and Kirk [2]). In reality, frame structures are seldom fully braced or completely unbraced and, in many applications, it is impossible to ascertain by inspection whether a story is braced or unbraced. Basically, whether a structure is braced or unbraced will depend on its stiffness against lateral deformation. To evaluate lateral drift effects, the ACI 318-14 [1] defines a braced compression member as a member within a story in which horizontal displacements do not significantly affect the moments in the structure. Numerically, a column in a story is considered braced against side sway if the second order moments (P-Δ moments) do not exceed 5% of the moments obtained from the first-order analysis of that story. The EC-2 [3] follows the same approach as the ACI 318-14 [1] and considers a column to be unbraced if the lateral displacement of the column ends increases the critical bending moments by more than 10% above the moments calculated from first-order analysis.

If the structure is classified as braced against side sway, it is unnecessary to perform nonlinear analysis that accounts for geometric nonlinearity. In the meantime, the classification of a structure as braced or unbraced can only be performed through conducting second order analysis, whereas the objective is to establish when second order analysis is unnecessary. In this paper, a more objective approach, based on first-order analysis, is developed to classify a story within a framed structural system into braced or unbraced without the need to perform a second order analysis.

Dario [4] presented a numerical method to investigate the minimum stiffness of the lateral bracing system required to achieve a non-sway buckling condition. The modified stability functions are applied to derive a numerical equation for evaluating the minimum stiffness for the lateral bracing structures and the corresponding buckling load for columns. The columns' layout in the plan and the shear deformations along columns presented by Timoshenko and Gere [5] are considered in his study. Dario [4] concluded that the minimum stiffness of the lateral bracing system is influenced by the geometric properties, shear stiffness, flexural stiffness, axial load, sizes, and end conditions of the columns. The proposed method is verified by numerous examples of framed buildings.

Nauman and Nazrul [6] studied the behavior of multistory reinforced concrete structures with different types of a bracing system using a software approach. The study considered the bracing system to be an effective retrofitting technique for multistory framed structures subjected to severe lateral loads in seismic or windy zones. The study concludes that compared to other bracing systems, the steel cross-bracing system has both economic and practical advantages. The overall mass of the building will not increase significantly after applying the steel cross-bracing system. The software analysis of the structure with different sorts of bracing systems shows a significant reduction in lateral deformations after adding the bracing system. By adding a cross-bracing system, the shear force and bending moments in columns are reduced along with the lateral load transferred to the foundation through axial action.

In codes of practice and available methods in literature, the determination of bracing conditions of RC frame structures essentially relies on performing second order analysis by considering geometric nonlinearity. The efforts encountered in such analysis or the availability of suitable software are sometimes beyond the capacity of design engineers. Therefore, the practical and simplified approach presented in this paper, to investigate if a story in RC framed structures is braced or unbraced, is significant and of practical use in design.

2. PROPOSED APPROACH:

2.1 Concepts and Assumptions:

According to the Egyptian Code of Practice for Reinforced Concrete Structures (ECP 203-17) [7], a building is classified as a braced structure if it has a lateral load-supporting wall distributed symmetrically in the horizontal plan as well as continuous in all stories of the building. Additionally, the building bracing index (α) should satisfy the following equations.

For buildings with four stories or more,

$$\alpha = H_b\sqrt{\frac{N}{EI}} \; < \; 0.6 \qquad (1a)$$

where H_b is the total height of the building, N is the summation of total working loads on all the vertical members, E is the modulus of elasticity of concrete, and I is the effective moment of inertia of the wall cross-section resisting the moment for the direction into consideration.

For buildings with several stories (n) less than four stories,

$$\alpha = H_b\sqrt{\frac{N}{EI}} \; < \; 0.2 + 0.1n \qquad (1b)$$

The same concept was introduced in DIN 1045-1 [8] for the nearly symmetrical layout of vertical stiffening elements. These stiffening elements or a building with these bracing elements must have sufficient stiffness to resist all the horizontal forces acting on the structure and to transfer them to the foundations.

The basic concept of the proposed approach is based on finding a flexural rigidity of the framed structural system equivalent to a cantilever shear wall system. This equivalent rigidity can be utilized in Eq. (1) to determine if the system is braced or not.

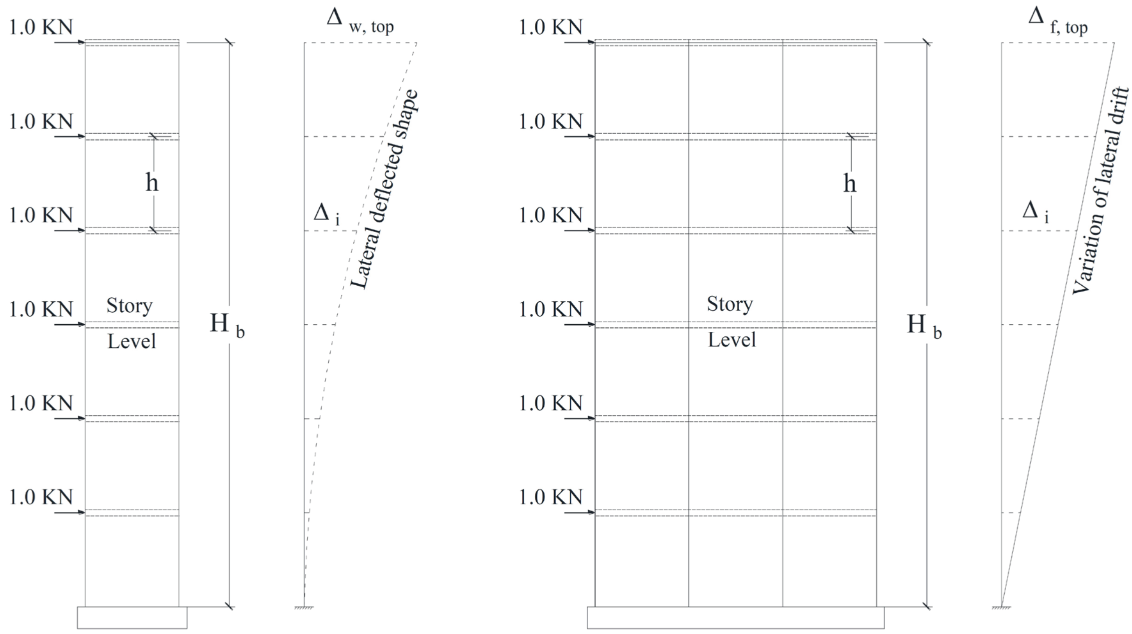
The lateral displacement of the equivalent shear wall system is obtained by applying 1.0 kN as a lateral force in each story. The lateral displacement of the structural frame system against 1.0 kN force at the slab level of each story is obtained from first order elastic analysis using a suitable finite element software. Since the framed system and the equivalent shear wall should have the same P-Δ effect, the equivalent flexural rigidity for the framed structural system is obtained by equating the average lateral displacement of both systems.

For simplicity, the following assumptions are proposed.

- All floors are identical in geometry and carry the same lateral load intensity.
- All stories have the same height.
- In frame analysis, the effective moment of inertia is the gross moment of inertia (I_g) multiplied by 0.35 and 0.7 for beams and columns, respectively.
- The P-Δ effect is a function of gravity loads and lateral displacement.

2.2 Deflected Shape

The equivalent shear wall system and its lateral deflected shape under 1.0 kN lateral force in each story are shown in Fig. 1a. Since the lateral load can be approximated as a distributed load of (1.0/h) kN/m, where h is the story height, the deflected shape can be assumed as a fourth order degree parabola. Then, the average lateral displacement is developed as follows.



a) Shear wall system and deformation mode (flexural mode)

b) Building frame system and deformation mode (shear mode)

Fig. 1 Shear wall, frame models and their lateral deflected shape.

The maximum lateral displacement at the top of the building (Δ_w, *top*), neglecting second order analysis (P-Δ effect), can be calculated from the following equation.

$$\Delta_{w,top} = \left(\frac{1}{h}\right)\left(\frac{H_b^4}{8EI}\right) \quad (2)$$

The average story displacement (Δ_w, *average*) can be obtained by calculating the area under the curve of deflected shape divided by the total height of the building (H_b).

The deflected shape is a fourth-degree parabola; therefore,

$$\Delta_{w,average} = \frac{0.4\, H_b\, \Delta_{w,top}}{H_b} = 0.4\, \Delta_{w,top} \tag{3}$$

From Eqs. (2) and (3),

$$\Delta_{w,average} = \frac{(\frac{H_b^4}{h})}{20\, EI} = \frac{n\, H_b^3}{20\, EI} \tag{4}$$

where *n* is the total number of stories.

The deformation mode of the shear wall is flexural while the deformation mode of the frame is shear. The software ETABS is used to obtain the story lateral displacement against 1.0 kN lateral force at each story. Upon approximating the deflected shape of the frame as a piecewise linear function, Fig. 1b, the average story displacement (Δ_f, *average*) can be calculated by dividing the summation of the story lateral displacements $(\sum_{i=1}^{n} \Delta_i)$ by the total number of stories (n) as follows:

$$\Delta_{f,average} = \frac{1}{n} \sum_{i=1}^{n} \Delta_i \tag{5}$$

By equating the average lateral displacement of both the frame and the equivalent wall system:

$$\frac{1}{n} \sum_{i=1}^{n} \Delta_i = \frac{n\, H_b^3}{20\, (EI)_{eq}} \tag{6}$$

Then, the equivalent flexural rigidity, $(EI)_{eq}$, of the structural frame system can be expressed as follows:

$$(EI)_{eq} = \frac{n^2\, H_b^3}{20\, \sum_{i=1}^{n} \Delta_i} \tag{7}$$

This equivalent flexural rigidity, $(EI)_{eq}$, can be introduced into Eq. (1).

3. NUMERICAL VERIFICATION:

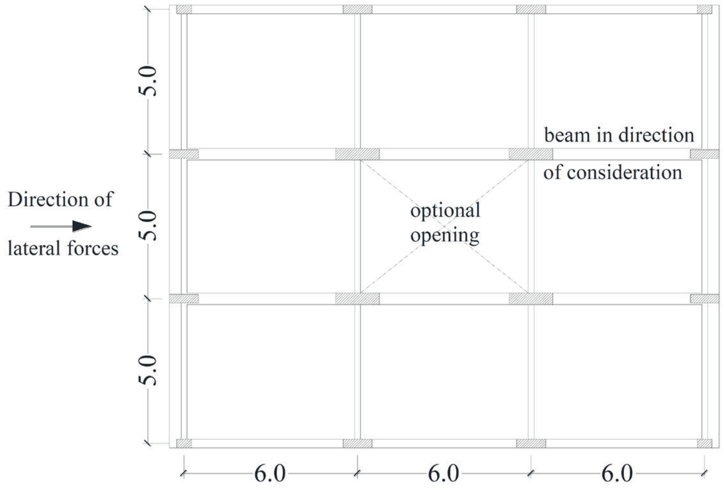
In order to verify the proposed approach, three different structural frame systems are analyzed in three-dimensions, 3D, for different heights of 3, 6, 9, 12, and 15 stories. To cover a wide range of plan variety, three plan options are used with three different aspect ratios and with optional openings. The plans remain symmetric around the axis in the direction of consideration. Floors with beams of different flexural rigidities, ranging from rigid, semi-rigid and flat plate without beams, are utilized in the study. A total of 144 cases were analyzed in 3D using ETABS software. The details of the studied frames are shown in Fig. 2 and presented in tables 1a and 1b. Due to the large number of analyzed cases, a coding system is used to simplify reading the output results. The code of each analyzed case consists of 10 cells. The first two cells indicate the number of stories. The 3rd and 4th cells indicate that the plan has rigid beams (RB), semi-rigid beams (SB), or without beams (NB) for the flat plate option. The 5th, 6th, and 7th cells mean 1st order analysis or 2nd order analysis. The 8th cell indicates the 1st, 2nd and 3rd plan options with different dimensions of the plan. The 9th and 10th cells mean a plan with an opening (WO) or without an opening (NO).

No. of stories	Column position	Columns› dimensions [mm] 1st plan option	Columns′ dimensions [mm] 2nd plan option	Columns′ dimensions [mm] 3rd plan option
3	corner	300 x 400	300 x 400	300 x 400
	edge	300 x 500	300 x 500	300 x 500
	interior	300 x 600	300 x 600	300 x 600
6	corner	300 x 500	300 x 500	300 x 500
	edge	300 x 600	300 x 600	300 x 600
	interior	300 x 950	300 x 1000	300 x 1000
9	corner	300 x 700	300 x 700	300 x 700
	edge	300 x 800	300 x 800	300 x 800
	interior	300 x 1400	300 x 1450	300 x 1450
12	corner	300 x 800	300 x 800	---
	edge	300 x 900	300 x 900	---
	interior	400 x 1500	400 x 1700	---
15	corner	---	300 x 900	---
	edge	---	300 x 1200	---
	interior	---	400 x 1900	---

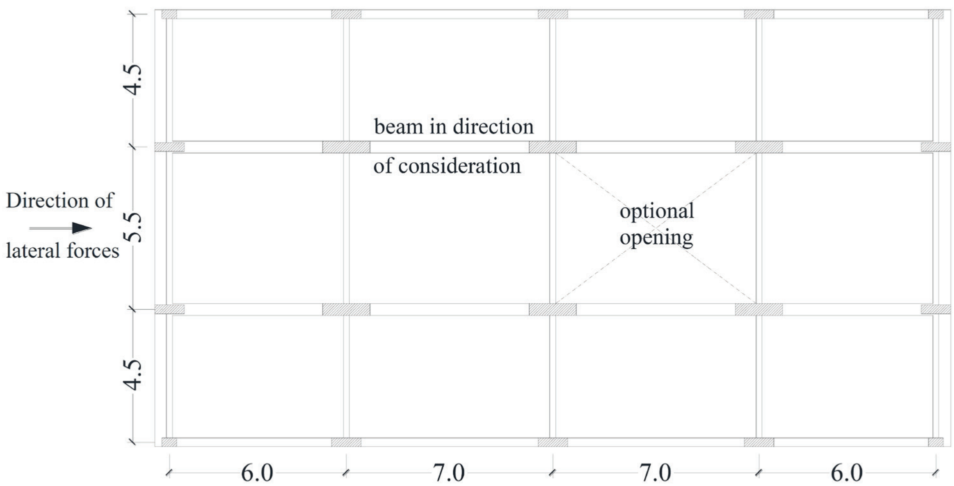
Table 1a: Concrete dimensions of columns of the frame systems used in the study.

No. of stories	Main beams’ dimensions [mm] All plans	Transverse beams’ dimensions [mm] All plans
3, 6, 9	300x700 (RB)	250x500 (RB)
	250x300 (SB)	120*300 (SB)
	without beams	without beams
12, 15	400x700 (RB)	250x500 (RB)
	250x300 (SB)	120*300 (SB)
	without beams	without beams
Note: Slab thickness is 160mm for plans with beams (RB & SB) and 220mm for flat plate option (NB).		

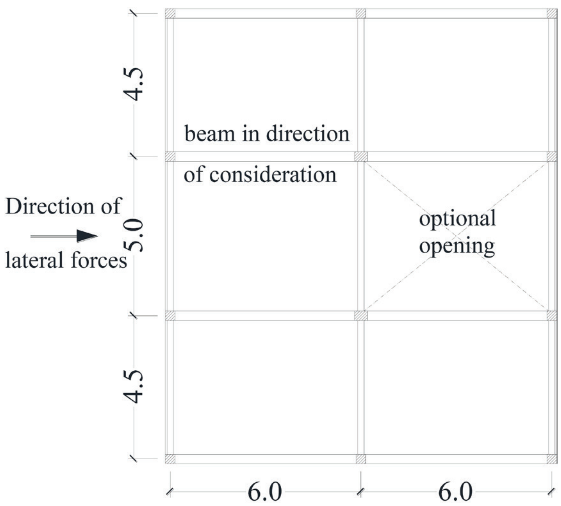
Table 1b: Concrete dimensions of beams of frame systems used in the study.



a) First Plan Option



b) Second Plan Option



b) Third Plan Option

Fig. 2 Layout of plans used in the study.

4. BRACED/UNBRACED CONDITION ANALYSIS:

The first order analysis and second order analysis are conducted in three-dimensions for the studied building frames using The ETABS software program. The maximum story displacement and total bending moment at the base level of columns due to 1.0 kN horizontal force at each story level are presented for all cases in tables 2 to 13. These obtained results are used to investigate the bracing conditions of the studied buildings according to ECP 203-17 [7], ACI 318-14 [1], and EC2 [9]. The bracing conditions of all studied cases are summarized in tables 14, 15, and 16 for 1st, 2nd, and 3rd plan options, respectively.

In general, the ECP 203-17 [7] provisions show slightly conservative results compared with the ACI 318-14 [1] and the EC2 [9] especially for building frames with number of stories more than 12-story. For instance, the code provisions for the bracing condition of 2nd plan option are shown in table 15. The 15-story building frame is classified as an unbraced building according to the value of the bracing index (a) in ECP 203-17 using first order analysis. However, the same building is classified as a braced structure according to the provisions of the ACI 318-14 [1] and the EC2 [9] using first and second order analysis. From the results, it is also obvious that the frame action produced by increasing the flexural rigidity of beams in floor slabs controls the bracing condition of the building frames with number of stories up to 12-stories.

Table 2: Story displacement and a base bending moment of the 15-story frame for the 2nd plan option.

Story number / Code of case		15RB1st2NO	15SB1st2NO	15NB1st2NO	15RB2nd2NO	15SB2nd2NO	15NB2nd2NO	15RB1st2WO	15SB1st2WO	15NB1st2WO	15RB2nd2WO	15SB2nd2WO	15NB2nd2WO
Maximum story displacement [mm]	Story15	0.3	1.7	1.9	0.3	2.1	2.5	0.4	1.2	0.6	0.4	1.5	0.8
	Story14	0.3	1.6	1.8	0.3	2	2.3	0.4	1.2	0.6	0.4	1.4	0.8
	Story13	0.3	1.5	1.6	0.3	1.8	2.1	0.4	1.1	0.6	0.4	1.3	0.7
	Story12	0.3	1.3	1.5	0.3	1.7	1.9	0.3	1	0.6	0.3	1.2	0.7
	Story11	0.2	1.2	1.3	0.3	1.5	1.7	0.3	0.9	0.5	0.3	1.1	0.7
	Story10	0.2	1.1	1.2	0.2	1.3	1.5	0.3	0.8	0.5	0.3	1	0.6
	Story9	0.2	1	1	0.2	1.2	1.3	0.3	0.7	0.4	0.3	0.9	0.5
	Story8	0.2	0.8	0.9	0.2	1	1.1	0.2	0.6	0.4	0.2	0.8	0.5
	Story7	0.2	0.7	0.7	0.2	0.8	0.9	0.2	0.5	0.3	0.2	0.6	0.4
	Story6	0.1	0.5	0.6	0.1	0.7	0.7	0.2	0.4	0.3	0.2	0.5	0.3
	Story5	0.1	0.4	0.4	0.1	0.5	0.6	0.1	0.3	0.2	0.1	0.4	0.2
	Story4	0.1	0.3	0.3	0.1	0.3	0.4	0.1	0.2	0.1	0.1	0.3	0.2
	Story3	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.1
	Story2	0.02908	0.1	0.1	0.03021	0.1	0.1	0.031	0.1	0.04352	0.03219	0.1	0.1
	Story1	0.008955	0.02298	0.0244	0.009263	0.02707	0.02979	0.00939	0.01819	0.01236	0.009712	0.02106	0.01438
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		2.638	12.423	13.524	2.739	15.227	17.330	3.340	9.118	5.256	3.342	11.321	6.614
EI_{eq} [kN/mm^2]		3.88606E+14	8.2521E+13	7.58005E+13	3.74217E+14	6.73246E+13	5.91557E+13	3.06897E+14	1.1243E+14	1.95049E+14	3.06758E+14	9.0553E+13	1.54989E+14
α		0.646	1.330	1.433	0.659	1.472	1.622	0.704	1.099	0.859	0.704	1.224	0.964
ECP 203-17 (braced/unbraced)		Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced
M_y		-1042822	-936865	-999198	-1042836	-936938	-999288	-960195	-854239	-904616	-960212	-854289	-904646
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 3: Story displacement and a base bending moment of the 12-story frame for the 1st plan option.

Story number / Code of case		12RB1st1NO	12SB1st1NO	12NB1st1NO	12RB2nd1NO	12SB2nd1NO	12NB2nd1NO	12RB1st1WO	12SB1st1WO	12NB1st1WO	12RB2nd1WO	12SB2nd1WO	12NB2nd1WO
Maximum story displacement [mm]	Story12	0.3	1.6	2	0.3	1.9	2.5	0.3	1.6	2	0.3	1.9	2.5
	Story11	0.2	1.4	1.8	0.3	1.7	2.3	0.2	1.5	1.9	0.3	1.7	2.3
	Story10	0.2	1.3	1.7	0.2	1.6	2.1	0.2	1.4	1.7	0.2	1.6	2.1
	Story9	0.2	1.2	1.5	0.2	1.4	1.9	0.2	1.2	1.5	0.2	1.4	1.9
	Story8	0.2	1	1.3	0.2	1.2	1.6	0.2	1.1	1.3	0.2	1.3	1.6
	Story7	0.2	0.9	1.1	0.2	1.1	1.4	0.2	0.9	1.1	0.2	1.1	1.4
	Story6	0.2	0.7	0.9	0.2	0.9	1.1	0.2	0.7	0.9	0.2	0.9	1.1
	Story5	0.1	0.6	0.7	0.1	0.7	0.9	0.1	0.6	0.7	0.1	0.7	0.8
	Story4	0.1	0.4	0.5	0.1	0.5	0.6	0.1	0.4	0.5	0.1	0.5	0.6
	Story3	0.1	0.3	0.3	0.1	0.3	0.4	0.1	0.3	0.3	0.1	0.3	0.4
	Story2	0.04011	0.1	0.1	0.04142	0.1	0.2	0.04021	0.1	0.2	0.04143	0.2	0.2
	Story1	0.01321	0.03654	0.0415	0.01358	0.04186	0.1	0.01323	0.03699	0.04191	0.01359	0.04203	0.04985
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		1.853	9.537	11.942	1.955	11.442	15.100	1.853	9.837	12.142	1.955	11.642	14.950
EI_{eq} [kN/mm^2]		1.81255E+14	3.52249E+13	2.81307E+13	1.71828E+14	2.93591E+13	2.22466E+13	1.81243E+14	3.4149E+13	2.76664E+13	1.71826E+14	2.88543E+13	2.247E+13
α		0.568	1.221	1.412	0.583	1.338	1.588	0.549	1.193	1.366	0.564	1.298	1.516
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced
M_y		-406350	-365124	-389805	-406357	-365162	-389858	-379169	-337943	-358690	-379176	-337979	-358739
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 4: Story displacement and a base bending moment of the 12-story frame for the 2nd plan option.

Story number / Code of case		12RB1st2NO	12SB1st2NO	12NB1st2NO	12RB2nd2NO	12SB2nd2NO	12NB2nd2NO	12RB1st2WO	12SB1st2WO	12NB1st2WO	12RB2nd2WO	12SB2nd2WO	12NB2nd2WO
Maximum story displacement [mm]	Story12	0.2	1.1	1.3	0.2	1.3	1.7	0.3	0.6	0.2	0.3	0.7	0.2
	Story11	0.2	1	1.2	0.2	1.2	1.5	0.2	0.6	0.1	0.2	0.7	0.1
	Story10	0.2	0.9	1.1	0.2	1.1	1.4	0.2	0.5	0.1	0.2	0.6	0.1
	Story9	0.2	0.8	1	0.2	0.9	1.2	0.2	0.5	0.03133	0.2	0.6	0.04316
	Story8	0.2	0.7	0.8	0.2	0.8	1	0.2	0.4	0.00203	0.2	0.5	0.006549
	Story7	0.1	0.6	0.7	0.1	0.7	0.9	0.2	0.4	0.02532	0.2	0.4	0.01963
	Story6	0.1	0.5	0.6	0.1	0.6	0.7	0.1	0.3	0.03858	0.1	0.3	0.03526
	Story5	0.1	0.4	0.4	0.1	0.4	0.5	0.1	0.2	0.04257	0.1	0.3	0.04098
	Story4	0.1	0.3	0.3	0.1	0.3	0.4	0.1	0.2	0.03873	0.1	0.2	0.03825
	Story3	0.04997	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.02925	0.1	0.1	0.02929
	Story2	0.0274	0.1	0.1	0.02828	0.1	0.1	0.02899	0.1	0.01703	0.02991	0.1	0.01718
	Story1	0.008758	0.02258	0.02531	0.009007	0.02562	0.03002	0.009095	0.01554	0.00579	0.009351	0.01727	0.005855
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		1.486	6.623	7.725	1.537	7.626	9.630	1.738	3.916	0.631	1.739	4.517	0.636
EI_{eq} [kN/mm^2]		2.26039E+14	5.07239E+13	4.34835E+13	2.18517E+14	4.40519E+13	3.48829E+13	1.93272E+14	8.57923E+13	5.32679E+14	1.93141E+14	7.43642E+13	5.28053E+14
α		0.599	1.196	1.335	0.609	1.284	1.491	0.626	0.886	0.367	0.627	0.952	0.368
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced
M_y		-813150	-728386	-777599	-813158	-728421	-777647	-747049	-662284	-701933	-747058	-662303	-701932
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 5: Story displacement and a base bending moment of the 9-story frame for the 1st plan option.

Story number / Code of case		09RB1st1NO	09SB1st1NO	09NB1st1NO	09RB2nd1NO	09SB2nd1NO	09NB2nd1NO	09RB1st1WO	09SB1st1WO	09NB1st1WO	09RB2nd1WO	09SB2nd1WO	09NB2nd1WO
Maximum story displacement [mm]	Story9	0.2	0.9	1.1	0.2	1	1.3	0.2	0.9	1.1	0.2	1	1.3
	Story8	0.2	0.8	1	0.2	0.9	1.1	0.2	0.8	1	0.2	0.9	1.2
	Story7	0.2	0.7	0.8	0.2	0.8	1	0.2	0.7	0.9	0.2	0.8	1
	Story6	0.1	0.6	0.7	0.1	0.6	0.8	0.1	0.6	0.7	0.1	0.7	0.8
	Story5	0.1	0.5	0.6	0.1	0.5	0.7	0.1	0.5	0.6	0.1	0.5	0.7
	Story4	0.1	0.3	0.4	0.1	0.4	0.5	0.1	0.3	0.4	0.1	0.4	0.5
	Story3	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
	Story2	0.04013	0.1	0.1	0.0413	0.1	0.2	0.04026	0.1	0.1	0.04134	0.1	0.2
	Story1	0.01362	0.03333	0.03795	0.01397	0.03669	0.04325	0.01365	0.03375	0.03829	0.01398	0.03693	0.0432
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		1.054	4.133	5.038	1.055	4.537	5.943	1.054	4.134	5.138	1.055	4.637	6.043
EI_{eq} [kN/mm^2]		7.565E+13	1.92862E+13	1.58231E+13	7.5541E+13	1.75714E+13	1.34129E+13	7.56385E+13	1.92842E+13	1.55141E+13	7.55374E+13	1.71916E+13	1.3191E+13
α		0.554	1.055	1.204	0.554	1.105	1.308	0.533	1.013	1.164	0.534	1.073	1.262
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced
M_y		-286497	-265197	-283357	-286501	-265212	-283378	-265668	-244368	-259514	-265671	-244382	-259533
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 6: Story displacement and a base bending moment of the 9-story frame for the 2[nd] plan option.

Story number / Code of case		09RB1st2NO	09SB1st2NO	09NB1st2NO	09RB2nd2NO	09SB2nd2NO	09NB2nd2NO	09RB1st2WO	09SB1st2WO	09NB1st2WO	09RB2nd2WO	09SB2nd2WO	09NB2nd2WO
Maximum story displacement [mm]	Story9	0.1	0.7	0.8	0.1	0.7	1	0.2	0.3	0.3	0.2	0.4	0.3
	Story8	0.1	0.6	0.7	0.1	0.7	0.8	0.2	0.3	0.2	0.2	0.3	0.2
	Story7	0.1	0.5	0.6	0.1	0.6	0.7	0.2	0.3	0.1	0.2	0.3	0.2
	Story6	0.1	0.4	0.5	0.1	0.5	0.6	0.1	0.2	0.1	0.1	0.3	0.1
	Story5	0.1	0.3	0.4	0.1	0.4	0.5	0.1	0.2	0.04891	0.1	0.2	0.1
	Story4	0.1	0.2	0.3	0.1	0.3	0.3	0.1	0.1	0.01996	0.1	0.2	0.02947
	Story3	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.003385	0.1	0.1	0.008718
	Story2	0.02986	0.1	0.1	0.03077	0.1	0.1	0.032	0.1	0.002968	0.03295	0.1	0.0006389
	Story1	0.009976	0.0237	0.02677	0.01024	0.02615	0.03056	0.01039	0.01556	0.002592	0.01066	0.01686	0.002025
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		0.740	3.024	3.627	0.741	3.526	4.231	1.042	1.616	0.778	1.044	1.917	0.941
EI_{eq} [kN/mm^2]		1.07748E+14	2.63638E+13	2.19799E+13	1.07578E+14	2.26071E+13	1.88429E+13	7.64744E+13	4.93427E+13	1.02487E+14	7.6385E+13	4.15868E+13	8.47276E+13
α		0.545	1.059	1.199	0.545	1.143	1.295	0.624	0.744	0.532	0.624	0.811	0.585
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced
M_y		-570737	-527234	-563654	-570741	-527249	-563675	-520189	-476686	-505792	-520194	-476693	-505787
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 7: Story displacement and a base bending moment of the 9-story frame for the 3[rd] plan option.

Story number / Code of case		09RB1st3NO	09SB1st3NO	09NB1st3NO	09RB2nd3NO	09SB2nd3NO	09NB2nd3NO	09RB1st3WO	09SB1st3WO	09NB1st3WO	09RB2nd3WO	09SB2nd3WO	09NB2nd3WO
Maximum story displacement [mm]	Story9	0.4	2.7	3.7	0.4	3.6	5.7	0.9	1.6	3	0.9	2.2	4.5
	Story8	0.4	2.6	3.5	0.4	3.4	5.3	0.7	1.6	2.8	0.7	2.1	4.3
	Story7	0.4	2.3	3.2	0.4	3.1	4.9	0.5	1.6	2.6	0.5	2.1	4
	Story6	0.3	2.1	2.8	0.4	2.8	4.4	0.4	1.5	2.4	0.4	1.9	3.6
	Story5	0.3	1.9	2.5	0.3	2.5	3.8	0.2	1.3	2.1	0.2	1.8	3.2
	Story4	0.3	1.6	2	0.3	2.1	3.2	0.1	1.2	1.8	0.1	1.5	2.7
	Story3	0.2	1.2	1.6	0.2	1.6	2.5	0.1	0.9	1.4	0.1	1.2	2.1
	Story2	0.2	0.8	1.1	0.2	1.1	1.7	0.005967	0.7	1	0.007533	0.9	1.5
	Story1	0.1	0.4	0.6	0.1	0.6	0.9	0.008072	0.3	0.5	0.007445	0.4	0.8
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		2.600	15.600	21.000	2.700	20.800	32.400	2.914	10.700	17.600	2.915	14.100	26.700
EI_{eq} [kN/mm^2]		3.06601E+13	5.11001E+12	3.79601E+12	2.95245E+13	3.83251E+12	2.46038E+12	2.73559E+13	7.45011E+12	4.52933E+12	2.73471E+13	5.65363E+12	2.98562E+12
α		0.698	1.643	1.967	0.712	1.898	2.443	0.697	1.275	1.678	0.697	1.464	2.067
ECP 203-17 (braced/unbraced)		Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced	Unbraced
M_y		-123252	-113724	-120975	-123258	-113768	-121047	-102423	-92895.0319	-97132.1486	-102417	-92920.8757	-97183.2767
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 8: Story displacement and a base bending moment of the 6-story frame for the 1st plan option.

Story number / Code of case		06RB1st1NO	06SB1st1NO	06NB1st1NO	06RB2nd1NO	06SB2nd1NO	06NB2nd1NO	06RB1st1WO	06SB1st1WO	06NB1st1WO	06RB2nd1WO	06SB2nd1WO	06NB2nd1WO
Maximum story displacement [mm]	Story6	0.1	0.4	0.6	0.1	0.5	0.6	0.1	0.5	0.6	0.1	0.5	0.6
	Story5	0.1	0.4	0.5	0.1	0.4	0.5	0.1	0.4	0.5	0.1	0.4	0.5
	Story4	0.1	0.3	0.4	0.1	0.3	0.4	0.1	0.3	0.4	0.1	0.3	0.4
	Story3	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3
	Story2	0.03831	0.1	0.1	0.03923	0.1	0.2	0.03844	0.1	0.1	0.03929	0.1	0.2
	Story1	0.01483	0.03756	0.04354	0.01515	0.04046	0.0482	0.01487	0.03809	0.04399	0.01517	0.04083	0.04832
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		0.453	1.438	1.944	0.454	1.540	2.048	0.453	1.538	1.944	0.454	1.541	2.048
EI_{eq} [kN/mm^2]		2.31664E+13	7.30237E+12	5.40128E+12	2.31031E+13	6.81459E+12	5.12528E+12	2.31577E+13	6.82509E+12	5.40003E+12	2.30991E+13	6.81295E+12	5.12498E+12
α		0.535	0.916	1.102	0.536	0.948	1.131	0.515	0.908	1.053	0.516	0.909	1.081
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced
M_y		-184547	-170347	-182220	-184548	-170352	-182227	-170661	-156461	-166325	-170662	-156466	-166331
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 9: Story displacement and a base bending moment of the 6-story frame for the 2nd plan option.

Story number / Code of case		06RB1st2NO	06SB1st2NO	06NB1st2NO	06RB2nd2NO	06SB2nd2NO	06NB2nd2NO	06RB1st2WO	06SB1st2WO	06NB1st2WO	06RB2nd2WO	06SB2nd2WO	06NB2nd2WO
Maximum story displacement [mm]	Story6	0.1	0.3	0.4	0.1	0.4	0.5	0.1	0.1	0.4	0.1	0.1	0.4
	Story5	0.1	0.3	0.3	0.1	0.3	0.4	0.1	0.1	0.3	0.1	0.1	0.3
	Story4	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.1	0.2	0.1	0.1	0.2
	Story3	0.04511	0.2	0.2	0.04625	0.2	0.2	0.04877	0.1	0.1	0.04993	0.1	0.1
	Story2	0.0285	0.1	0.1	0.02921	0.1	0.1	0.0294	0.03633	0.03895	0.0301	0.03858	0.0462
	Story1	0.01079	0.02663	0.03057	0.01103	0.02873	0.03387	0.01078	0.01304	0.007487	0.01101	0.01372	0.009375
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		0.384	1.127	1.331	0.386	1.229	1.534	0.389	0.449	1.046	0.391	0.452	1.056
EI_{eq} [kN/mm^2]		2.73091E+13	9.3177E+12	7.88955E+12	2.71614E+13	8.54346E+12	6.84387E+12	2.69896E+13	2.33607E+13	1.00318E+13	2.68453E+13	2.32094E+13	9.94491E+12
α		0.580	0.954	1.072	0.582	0.996	1.151	0.562	0.578	0.910	0.564	0.580	0.914
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Braced	Unbraced	Braced	Braced	Unbraced
M_y		-369111	-340109	-364063	-369112	-340114	-364070	-335412	-306410	-325488	-335414	-306411	-325483
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 10: Story displacement and a base bending moment of the 6-story frame for the 3rd plan option.

Story number / Code of case		06RB1st3NO	06SB1st3NO	06NB1st3NO	06RB2nd3NO	06SB2nd3NO	06NB2nd3NO	06RB1st3WO	06SB1st3WO	06NB1st3WO	06RB2nd3WO	06SB2nd3WO	06NB2nd3WO
Maximum story displacement [mm]	Story6	0.1	0.7	0.8	0.1	0.7	0.9	0.5	0.02228	0.2	0.5	0.01775	0.2
	Story5	0.1	0.6	0.7	0.1	0.6	0.8	0.4	0.1	0.04478	0.4	0.1	0.04932
	Story4	0.1	0.4	0.6	0.1	0.5	0.6	0.2	0.1	0.03563	0.2	0.1	0.03449
	Story3	0.1	0.3	0.4	0.1	0.3	0.4	0.1	0.1	0.1	0.1	0.1	0.1
	Story2	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
	Story1	0.02224	0.1	0.1	0.0227	0.1	0.1	0.008602	0.03093	0.02545	0.008938	0.03216	0.02614
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		0.522	2.300	2.800	0.523	2.400	3.000	1.309	0.453	0.506	1.309	0.450	0.510
EI_{eq} [kN/mm^2]		2.01011E+13	4.56417E+12	3.74914E+12	2.00834E+13	4.374E+12	3.4992E+12	8.022E+12	2.31628E+13	2.0752E+13	8.01994E+12	2.33327E+13	2.05855E+13
α		0.459	0.923	1.051	0.459	0.943	1.087	0.682	0.382	0.414	0.682	0.381	0.416
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Unbraced	Braced	Braced	Unbraced	Braced	Braced
M_y		-78418.0386	-72066.1808	-76681.9659	-78419.2823	-72070.9546	-76688.4394	-64531.9965	-58180.1388	-60786.5381	-64529.5358	-58180.8189	-60786.4956
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 11: Story displacement and a base bending moment of the 3-story frame for the 1st plan option.

Story number / Code of case		03RB1st1NO	03SB1st1NO	03NB1st1NO	03RB2nd1NO	03SB2nd1NO	03NB2nd1NO	03RB1st1WO	03SB1st1WO	03NB1st1WO	03RB2nd1WO	03SB2nd1WO	03NB2nd1WO
Maximum story displacement [mm]	Story3	0.03191	0.1	0.1	0.03234	0.1	0.2	0.03199	0.1	0.1	0.03239	0.1	0.2
	Story2	0.02468	0.1	0.1	0.02504	0.1	0.1	0.02474	0.1	0.1	0.02507	0.1	0.1
	Story1	0.01187	0.0274	0.03199	0.01204	0.02847	0.03368	0.01189	0.02778	0.03233	0.01205	0.02879	0.03389
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		0.068	0.227	0.232	0.069	0.228	0.334	0.069	0.228	0.232	0.070	0.229	0.334
EI_{eq} [kN/mm^2]		4.79185E+12	1.44261E+12	1.41407E+12	4.72558E+12	1.43586E+12	9.83128E+11	4.78068E+12	1.44021E+12	1.412E+12	4.71946E+12	1.43385E+12	9.82509E+11
α		0.412	0.721	0.753	0.415	0.722	0.903	0.396	0.691	0.719	0.399	0.692	0.862
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced
M_y		-90367.6877	-83267.6544	-89145.7949	-90367.9173	-83268.3311	-89146.7028	-83424.6667	-76324.6334	-81198.081	-83424.8787	-76325.2629	-81198.915
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 12: Story displacement and a base bending moment of the 3-story frame for the 2nd plan option.

Story number / Code of case		03RB1st2NO	03SB1st2NO	03NB1st2NO	03RB2nd2NO	03SB2nd2NO	03NB2nd2NO	03RB1st2WO	03SB1st2WO	03NB1st2WO	03RB2nd2WO	03SB2nd2WO	03NB2nd2WO
Maximum story displacement [mm]	Story3	0.02487	0.1	0.1	0.02524	0.1	0.1	0.009041	0.1	0.3	0.009178	0.1	0.3
	Story2	0.01918	0.1	0.1	0.01948	0.1	0.1	0.01031	0.02822	0.1	0.01044	0.02978	0.1
	Story1	0.009163	0.02117	0.02456	0.009308	0.02207	0.02594	0.005645	0.003798	0.03499	0.005716	0.004222	0.03768
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		0.053	0.221	0.225	0.054	0.222	0.226	0.025	0.132	0.435	0.025	0.134	0.438
EI_{eq} [kN/mm^2]		6.16485E+12	1.48325E+12	1.46086E+12	6.07185E+12	1.47724E+12	1.45193E+12	1.31241E+13	2.48489E+12	7.54155E+11	1.2949E+13	2.4481E+12	7.4952E+11
α		0.427	0.836	0.872	0.431	0.838	0.875	0.282	0.619	1.161	0.284	0.624	1.164
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced
M_y		-180835	-166334	-178229	-180835	-166335	-178230	-163986	-149485	-158942	-163986	-149484	-158940
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

Table 13: Story displacement and a base bending moment of the 3-story frame for the 3rd plan option.

Story number / Code of case		03RB1st3NO	03SB1st3NO	03NB1st3NO	03RB2nd3NO	03SB2nd3NO	03NB2nd3NO	03RB1st3WO	03SB1st3WO	03NB1st3WO	03RB2nd3WO	03SB2nd3WO	03NB2nd3WO
Maximum story displacement [mm]	Story3	0.04754	0.2	0.2	0.04815	0.2	0.2	0.01873	0.01974	0.1	0.019	0.02096	0.1
	Story2	0.0367	0.1	0.1	0.03721	0.1	0.1	0.02309	0.03568	0.03885	0.02338	0.03675	0.0416
	Story1	0.01759	0.04062	0.0468	0.01783	0.04212	0.04906	0.01577	0.02036	0.0007581	0.01596	0.02087	0.00142
	Base	0	0	0	0	0	0	0	0	0	0	0	0
Sum of story displacement [mm]		0.102	0.341	0.347	0.103	0.342	0.349	0.058	0.076	0.140	0.058	0.079	0.143
EI_{eq} [kN/mm^2]		3.22155E+12	9.63097E+11	9.45934E+11	3.17909E+12	9.58874E+11	9.3981E+11	5.6963E+12	4.32898E+12	2.34979E+12	5.62307E+12	4.17473E+12	2.29374E+12
α		0.402	0.704	0.733	0.404	0.705	0.735	0.283	0.309	0.431	0.285	0.315	0.436
ECP 203-17 (braced/unbraced)		Braced	Unbraced	Unbraced	Braced	Unbraced	Unbraced	Braced	Braced	Braced	Braced	Braced	Braced
M_y		-38508.4193	-35332.4904	-37640.383	-38508.637	-35333.1278	-37641.2167	-31565.3983	-28389.4694	-29692.6691	-31565.5069	-28389.6021	-29692.357
ACI 318-14 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--
EC2 (braced/unbraced)		Braced	Braced	Braced	--	--	--	Braced	Braced	Braced	--	--	--

No. of stories	Code Type		Floor slab with rigid beams		Floor slab with semi-rigid beams		Flat plate floor slab	
			NO*	WO**	NO*	WO**	NO*	WO**
12	ECP 203-17	α	0.568	0.548	1.221	1.193	1.412	1.366
		Condition	braced	braced	unbraced	unbraced	unbraced	unbraced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.0017	0.0018	0.0104	0.0107	0.0136	0.0137
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
9	ECP 203-17	α	0.553	0.533	1.055	1.013	1.204	1.164
		Condition	braced	braced	unbraced	unbraced	unbraced	unbraced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.0013	0.0011	0.0057	0.0057	0.0074	0.0073
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
6	ECP 203-17	α	0.535	0.515	0.916	0.908	1.102	1.052
		Condition	braced	braced	unbraced	unbraced	unbraced	unbraced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.0005	0.0006	0.0029	0.0032	0.0038	0.0036
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
3	ECP 203-17	α	0.412	0.396	0.721	0.691	0.753	0.719
		Condition	braced	braced	unbraced	unbraced	unbraced	unbraced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.0003	0.0003	0.0008	0.0008	0.001	0.001
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced

*NO: abbreviation for without openings in floor plans.
**WO: abbreviation for with openings in floor plans.

Table 14: Code provisions for a bracing condition of the 1st plan option.

No. of stories	Code Type		Floor slab with rigid beams		Floor slab with semi-rigid beams		Flat plate floor slab	
			NO*	WO**	NO*	WO**	NO*	WO**
15	ECP 203-17	α	0.646	0.704	1.329	1.098	1.432	0.899
		Condition	unbraced	unbraced	unbraced	unbraced	unbraced	unbraced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.0013	0.0018	0.0078	0.0058	0.009	0.0033
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
12	ECP 203-17	α	0.599	0.626	1.196	0.886	1.335	0.337
		Condition	braced	unbraced	unbraced	unbraced	unbraced	braced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.001	0.0012	0.0048	0.0028	0.0062	0.0001
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
9	ECP 203-17	α	0.545	0.623	1.059	0.744	1.199	0.532
		Condition	braced	unbraced	unbraced	unbraced	unbraced	braced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.0007	0.0009	0.0028	0.0015	0.004	0.001
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
6	ECP 203-17	α	0.58	0.562	0.953	0.578	1.072	0.91
		Condition	braced	braced	unbraced	braced	unbraced	unbraced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0.0002	0.0006	0.0015	0.0003	0.0019	0.0015
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
3	ECP 203-17	α	0.427	0.282	0.835	0.619	0.872	1.161
		Condition	braced	braced	unbraced	unbraced	unbraced	unbraced
	$M_{P\Delta\text{-effect}} / M_{1st\ order}$ %		0	0	0.0006	0.0006	0.0005	0.0005
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced

*NO: abbreviation for without openings in floor plans.
**WO: abbreviation for with openings in floor plans.

Table 15: Code provisions for a bracing condition of the 2nd plan option.

No. of stories	Code Type		Floor slab with rigid beams		Floor slab with semi-rigid beams		Flat plate floor slab	
			NO*	WO**	NO*	WO**	NO*	WO**
9	ECP 203-17	α	0.698	0.696	1.643	1.275	1.967	1.678
		Condition	unbraced	unbraced	unbraced	unbraced	unbraced	unbraced
	$M_{P\Delta\text{-effect}}$ / $M_{1st\ order}$ %		0.0049	0.0058	0.0387	0.0278	0.0595	0.0526
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
6	ECP 203-17	α	0.459	0.682	0.923	0.382	1.051	0.414
		Condition	braced	unbraced	unbraced	braced	unbraced	braced
	$M_{P\Delta\text{-effect}}$ / $M_{1st\ order}$ %		0.0016	0.0038	0.0066	0.0012	0.0084	0.0007
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced
3	ECP 203-17	α	0.402	0.283	0.704	0.309	0.733	0.431
		Condition	braced	braced	unbraced	braced	unbraced	braced
	$M_{P\Delta\text{-effect}}$ / $M_{1st\ order}$ %		0.0006	0.0003	0.0018	0.0005	0.0022	0.0011
	ACI 318-14		braced	braced	braced	braced	braced	braced
	EC2		braced	braced	braced	braced	braced	braced

*NO: abbreviation for without openings in floor plans.
**WO: abbreviation for with openings in floor plans.

Table 16: Code provisions for a bracing condition of the 3rd plan option.

The maximum lateral story displacement of all studied cases is shown in Figs. 3 to 5. In general, using rigid beams (RBs) in floor slabs produces frame action that reduces the lateral sway displacement. For instance, from the first order analysis of the 15-story building in 2nd plan option, the top story sway displacement of cases 15SB1st2NO and 15NB1st2NO increased by 4.7 and 5.3 times the top displacement of case 15RB1st2NO, respectively. This increase in top story sway reaches 6.0 and 7.3 times for the same cases in second order analysis. Moreover, the reduction in the lateral sway displacement due to the existence of rigid beams (RB) becomes noteworthy by reducing the height of the frame building. For instance, from the first order analysis of the 12-story building in 2nd plan option, the top story sway displacement of cases 12SB1st2NO and 12NB1st2NO increased by 5.5 and 6.5 times the top displacement of case 12RB1st2NO, respectively. This increase in top story sway reaches 6.5 and 8.5 times for the same cases in second order analysis.

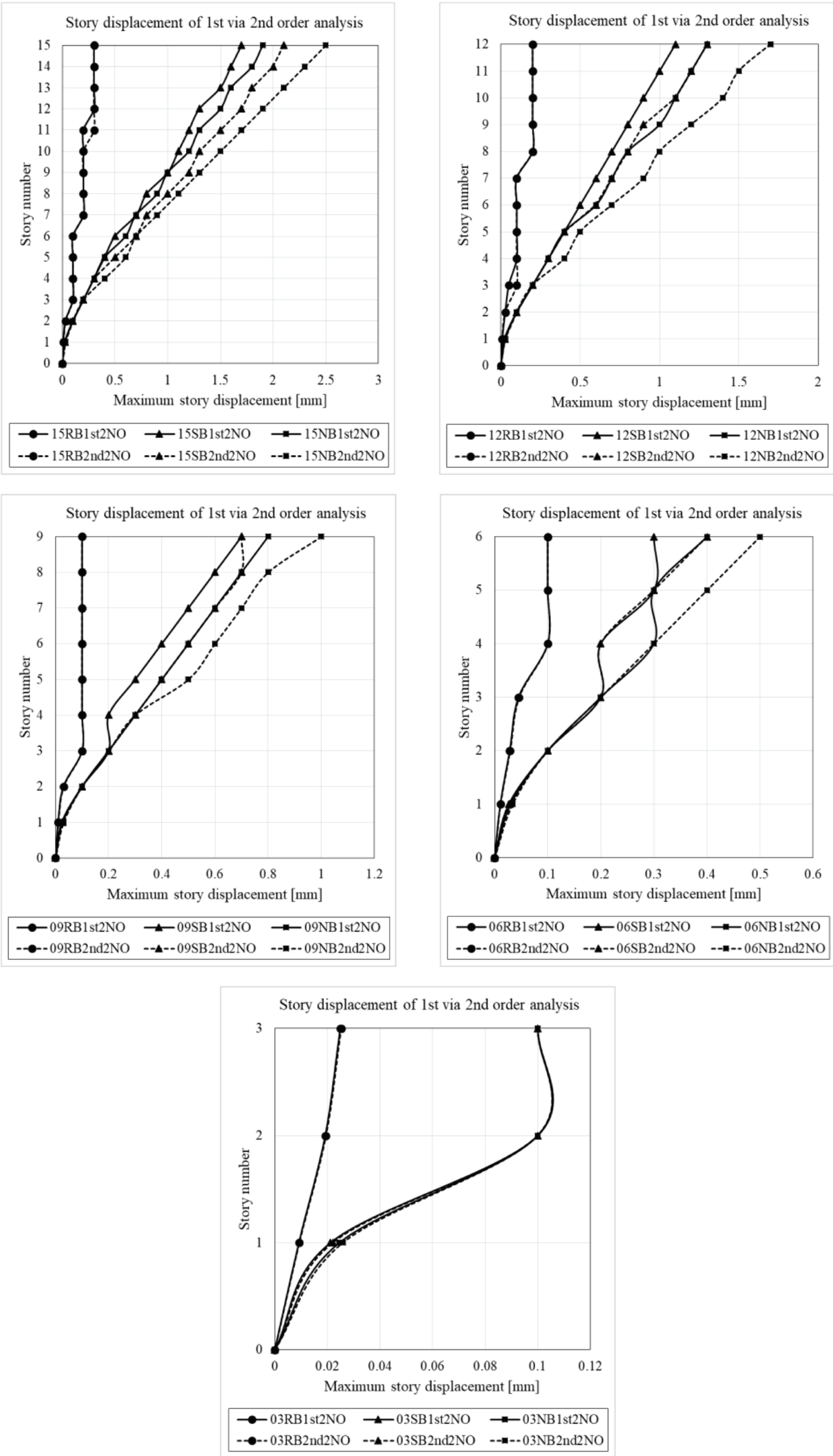


Fig. 3: Story lateral displacement for the 2^{nd} plan option.

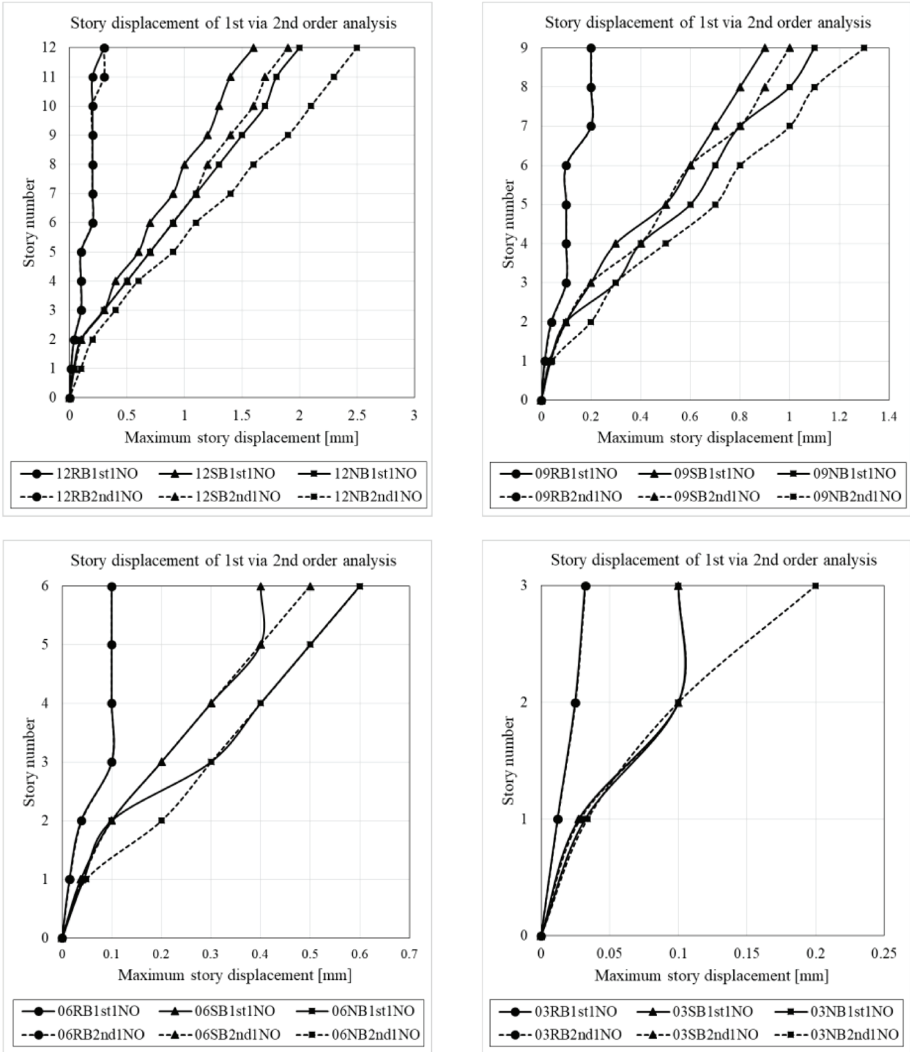


Fig. 4: Story lateral displacement for the 1st plan option.

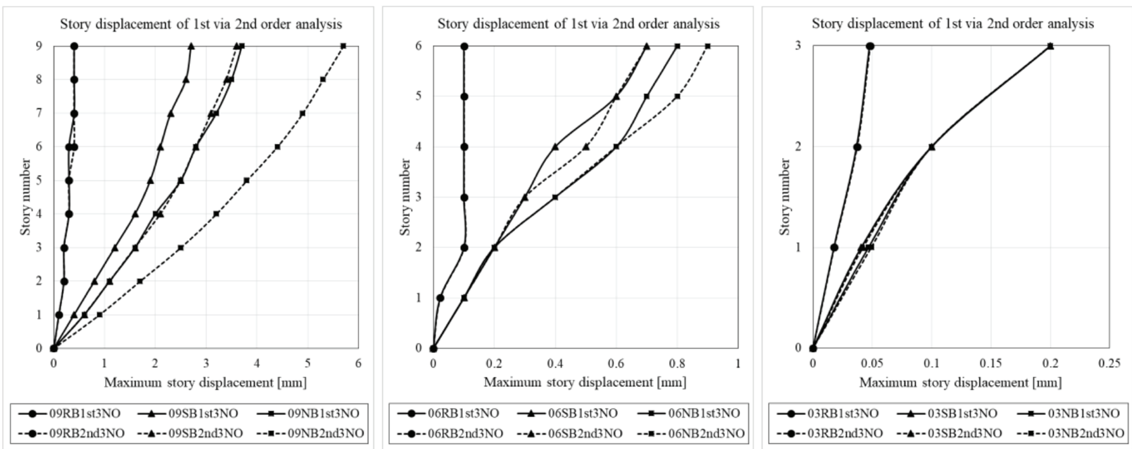


Fig. 5: Story lateral displacement for the 3rd plan option.

5. CONCLUSIONS:

A simplified approximate method for classifying columns in sway frames as braced/unbraced has been developed. The method depends on finding an equivalent wall stiffness that has the same lateral restraint effect as the frame. The equivalent wall stiffness is used in Eq. (1) to determine if the building is braced or unbraced. This simplified approach eliminates the need to perform a second order analysis to determine if a building is braced or unbraced. The proposed procedure has been verified and it is always on the safe side.

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Received:00/00/00 *Accepted:00/00/00*