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THE EFFECT OF INFILL WALLS ON THE SEISMIC RESPONSE OF IRREGULAR R.C FRAMES

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Abstract: Reinforced concrete (RC) frames with unreinforced masonry (URM) infill walls are commonly used as the structural system for buildings in many seismically active regions around the world. Structural engineers recognize that many buildings of this type have performed poorly during earthquakes. On the other hand, URM infill walls are generally treated as non-structural elements because they are used mainly for architectural purposes, and structural engineers often ignore their effect during structural design. It is worth noting that Infill walls contribute to the lateral force resisting capacity of the structure where they increase the initial stiffness and decrease the fundamental period of the structure. This might be beneficial or detrimental, depending on the frequency content of the ground motion. However, Masonry infills in reinforced concrete buildings cause several undesirable effects under seismic loading such as short-column effect, soft-story effect, and torsion in case of asymmetrical distribution of walls. But the continuity of these walls is not always assured, due to the need to have an open floor for parking, which may cause soft story effect at the building. In this research, the effect of infill walls' presence and distribution on the performance of the soft-story R.C frames will be studied by generating finite element models for 2D frames with different number of floors, infill percentage and by applying Performance-based seismic design (PBSD) which went virally throughout the past years and by introducing recently defined performance factor (P) as an alternative to response modification factor (R) overcoming any limitations restricted by the usage of (R) factor, and by studying the performance objective under seismic events.

Index Terms **– Seismic Analysis, Non-linear Pushover Analysis, Masonry Infills, Soft Storey, Irregular Structures, Performance Factor, Response Modification Factor, RC Moment Resisting Frames.**

1 INTRODUCTION

Infill walls contribute to the lateral force resisting capacity of the structure where they increase the initial stiffness and decrease the fundamental period of the structure, which might be beneficial or detrimental, depending on the frequency content of the ground motion. On the other hand, masonry infills in reinforced concrete buildings cause several undesirable effects under seismic loading such as short-column effect, soft-story effect, and torsion in case of asymmetrical distribution of walls causing the increase of lateral forces demand to be even higher than that of bare frame without infills. For example, what happened in the Jabalpur earthquake in India 1997, where the only RC frame buildings which were damaged where that of soft-first story due to the absence of infills to fulfill parking demands.

The interpolation of infills in the design of RC frame is a point of conflict between structure engineers where there are two points of view:

- Infills are not contributing to lateral load resisting and the whole load is carried by the bare frame either because of the infills are totally separated from the RC frames or built integral with the RC frame but considered as non-structural elements.
- Infills are considered as structural elements, acting as a diagonal strut changing the behavior of building from frame to truss action, increasing the axial forces on the columns, and reducing the bending moments and shear forces.

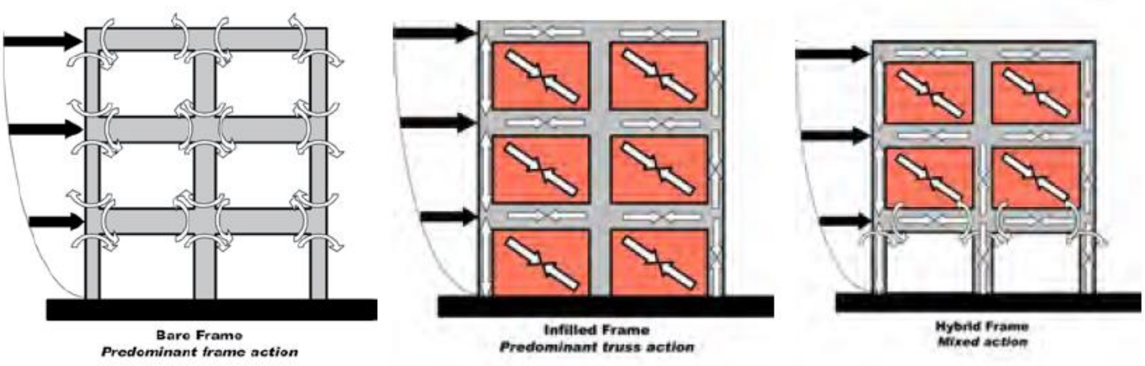

Figure 1: Effect of Infill wall on the behavior of RC frames

1.1 Stiffness-Soft Story:

One of the types of the vertical structural irregularity is stiffness-soft story, in which a story has a lateral stiffness less than that of the story above causing large earthquake demands and the discontinuity of flow of lateral force in the soft story, the percentage of reduction of stiffness causing the soft story varies from one code to another, in ASCE 7-16 stiffness-soft story irregularity is defined to exist where there is a storey in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above. However, in ECP-201 stiffness-soft story irregularity is defined to exist where there is a story in which the lateral stiffness is less than 75% of that in the story above. This commonly occurs in multistory buildings due to the need to have one or more stories for parking purposes having these stories widely opened leaving the building more likely to have soft story effect during earthquakes causing the localization of seismic deformation and failure in the bottom storey which may finally leads to the failure of vertical elements there.

1.2 Modeling of Infill Walls:

Over the history, there were two methods for modelling of infills which are micro and macro modeling, micro modeling is more accurate taking into consideration the local effects but consumes much time and needs complicated calculations where masonry bricks and mortar are modeled explicitly by means of Discrete Element Modeling approaches.

On the other hand, macro modeling was widely adopted to overcome the difficulties faced while using the micro-modeling, where the computational time and cost is noticeably reduced and the global effects are well captured, including the initial increase in stiffness, post-peak degradation behavior and the changing of the global plastic mechanism, however the local effects are not captured efficiently.

Equivalent diagonal compression strut is the most common strategy adopted for macro-modeling of infill walls. For the calculation of infill in-plane stiffness, FEMA-356 recommends the following equations.

$$a = 0.175(\lambda_1 h_{col})^{-0.4} \tag{1}$$

where:

$$\lambda_1 = \sqrt[4]{\frac{Eme\ tinf\ sin2\theta}{4\ Efe\ Icol\ hinf}} \tag{2}$$

and

h_{col} = Column height between centerlines of beams.
h_{inf} = Height of infill panel.
E_{fe} = Expected modulus of elasticity of frame material.
E_{me} = Expected modulus of elasticity of infill material.
I_{col} = Moment of inertia of column.
L_{inf} = Length of infill panel.
r_{inf} = Diagonal length of infill panel.
t_{inf} = Thickness of infill panel and equivalent strut.

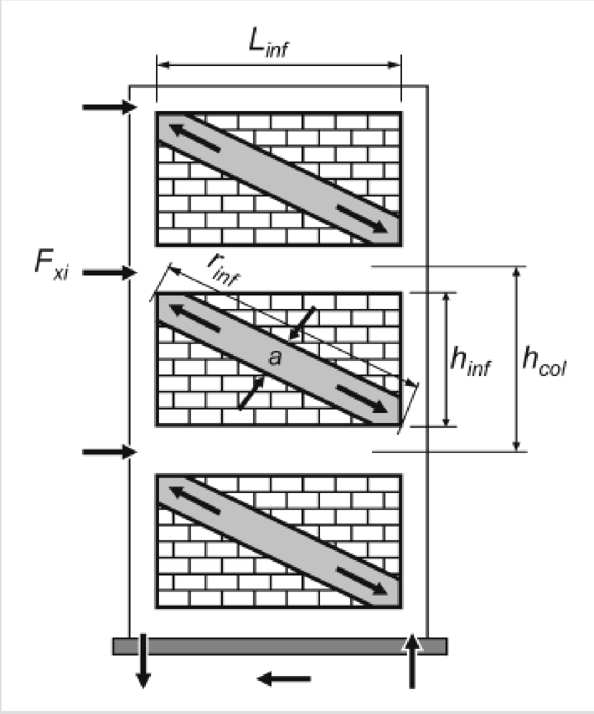

Figure 2: Compression Strut Analogy

2 METHODOLOGY

Pushover analysis is a method to perform non-linear static analysis (NSA) where the structure is subjected incrementally to a monotonically increasing load pattern till a target displacement is reached or till the structure comes to a limit state. Consequently, some structural members yield. The model is then modified to take into consideration the reduced stiffness of the building and the building is then reloaded till additional member yields and so on. The result of this procedure is a non-linear force displacement curve called pushover curve, showing the behavior of the structure and the plastic hinges formation during the post-elastic region.

The building goes through several performance levels showing the damage condition of the building, these performance levels are illustrated as the following:

- Immediate Occupancy: No damage to the structural components and few damage to the nonstructural elements.
- Life Safety: Some damage to the structural components which will need repair and significant damage to the nonstructural elements.
- Collapse Prevention: Extensive damage near collapse to the structural and nonstructural components.

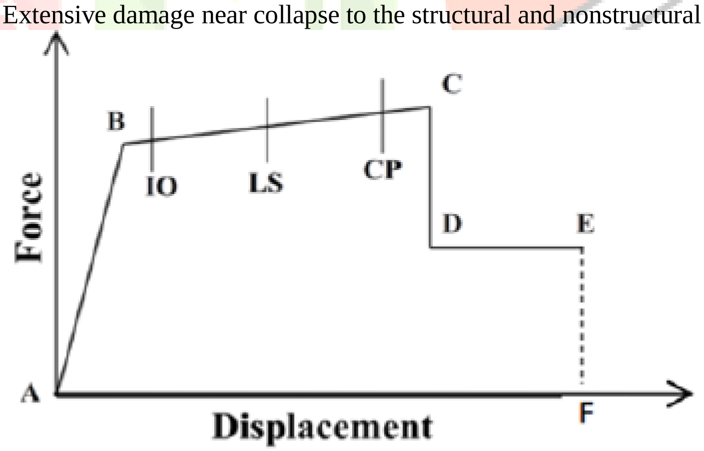

Figure 3: Force-deformation criteria for hinges used in pushover analysis

2.1 Nonlinear static analysis methodologies for Performance assessment of buildings

2.1.1 Capacity Spectrum Method (ATC-40,1997)

Capacity Spectrum Method, CSM was presented by Freeman et al. (1975) as a rapid seismic assessment tool for buildings. Subsequently, the method was adopted as a seismic design tool. The performance point is achieved by the intersection of two curves the capacity curve and demand curve taking into consideration the effect of hysteretic damping.

Capacity curve is generated from the conversion of pushover curve including the relation between lateral force and displacement (V vs d) curve into capacity spectrum curve including the relation between the spectral acceleration and spectral displacement (Sa vs Sd) curve.

Demand curve is generated from the conversion of traditional Response spectrum including the relation between spectral acceleration and time (Sa vs T) into demand spectrum including the relation between spectral acceleration and spectral displacement (Sa vs Sd) curve, Therefore the capacity curve and seismic demand curve can be plotted on the same axes.

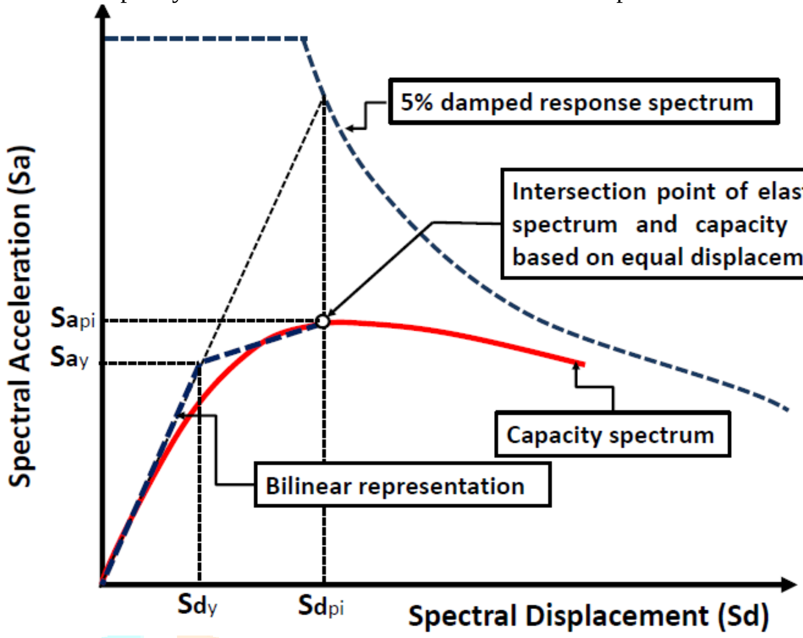

Figure 4: Capacity Spectrum Method

2.1.2 Displacement Coefficient Method (FEMA-356)

In Displacement Coefficient Method the pushover curve is used to determine effective stiffness and period which are used with response spectrum giving spectral acceleration. Spectral acceleration in return is converted to inelastic displacement by applying modification factors. The result is the target displacement used to determine the performance of the structure.

C0=Modification factor to relate spectral displacement to building roof displacement, as determined by Table 3-2 of FEMA 356.

C1=Modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response

C2=Modification factor to represent the effect of pinched hysteretic shape, stiffness degradation and strength deterioration on maximum displacement response. Taken from Table 3-3 of FEMA 356 for different framing systems and structural performance levels

C3=Modification factor to represent increased displacement due to dynamic P-D effects.

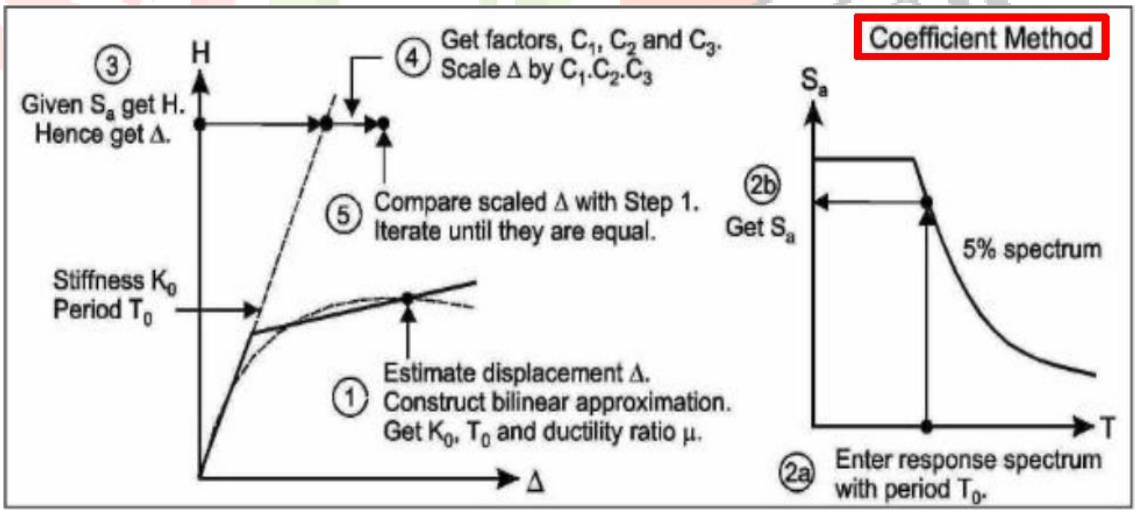

Figure 5: Displacement Coefficient Method

2.1.3 FEMA-440 Improvement for nonlinear static seismic analysis procedures

FEMA 440 has developed a more accurate versions of both CSM and DCM methods to be compatible with the performance-based seismic design. CSM was developed by introducing a more efficient bilinear approximation of the pushover curve. Also, improving the procedures for estimating the effective viscous damping and time period. For the DCM, FEMA-440 adjusted the C2 coefficient to represent the stiffness degradation only. And for C3, it was suggested to be eliminated and replaced with minimum strength which was intended to account for the dynamic instability. The prementioned modifications for DCM method were later incorporated in the ASCE, 2007b and ASCE, 2014.

Also, FEMA-440 explained that using multiple load patterns as the ones found in the requirements of FEMA-356 that the analysis should be executed by two separate load patterns only make little enhancement to the accuracy of the NSPs and that it is more recommended to use a single load pattern based on the first mode of vibration.

2.2 Nonlinear static analysis methodologies for Performance assessment of buildings

Response Modification factor is used to determine the inelastic behavior of building during earthquakes by dividing the elastic response by this factor permitting the damage of structure to a considered extent. Different codes suggest different values for R factor depending on the structure lateral load resisting system, geometry and ductility detailing stated by the code for example ECP-201 has R-factor equals to 5 and 7 for RC moment-resisting frames with limited and sufficient ductility respectively.

2.3 Calculation of P-factor:

P-factor will be calculated using the ATC-19 method to calculate the R-factor which was first developed by Berkeley in the mid-1980s from experimental research at the University of California. Where R-factor is the product of three factors standing for ductility, overstrength and redundancy.

$$R = Rs * RR * R\mu \qquad (3)$$

Strength Factor (Rs): calculated by dividing the ultimate strength (Vu) by the design strength (Vd), it represents the additional strength the structure can withstand beyond the design strength.

$$Rs = Vu / Vd \qquad (4)$$

Ductility Reduction Factor (Rμ): calculated by dividing the ultimate deformation δu by the yield deformation. Ductility could be defined as the capability of structure to undergoes deformation past its elastic limit without significant loss in its strength

$$\mu = \delta u / \delta y \qquad (5)$$

Redundancy Reduction Factor (R_R): A redundant system includes many vertical lines of framing resisting lateral loads and transferring it to the foundation, for redundant system the factor is equals to unity.

3 MODELING

3.1 Verification

In this paper commercial finite element software Etabs V17 is used in generating the infilled frames models, The experimental push and pull envelopes of the cyclic experimental results carried out by Liborio Cavaleri et al. were used to verify the results of modeling technique which will be used later in the comparative study including the modeling of infill. A single-storey single bay model was generated, the infill was defined as an equivalent diagonal single strut and that was represented as a multi-linear plastic link member in the Etabs model with properties varying according to the infill material as shown in **Error! Reference source not found.**.

Moreover, due to the difficulty in determining the δyield in case of infilled frames, an assumption was made by Feras to calculate the initial effective stiffeness allowing for any uncertainties could arise due to the cracking of infill as shown in **Error! Reference source not found.**. The ductility factor based on Feras assumption for the $K_{effect,infill}$, was verified by the one used by Cavaleri in his paper to calculate the ductility factor where he used the term $\mu_{0.85}$ and the error was 7.5%.

$\mu_{0.85}$ = The ratio between the displacements corresponding to the two points (one on the ascending and one on the descending branch of the pushover curve) intersecting a horizontal straight line drawn at 85% of the peak strength.

Another verification was made for samples of the models generated by Feras to make sure of the validity of the results of the thesis and to build up the comparative study based on these models and the result of the verification are shown in Figure 10.

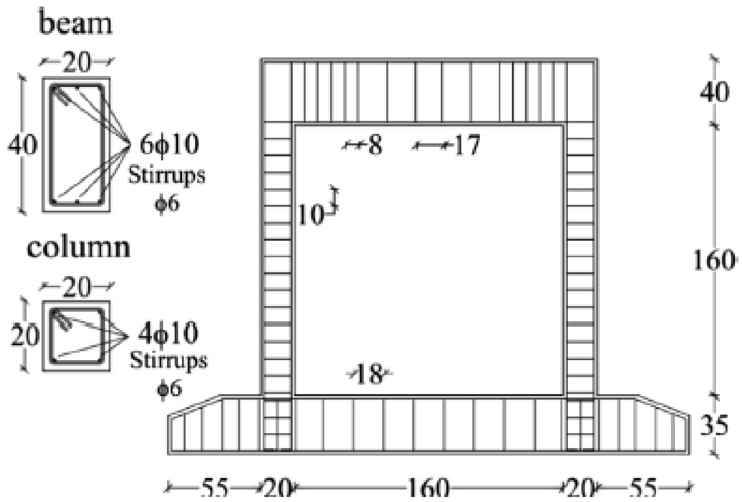

Figure 6: S1B clay infilled frame tested by Cavaleri et al.

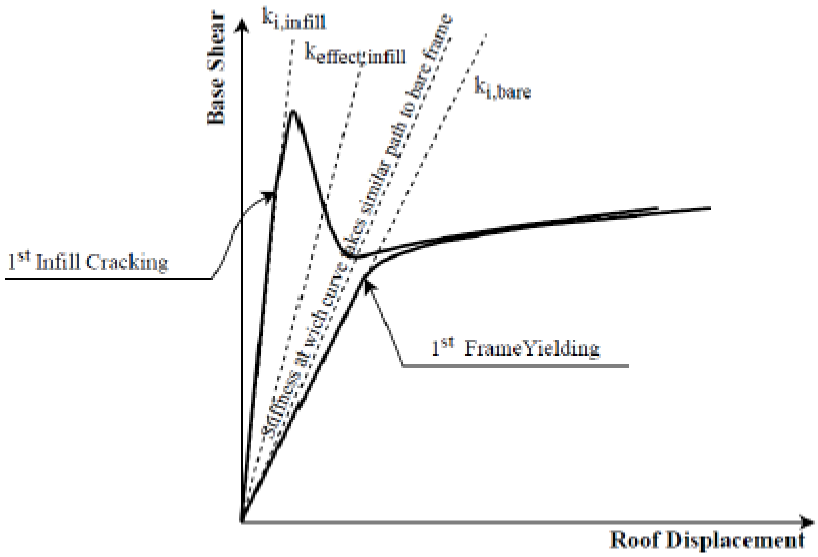

Figure 7: Assumed procedure for calculating effective initial stiffness for infilled frames Feras (2021)

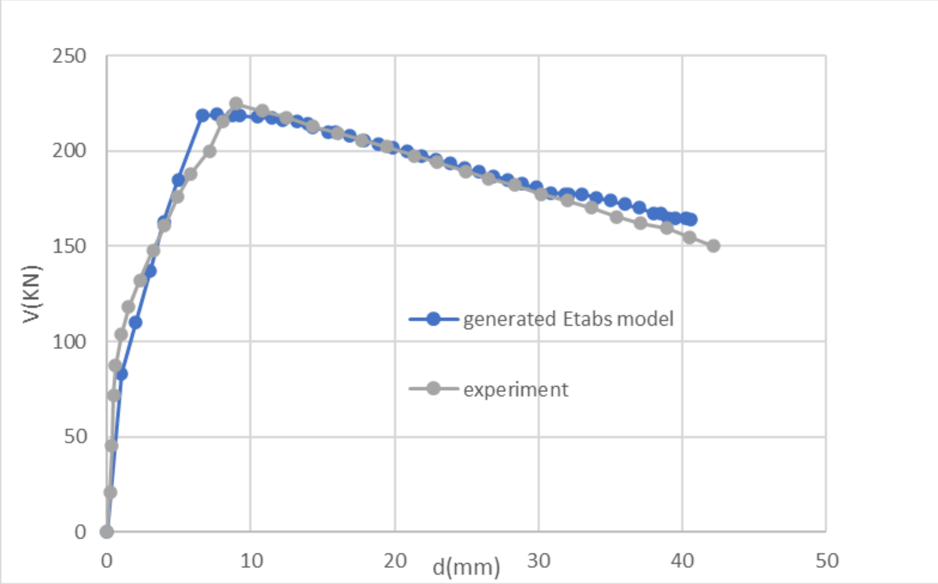

Figure 8: Pushover Results for S1B frame

	δmax	δyield	μmodel	μthesis	% of error
	27.3	5	5.46	5.08	7.48%

Figure 9: Results for ductility factor verification

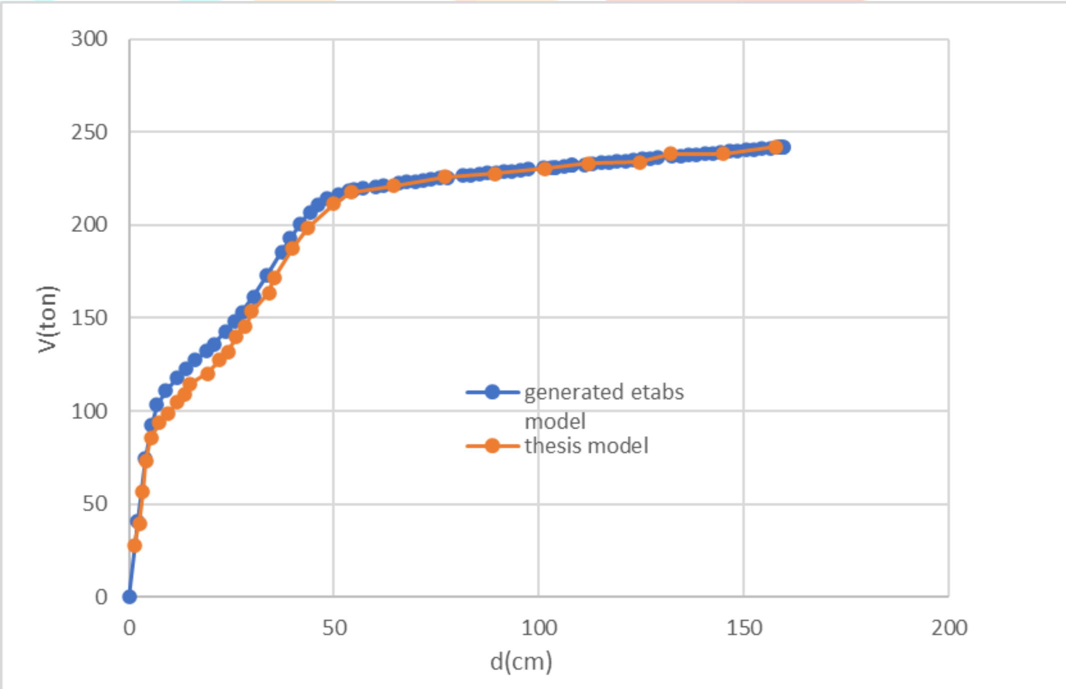

Figure 10: Verification Results for 25-CCD 100% infilled frame

3.2 Modeling and Analysis

In this paper the models generated by Feras et al, were used to study the effect of soft storey on the infilled R.C frames. Feras grouped 2D frames models into ten different groups depending on the height, infill's percentage, and performance level of the frame.

Groups (A, D, G, and I) were designed according to the ECP-201 FBD design method and were distinguished as code complaint designed (CCD) models, another different performance levels models were generated by neglecting the limitation of horizontal design spectrum, which were categorized as groups (B, E and H) for life safety and (C and F) for collapse prevention.

Groups (C, F, H and J) were first designed under vertical loads only. For groups (C and F) the structures showed collapse prevention performance (CP), so were redesigned for seismicity with no spectral limitation to enhance the performance level and creating groups (B and E) showing life safety (LS) performance level. Group H showed life safety (LS) performance directly when designed under vertical loading, while group (J) showed immediate occupancy (IO) performance under vertical loading.

3.2.1 Material Properties

Concrete:

- Compressive Cube Concrete Strength (Fcu)= 35 MPA
- Density of reinforced concrete (Yc)= 25 KN/m3
- Modulus of Elasticity (Ec)= 26030.75 MPA

Reinforcement: High strength steel reinforcement is used.

- Longitudinal and Confinement tie bars: Fy= 420 MPA, Fu= 525 MPA

Masonry: Red clay bricks are used:

- Density of masonry infill (Ym)= 18 KN/m3
- Fcu= 15MPA (Single unit)
- F'm= 4.8 MPA (Brick wall)
- Fdesign= 0.85*F'm= 4.08 MPA
- Modulus of Elasticity (Em)= 700* F'm= 3360 MPA
- Shear Modulus (GURM)= 0.4*Em=1344 MPA
- Dimension of single brick= length* thickness *height= 240mm*112mm*70mm

3.2.2 Vertical Loads

All frames are designed as an intermediate frame where loads are imposed from both sides of adjacent bays.

- 15cm thickness reinforced slab= 0.375 ton/m2
- 4cm thickness marble floor cover= 0.1 ton/m2
- Live load for office buildings= 0.25 ton/m2
- 1.8 ton/m3 density infill walls taken as line loads on beams= 0.5 ton/m'

3.2.3 Seismic Loads

Seismic loads are defined as per ECP-201 as follows

- Soil Type: D
- Seismic Zone: 5B
- Importance Factor: 1.0
- Response Spectrum Type: Type 1
- Ground Acceleration (ag): 0.3g

For the comparative study, first all Feras infilled frame models were generated, then every single model is subdivided into three groups by removing the infills represented in the models in the form of links as following:

- First Group: the infills are removed from the first storey.
- Second Group: the infills are removed from the first and the second stories.
- Third Group: the infills are removed from the first, second and third stories.

These groups with the original infilled frame models forming 160 models, all are generated, and the results are shown in the following section.

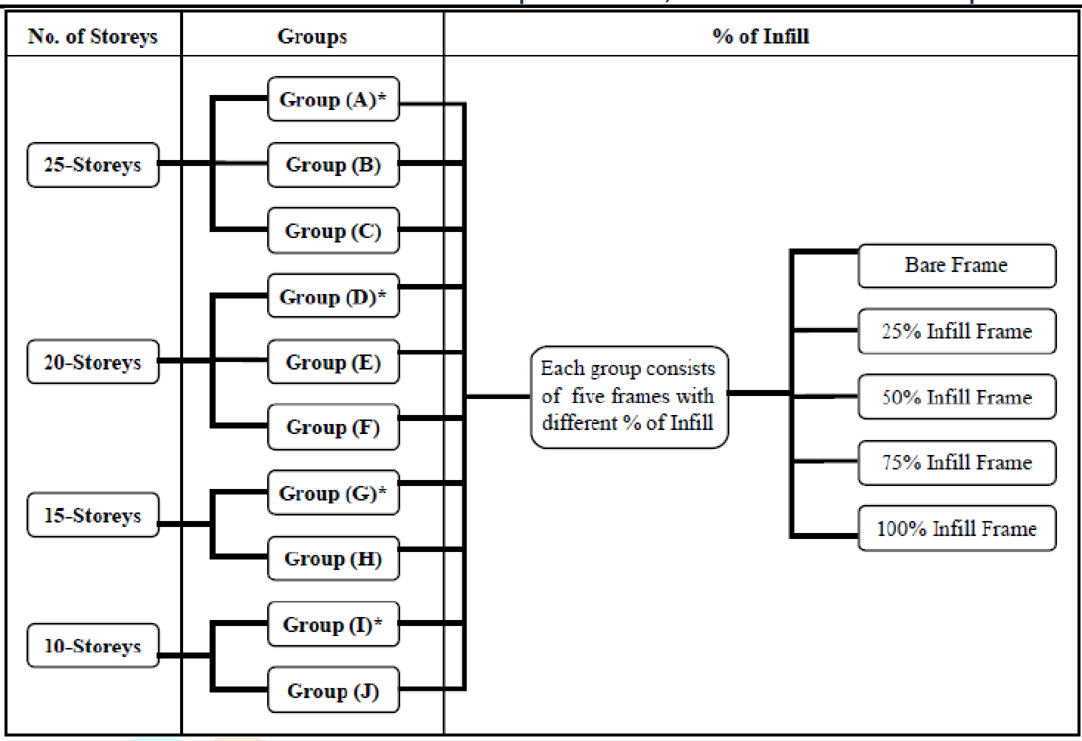

Figure 11: Feras (2021) structural models group classifications

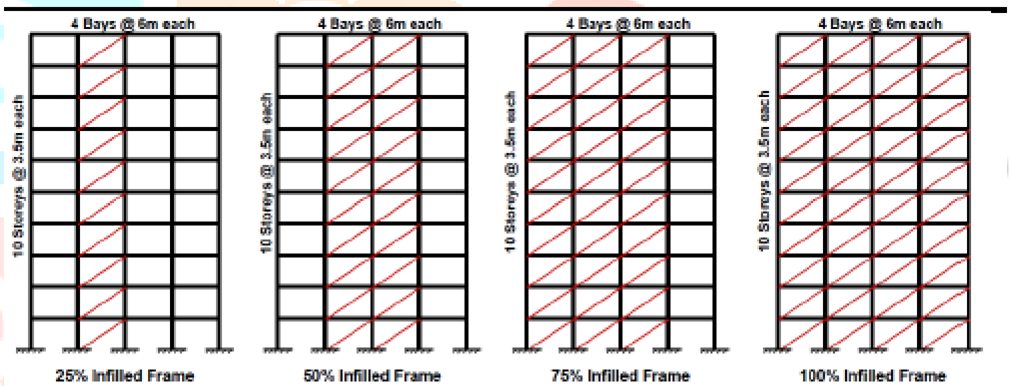

Figure 12: Example of infill distribution in 10-storey frame

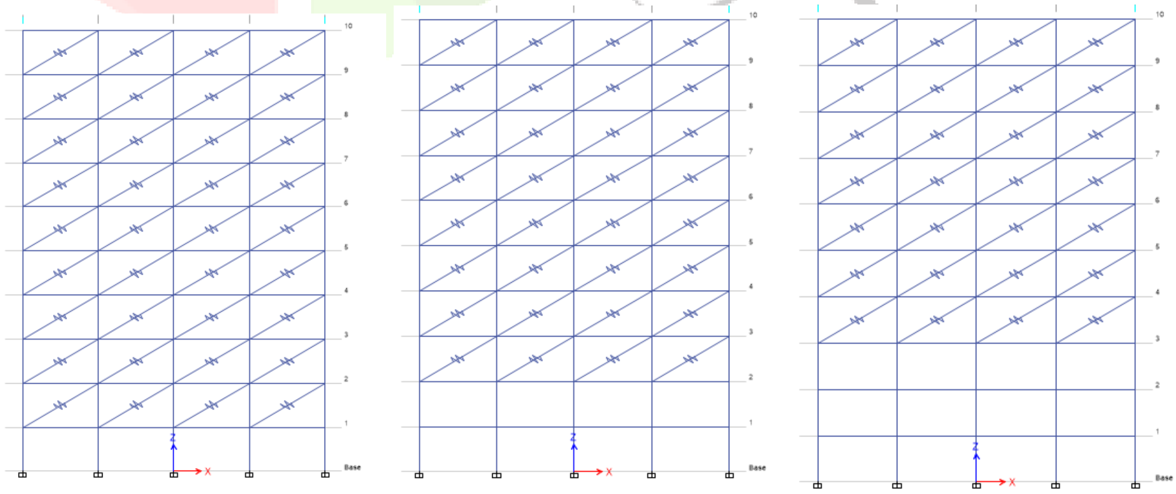

Figure 13: Example of Generated soft stories models in 10-storey frame

No of stories	Group	Bare Frame P-Factor
25 storey	A*	5.56
	B	13.64
	C	15.6
20 storey	D*	4.5
	E	13.71
	F	15.15
15 storey	G*	4.28
	H	13.68
10 storey	I*	5.35
	J	7.07

Figure 14: Feras (2021) P-Factor of Bare Frames

4 Results and Discussions

Models with different heights, infilled percentage and non-infilled stories are subjected to Pushover analysis, the improved version of Capacity Spectrum Method stated by FEMA-440 is applied to get the performance point. In this section, a comparative study is made to discuss the effect of soft story on the seismic behavior of infilled RC frames where the effect of soft stories is studied and the results are shown in the following figures based on the change in P-factor, drift values and performance level.

4.1 25-Storey Frames Models Results

4.1.1 Difference in P-Factor

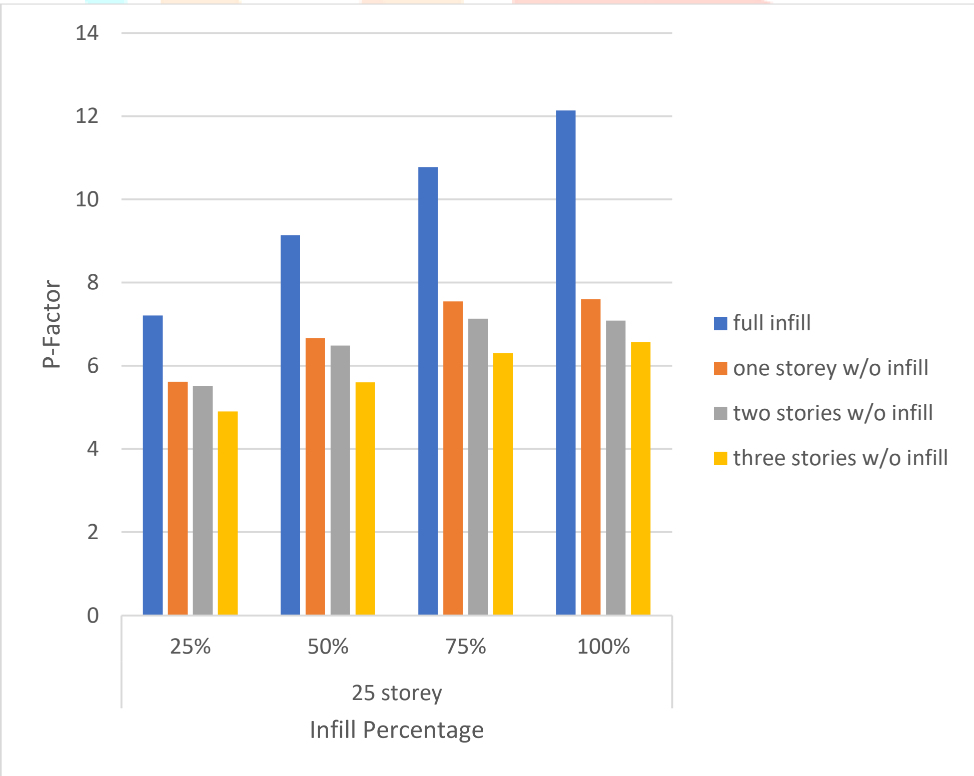

Figure 15: Group A* models

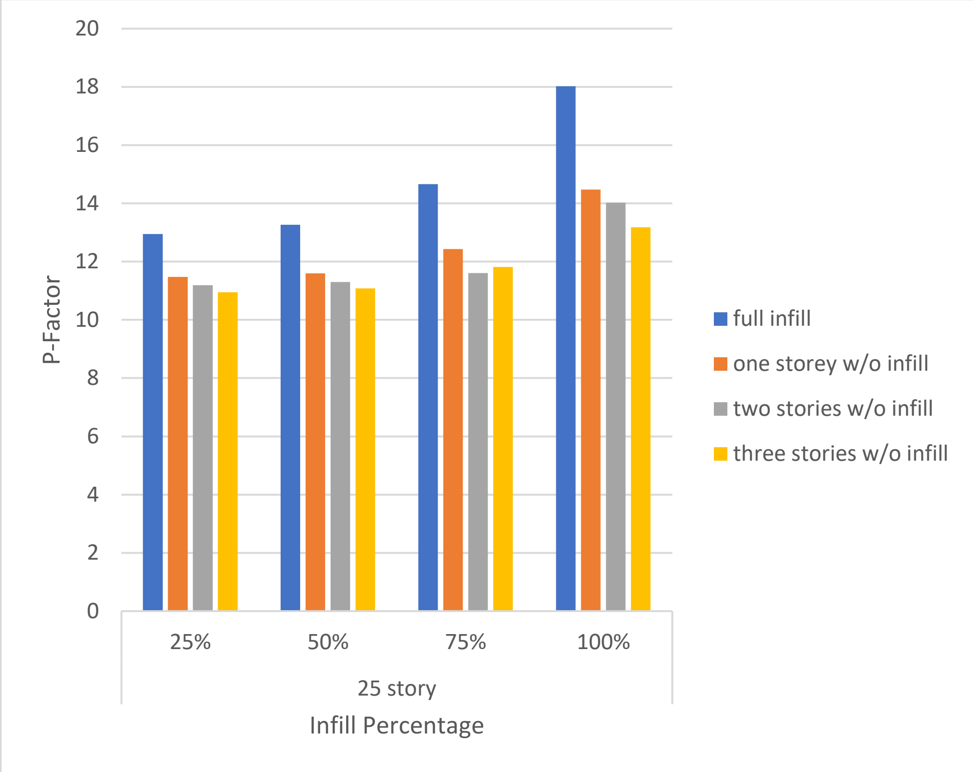

Figure 16: Group B models

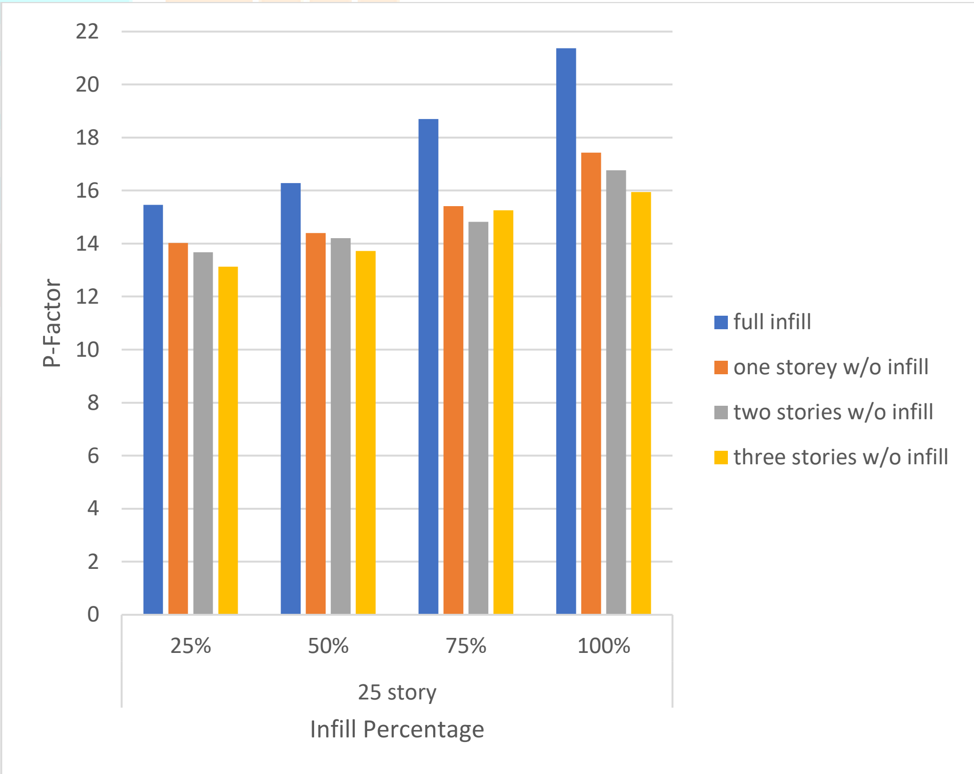

Figure 17: Group C models

4.1.2 Change in drift

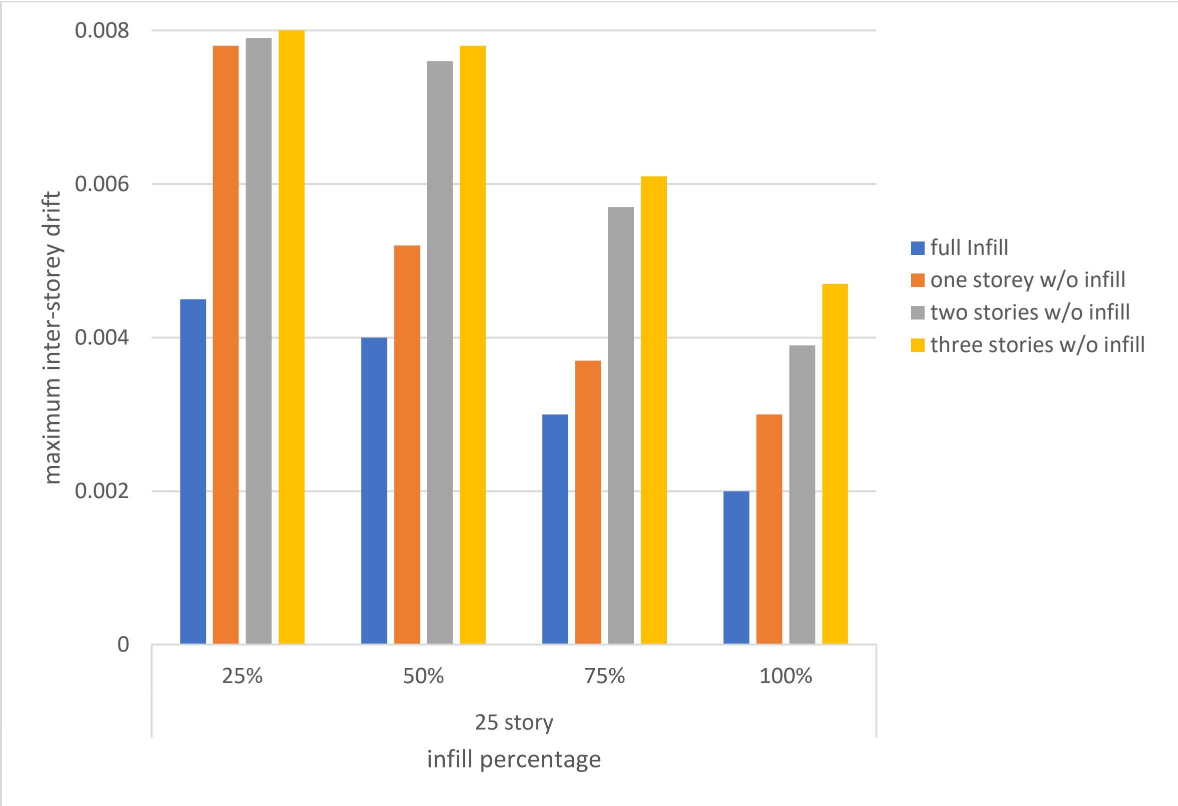

Figure 18: Group A* models

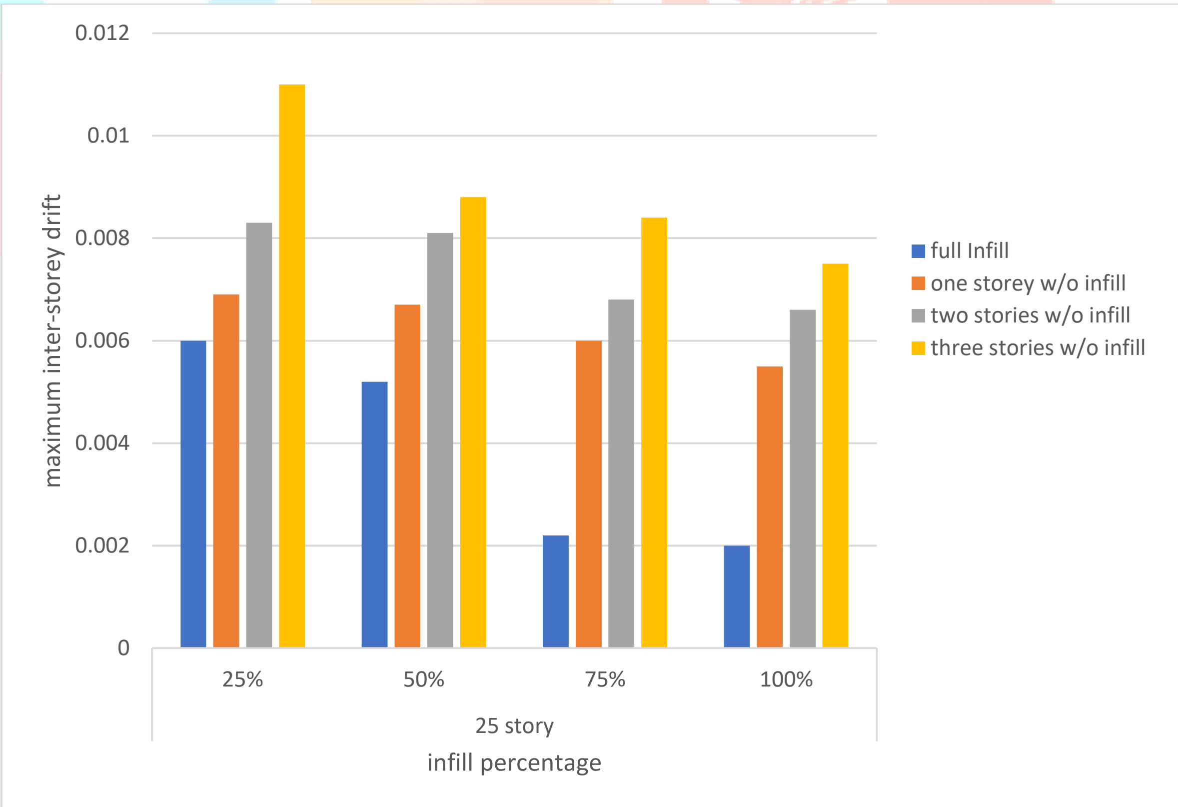

Figure 19: Group B models

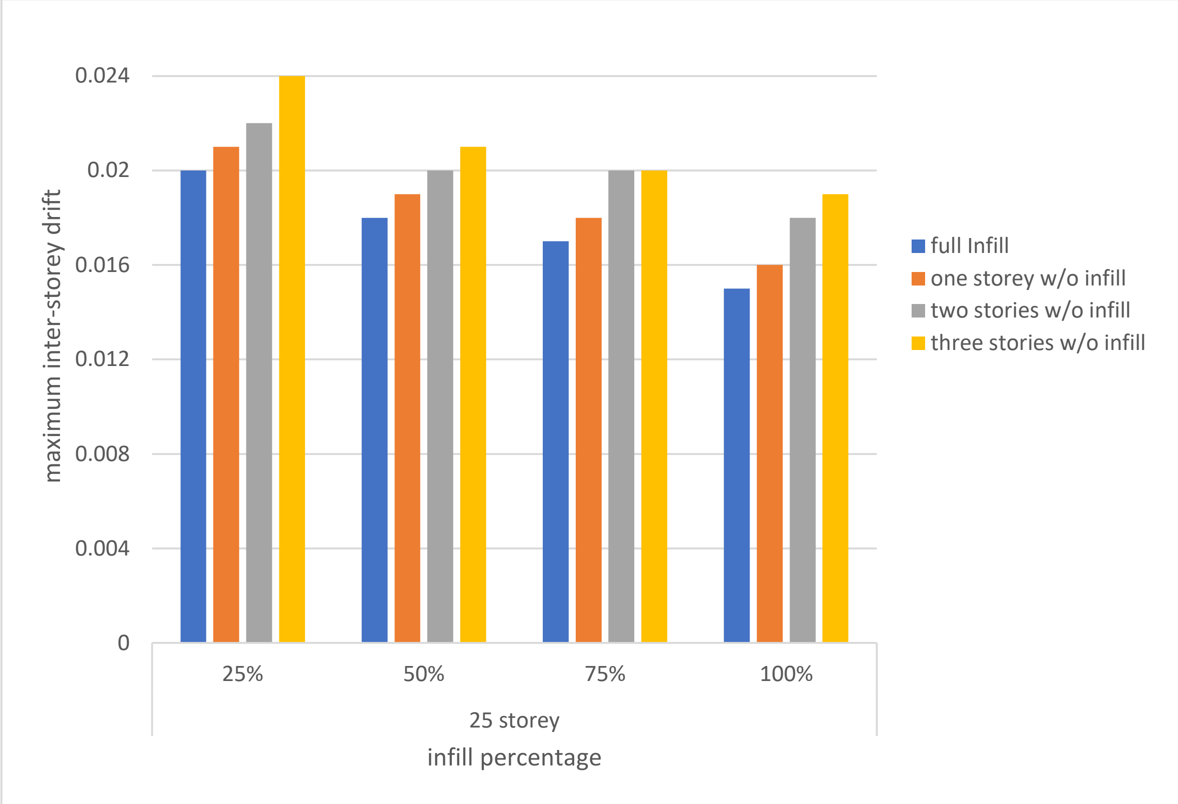

Figure 20: Group C models

4.1.3 Performance level

Table 1: Performance level for 25 storey models

No of stories	Group	% of infill	Performance level-Infill	Performance level-one storey w/o infill	Performance level-two stories w/o infill	Performance level-three stories w/o infill
25 storey	A*	25%	IO	IO	IO	IO
		50%	IO	IO	IO	IO
		75%	IO	IO	IO	IO
		100%	IO	IO	IO	IO
	B	25%	IO	IO	IO	IO
		50%	IO	IO	IO	IO
		75%	IO	IO	IO	IO
		100%	IO	IO	IO	IO
	C	25%	LS(75)	LS(85)	LS(87)	CP(4)
		50%	LS(73)	LS(74)	LS(77)	LS(81)
		75%	LS(69)	LS(72)	LS(74)	LS(76)
		100%	LS(48)	LS(49)	LS(64)	LS(66)

Results for 25-stories show the following:
As the number of stories without infill increases

- The P-factor decreases reaching a maximum decrease in 100% infilled frames models of 42% in Group A models, 27% in Group B models and 25.4% in Group C models.
- The drift values increase but still within the IO limits in Group A models, however at low percentage infilled frames the drift values push to Life safety and Collapse prevention performance levels at Group B and C respectively.
- The number of hinges formed increase and at those with low infill percentage the drift values push to Collapse prevention performance level in Group C.

4.2 20-Storey Frames Models Results

4.2.1 Difference in P-Factor

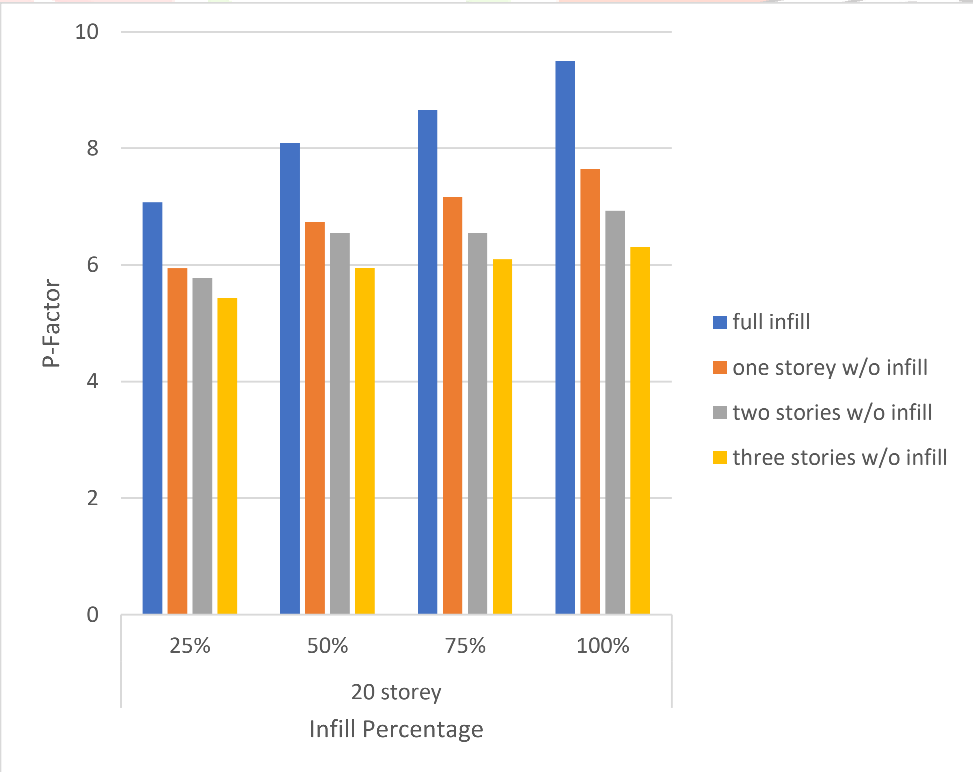

Figure 21: Group D* models

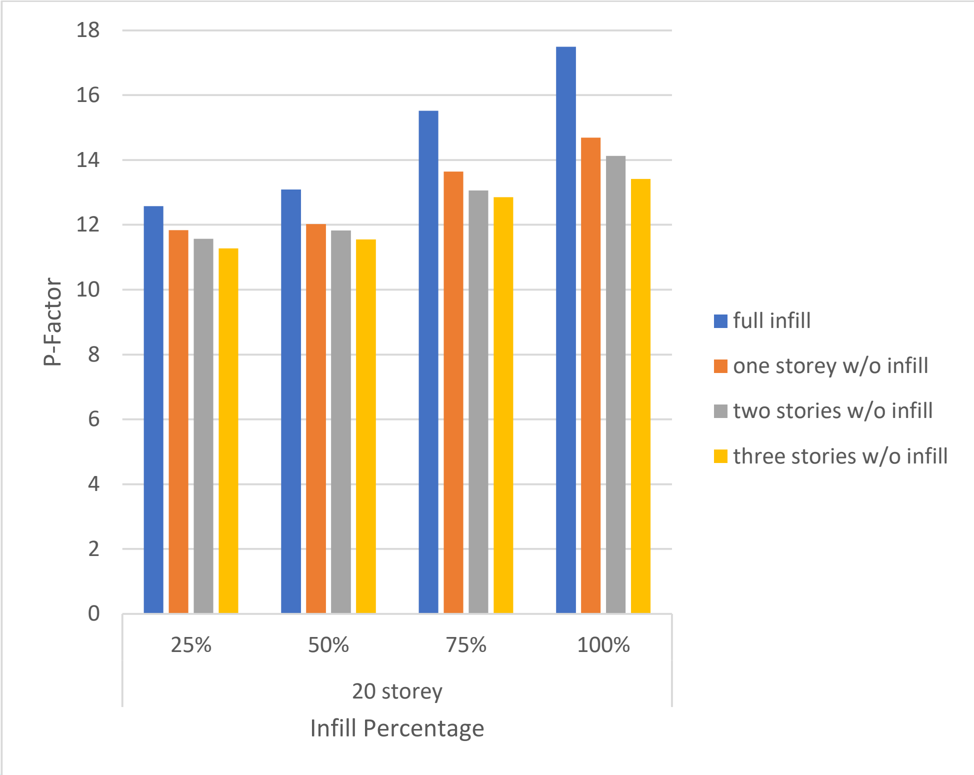

Figure 22: Group E models

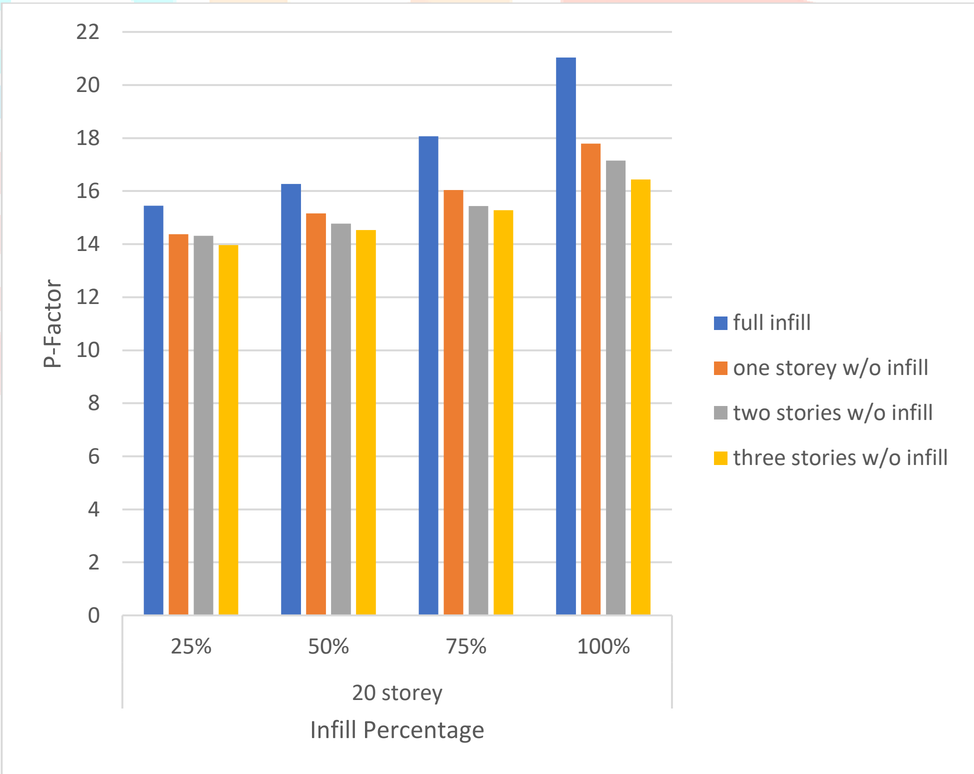

Figure 23: Group F models

4.2.2 Change in drift

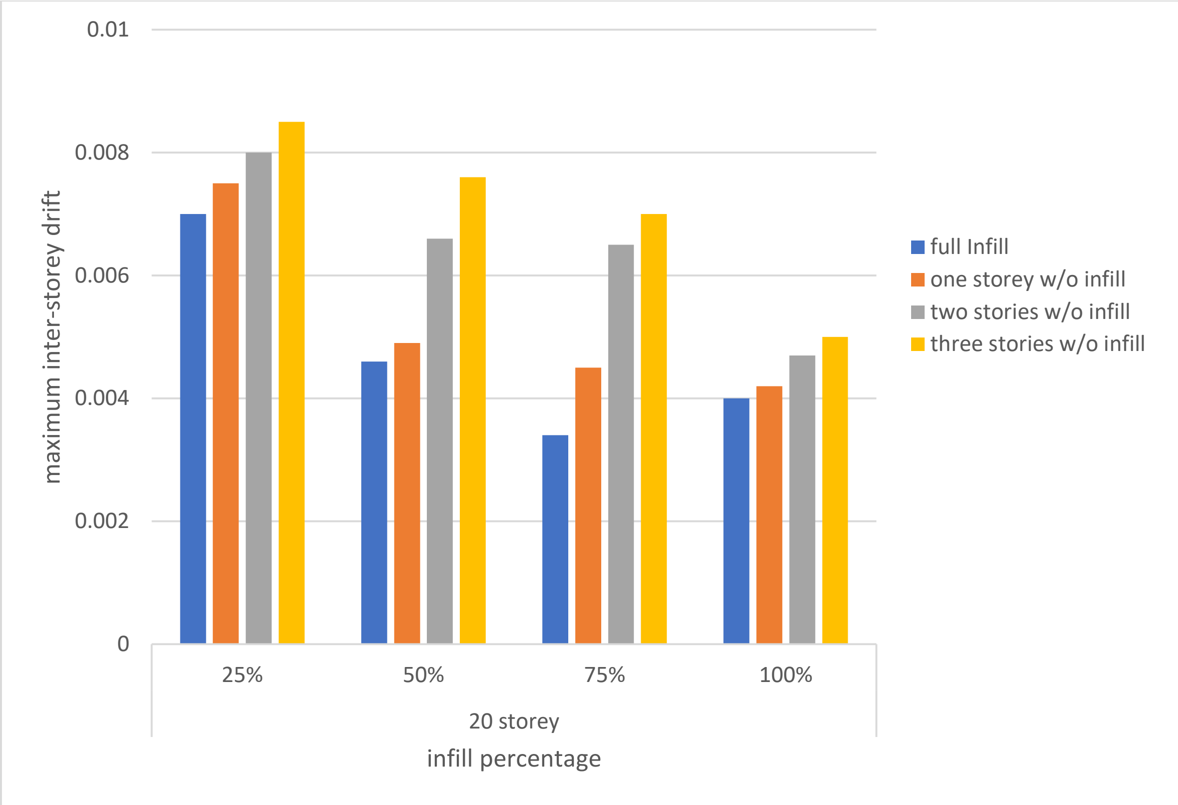

Figure 24: Group D* models

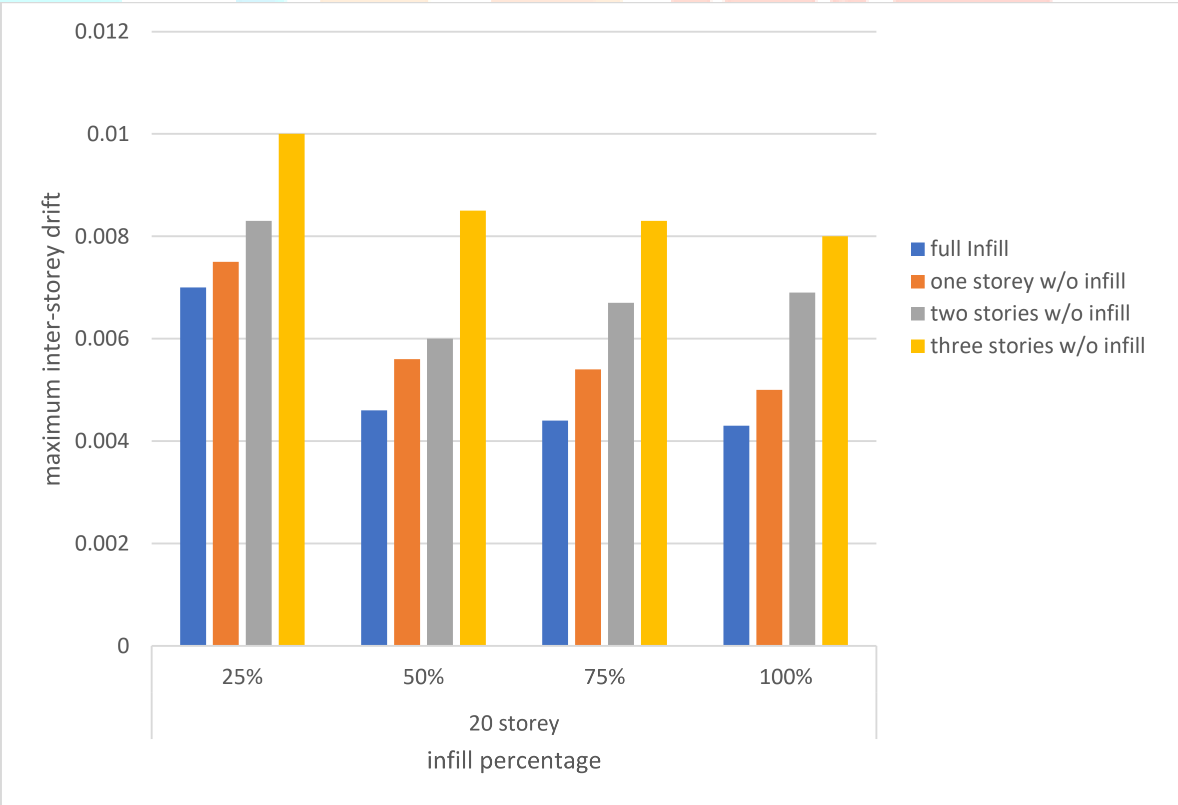

Figure 25: Group E models

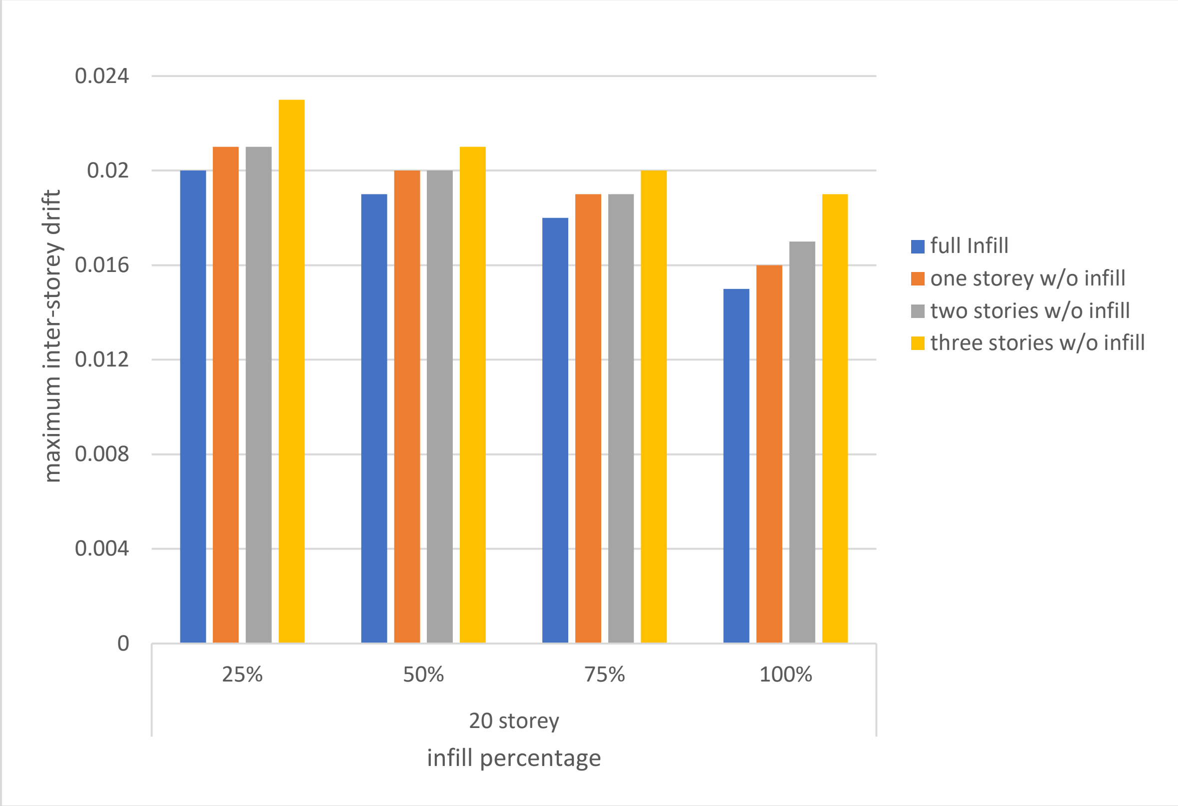

Figure 26: Group F models

4.2.3 Performance level

Table 2: Performance level for 20 storey models

No of stories	Group	% of infill	Performance level-Infill	Performance level-one storey w/o infill	Performance level-two stories w/o infill	Performance level-three stories w/o infill
20 storey	D*	25%	IO	IO	IO	IO
		50%	IO	IO	IO	IO
		75%	IO	IO	IO	IO
		100%	IO	IO	IO	IO
	E	25%	IO	IO	IO	IO
		50%	IO	IO	IO	IO
		75%	IO	IO	IO	IO
		100%	IO	IO	IO	IO
	F	25%	LS(73)	LS(78)	LS(81)	CP(2)
		50%	LS(69)	LS(65)	LS(71)	LS(74)
		75%	LS(60)	LS(60)	LS(65)	LS(67)
		100%	LS(44)	LS(47)	LS(50)	LS(59)

Results for 20-stories show the following:
As the number of stories without infill increases

- The P-factor decreases reaching a maximum decrease in 100% infilled frames models of 33.6% in Group-D models, 23.3% in Group-E models and 21.8% in Group-F models.
- The drift values increase but still within the IO limits in Group D* models, however at low percentage infilled frames the drift values push to Life safety and Collapse prevention performance levels at Group E and F respectively.
- The number of hinges formed increase and at those with low infill percentage the performance level pushes to Collapse prevention performance level in Group F.

4.3 15-Storey Frames Models Results

4.3.1 Difference in P-Factor

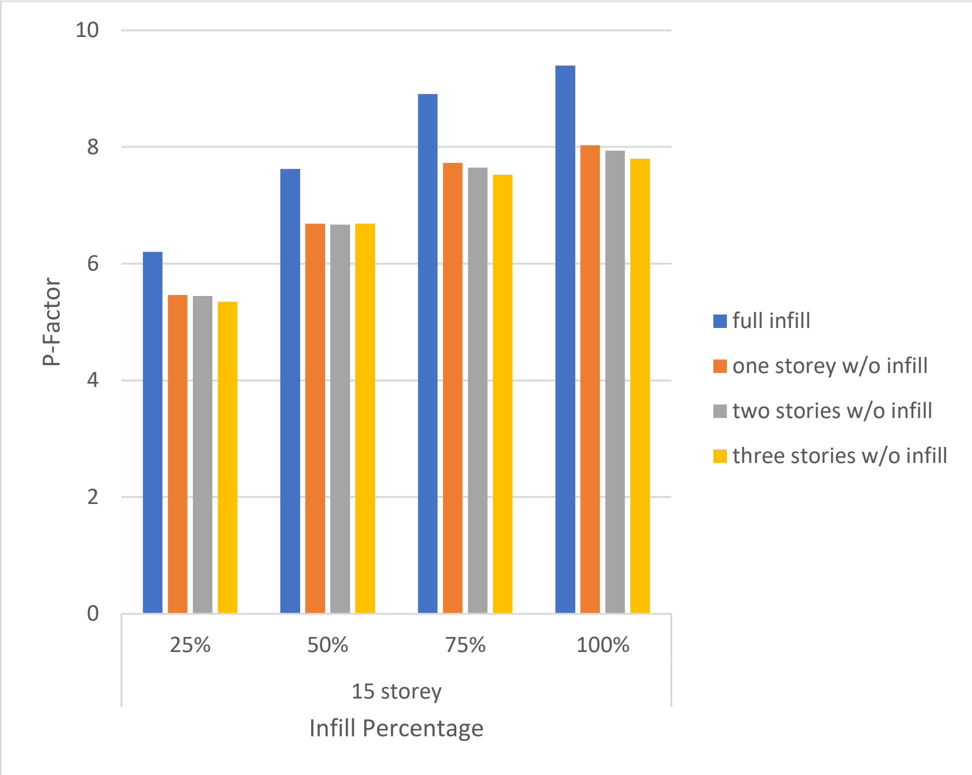

Figure 27: Group G* models

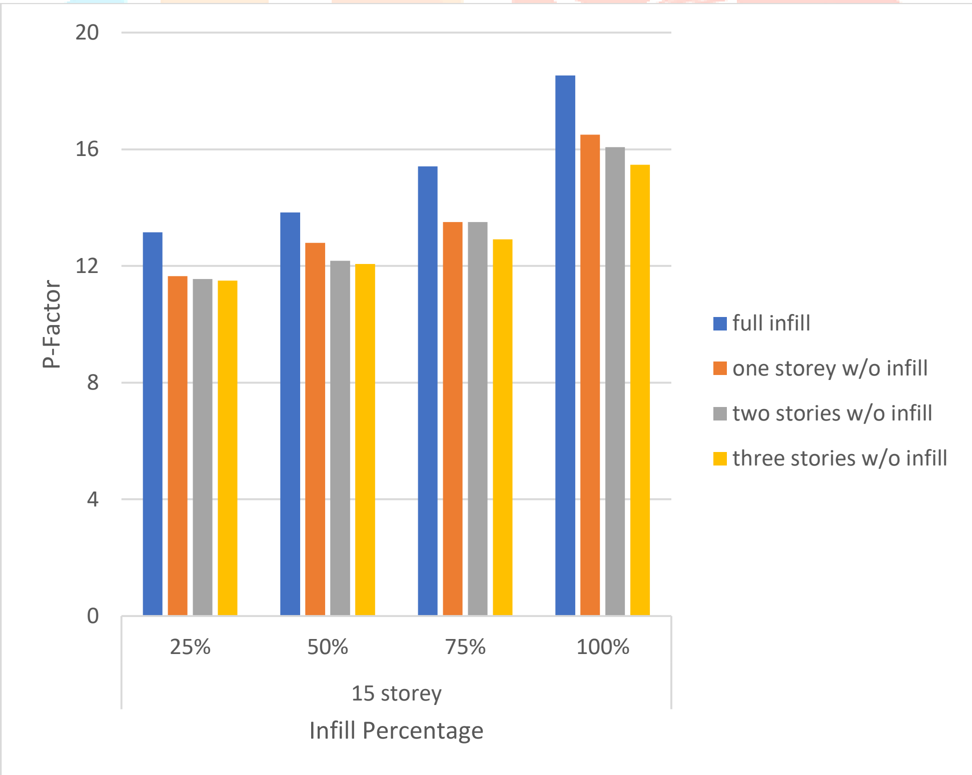

Figure 28: Group H models

4.3.2 Change in drift

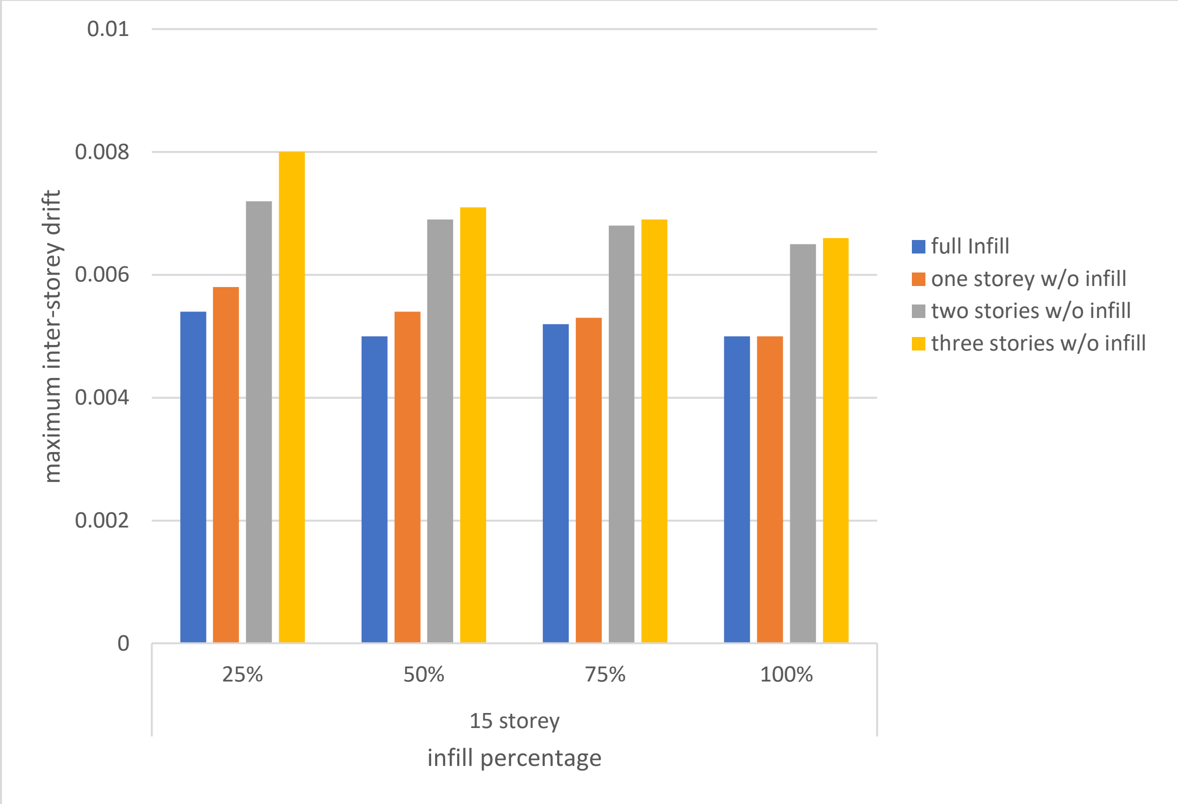

Figure 29: Group G* models

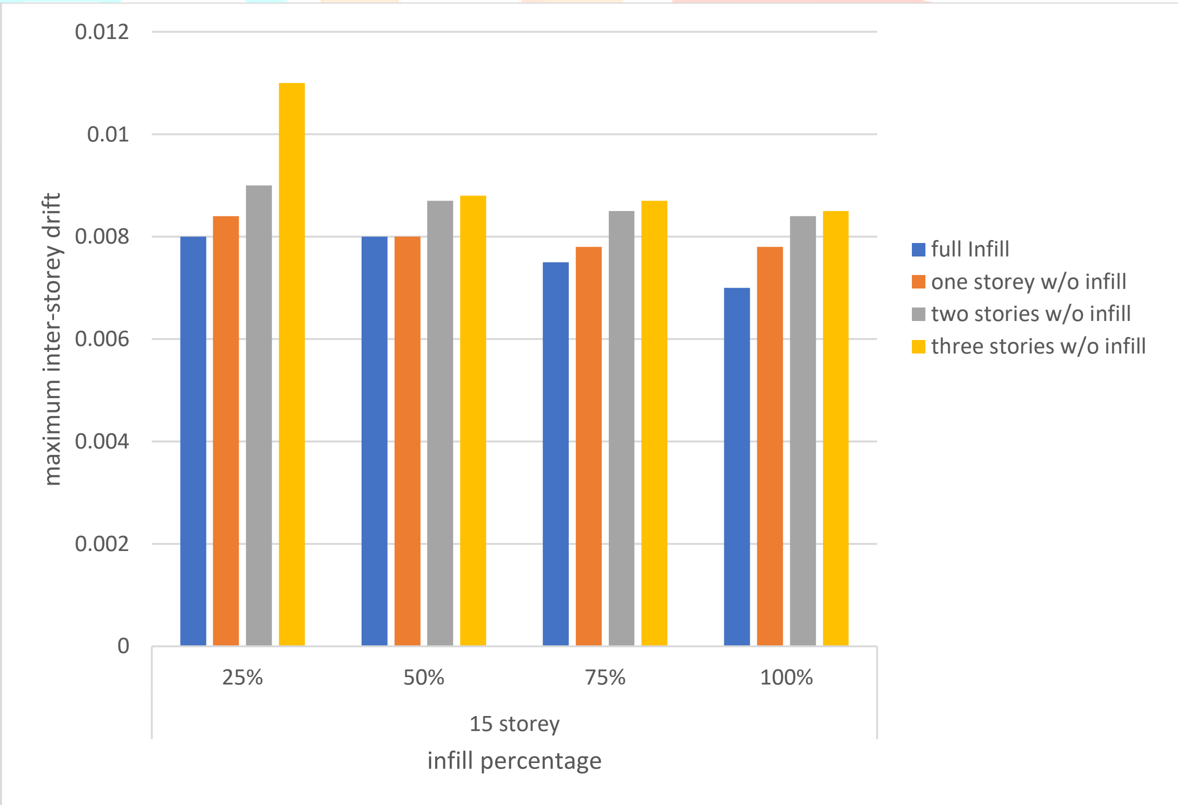

Figure 30: Group H models

4.3.3 Performance level

Table 3: Performance level for 15 storey models

No of stories	Group	% of infill	Performance level-Infill	Performance level-one storey w/o infill	Performance level-two stories w/o infill	Performance level-three stories w/o infill
15 storey	G*	25%	IO	IO	IO	IO
		50%	IO	IO	IO	IO
		75%	IO	IO	IO	IO
		100%	IO	IO	IO	IO
	H	25%	IO	IO	IO	IO
		50%	IO	IO	IO	IO
		75%	IO	IO	IO	IO
		100%	IO	IO	IO	IO

Results for 15-stories show the following:
As the number of stories without infill increases

- The P-factor decreases reaching a maximum decrease in 100% infilled frames models of 18.2% in Group G* models and 16.5% in Group H model.
- The drift values increase but still within the IO limits in both Group G*, however at low percentage infilled frames the drift values push to Life safety performance levels at Group H.
- The number of hinges formed increase but still within IO for both of Group G* and H.
- 10-Storey Frames Models Results

4.3.4 Difference in P-Factor

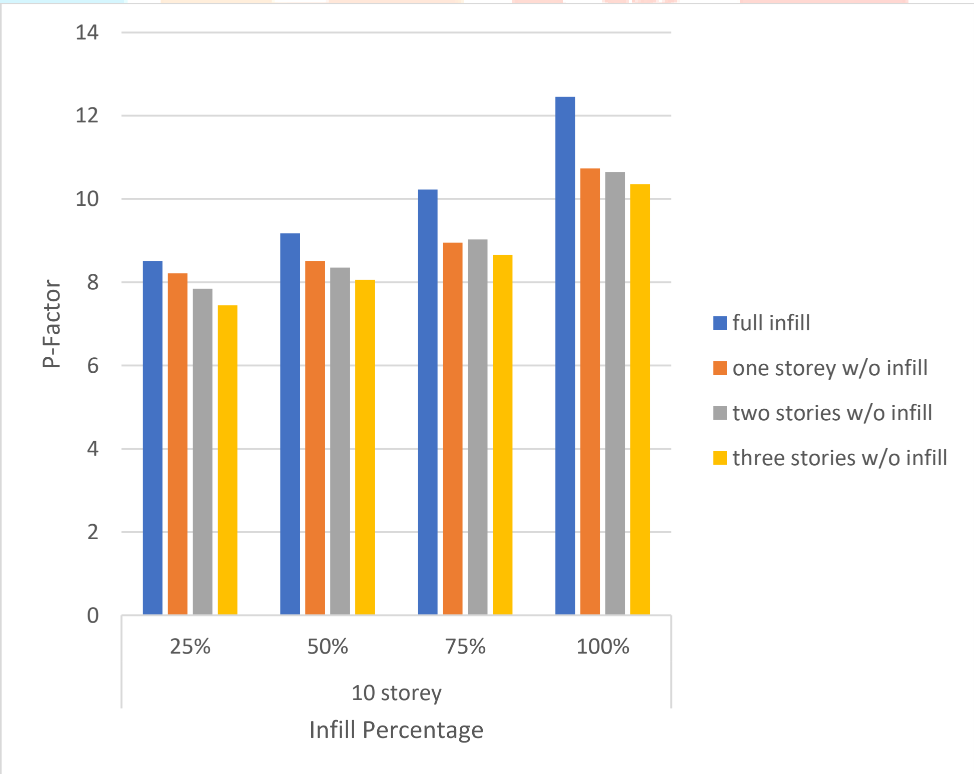

Figure 31: Group I* models

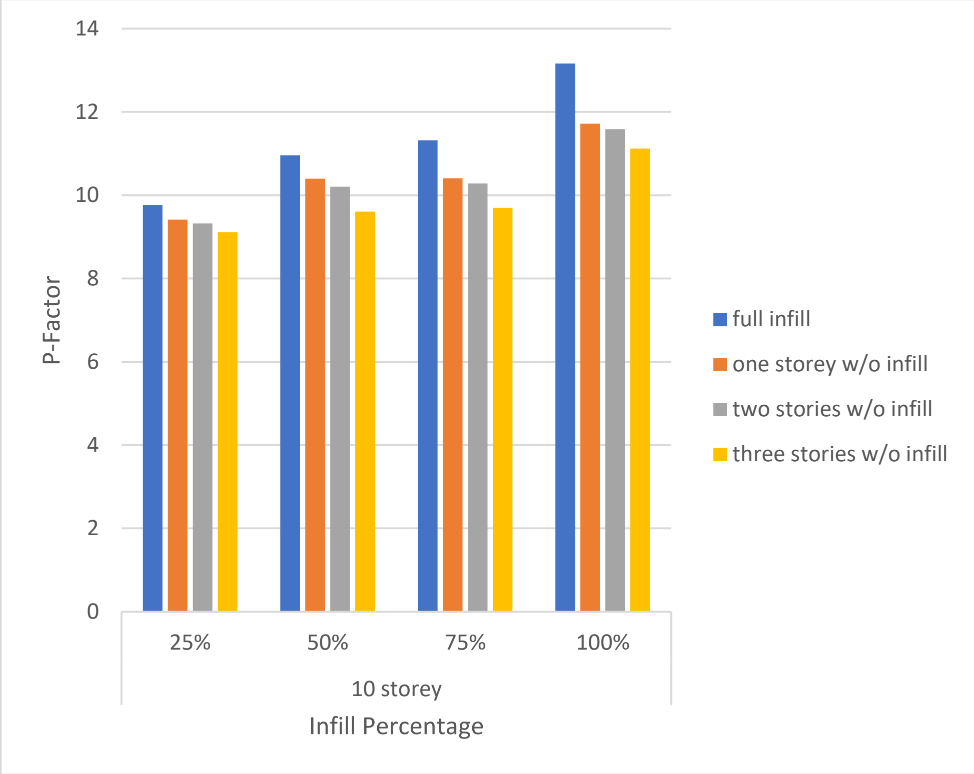

Figure 32: Group J models

4.3.5 Change in drift

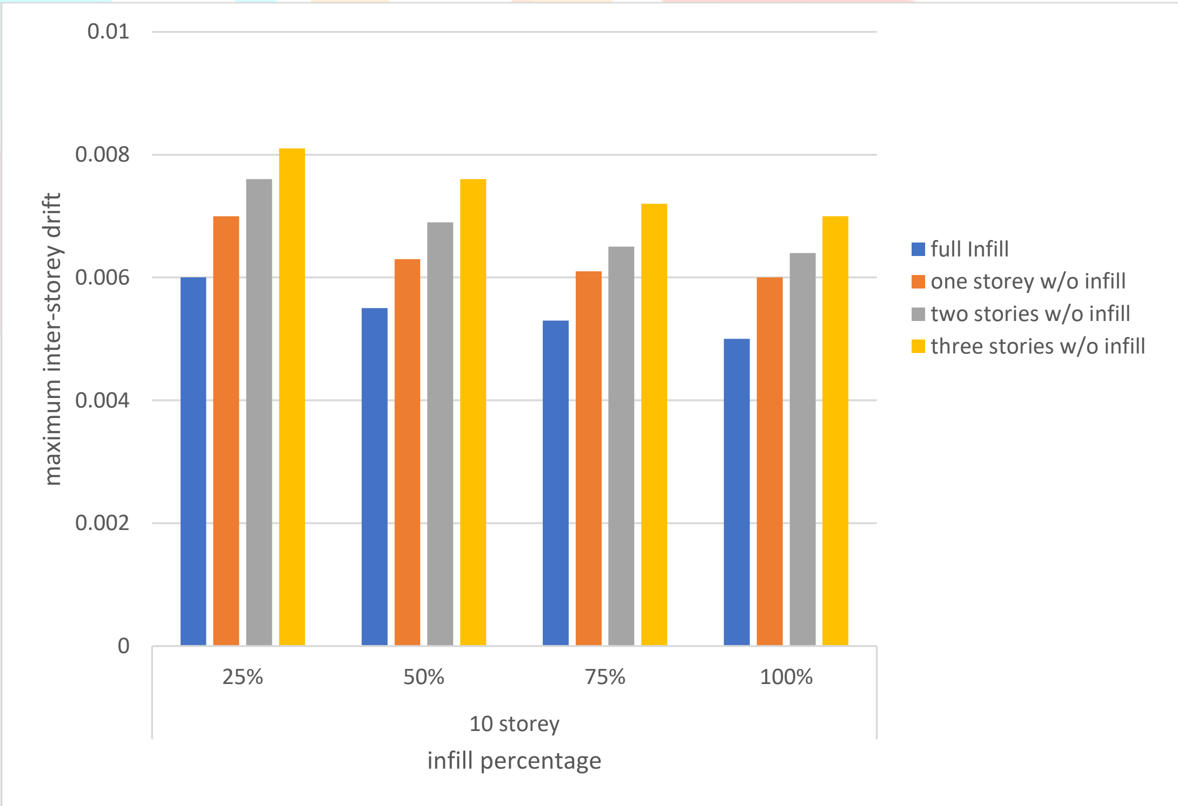

Figure 33: Group I* models

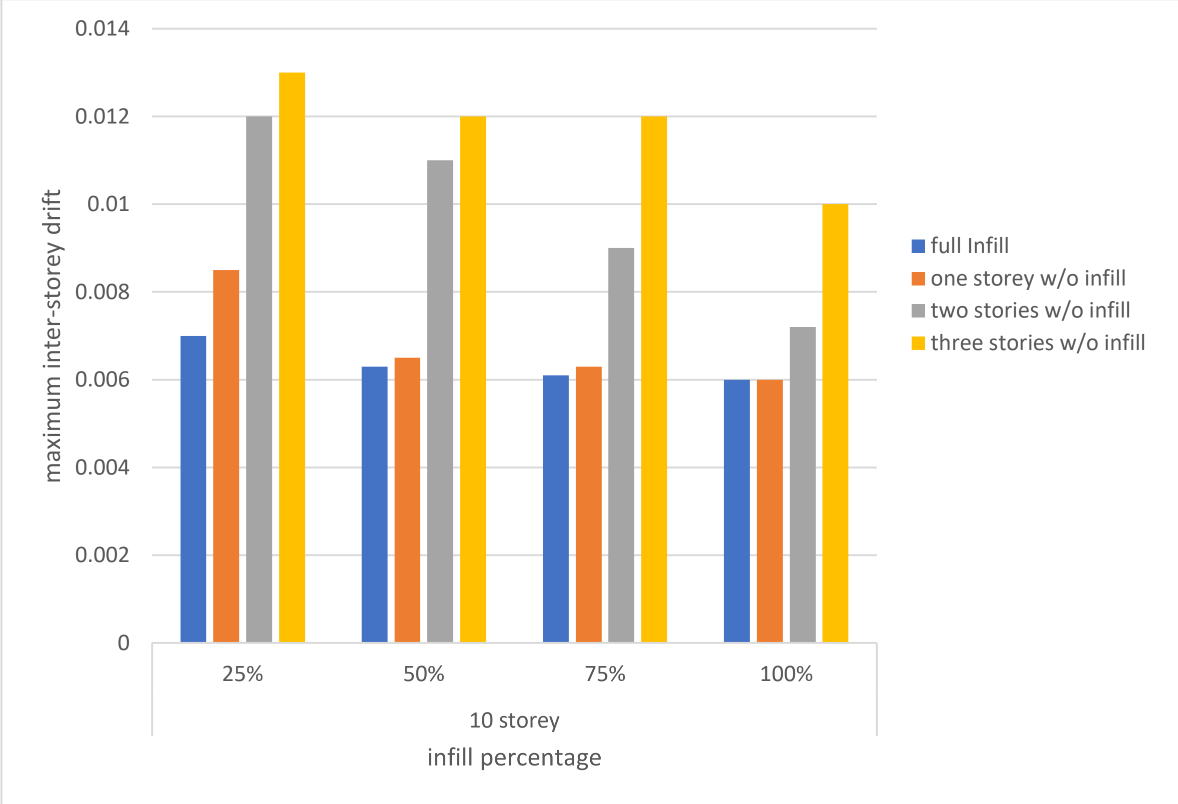

Figure 34: Group J models

4.3.6 Performance level

Table 4: Performance level for 10 storey models

No of stories	Group	% of infill	Performance level-Infill	Performance level-one storey w/o infill	Performance level-two stories w/o infill	Performance level-three stories w/o infill
10 storey	I*	25%	IO	IO	IO	IO
		50%	IO	IO	IO	IO
		75%	IO	IO	IO	IO
		100%	IO	IO	IO	IO
	J	25%	IO	IO	IO	LS(11)
		50%	IO	IO	IO	LS(8)
		75%	IO	IO	IO	LS(8)
		100%	IO	IO	IO	LS(7)

Results for 10-stories show the following:
As the number of stories without infill increases

- The P-factor decreases reaching a maximum decrease in 100% infilled frames models of 16.5% in Group I* models, 13.5% in Group J model.
- The drift values increase but still within the IO limits in both Group I*, however at low percentage infilled frames the drift values push to Life safety performance levels at Group J.
- The number of hinges formed increase and at those with low infill percentage the performance level pushes to Life Safety performance level in Group H.

4.4 Summary and Conclusion

The aim of this study was to investigate the effect of stiffness soft storey due to the removal of infills from successive stories assembling the presence of parking at the base stories of the building, Pushover analysis was performed upon Feras' models which were constructed based on subsoil class D, ground acceleration of 0.3g, and spectrum type (1) of the Egyptian code (ECP, 2012), with different heights and infill percentage after removing the infills from the base three stories on three steps, Effects of removal of infills was looked in detail from three main perspectives, distinguished as: P-factor, drift values and performance level on seismic events, Analyzing the results has given the following conclusions:

- As the number of stories increases the reduction in P-Factor increases.
- As the infill percentage increases the effect of removal of infills from stories becomes more critical concerning the reduction of P-factor.
- The percentage of P-factor reduction due to removal of infill from stories relies on the initial level of performance the bare frame was designed upon where the highest reduction was in the CCD models, then the LS models and CP models respectively, which is coping with Feras conclusion that the frames designed based on the guidelines set by codes drift limits can absorb much higher percentage of seismic energy than the infills as compared to other less performing frames, thus leaving infills less susceptible to early damage during an earthquake.
- The P-Factor of CCD models with soft stories reduced compared to that of full infill, however it is still higher than that of bare frame models, reflecting the conservative R-Factor used by ECP-201, and the high positive contribution of infill in seismic behavior of RC frames.
- Despite the low contribution of infills to LS and CP models, The P-Factor reduced to values less than that of bare frame (except for the 100% infilled frames) aiming to the less conservative design limits followed during the design of these frames, and that the negative effect of soft storey is more than the positive effect of infills in the LS and CP frames.
- For both the CCD and LS models of 10-storey frames the P-factor reduced but not to values lower than that of bare frames showing that the Gravity load combinations found in ECP-201 (ECP, 2007) are mainly controlling the design of short-period structures yielding in concrete sections and reinforcement ratios.
- Stiffens soft storey irregularity demonstrated in this study has shown that the code assumptions for an R value of 5.0 for RC moment frame structures with limited ductility class are still valid, despite their negative impact on the structure performance.
- The low infill percentage models show higher drifts values on removal of infills leading to the pushing of frames to another performance level, which shows the importance of infills in reducing the deformities of buildings.
- The drift values in some cases govern the determination of frames performance levels, which reflects the importance of taking the drift values assessment into consideration as well as the hinges formed.
- The pushover curve is affected by the removal of infills from successive stories where at pre-yielding stage, as the number of stories without infill increases, the stiffness decreases, and at post-yielding stage, as the number of stories without infill increases, the behavior becomes more brittle and the δmax decreases.

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