Numerical Investigation on Seismic Performance of Soft Story Vertical Irregular RC Buildings With Infill Walls

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Abstract: The soft story vertical irregularity is a structural irregularity characterized by the existence of unequal lateral stiffness along a building that makes it vulnerable to collapse or severe earthquake damage during seismic events. In this study, using SAP2000, different structural parameters would be applied to a regular reinforced concrete building model to create soft story irregular models, where one of the varied parameters would be the application of masonry concrete hollow block (CHB) walls, a commonly used construction material in low-rise buildings in the Philippines often considered as nonstructural elements during structural analysis, thus not included during structural modeling, which can affect the resulting structural performance of a building as excluding the additional effects brought by the presence of the infill walls may induce negative repercussions or irregularities not considered by the resulting structural design. Hence, the goal of this study is to observe how the presence of masonry CHB walls would affect the resulting seismic behavior of the regular and soft story RC building models, and therefore their safety and resilience. This study applied nonlinear static pushover analysis on the bare and CHB infilled models of 3 different case studies with different structural configurations, and it was found that as severity of the soft irregularity increased, the base shear capacities of the models decreased, which also caused the force required to cause the 1st plastic (significant damage) and the 1st collapse prevention (structural collapse) hinge development of the models to also decrease. Moreover, it was found that masonry walls do have the ability to significantly affect the structural and seismic behavior of a regular and irregular building, it is also beneficial in terms of mitigating the 1st structural damage and is a detriment for the 1st structural collapse if the walls are not placed continuously starting at the base.

Key Words: earthquake engineering; reinforced concrete building; soft story; SAP2000; masonry infill wall

1. INTRODUCTION

With its varied intensity, earthquakes always have the potential to cause small to massive amounts of damage to any country's economy and population. In earthquakes, the deaths occurring during a major instance of this hazard is not caused by the ground motion itself, but rather from the three main earthquake effects of structural collapse, non-structural causes, and follow-on disasters such as tsunamis and landslides. And of the three main consequences, structural collapse is estimated to cause about 75% of the deaths that occur during major earthquakes (Coburn et al., 1992).

Hence, with such high potential for numerous deaths and destruction of properties, there is a need to investigate the seismic performance and behavior of buildings when it comes to how they distribute and dissipate the acting seismic forces introduced by earthquakes, especially when vertical structural irregularities such as the soft story are present in the buildings, so that there would be countermeasures and designs to prevent such buildings from being susceptible to collapsing behavior.

A vertical irregularity has been described by Dy (2014) to be composed of building characteristics that encourage or cause seismic loads to concentrate on the parts of a building that contain the irregularities. On the other hand, Soni and Mistry (2006) further describes vertical irregularities to be characterized by any vertical discontinuity present along the structure's mass, stiffness, and strength, where any failure in distributing these properties during seismic loadings would create a weakness that the seismic loads would focus on to cause the structure's collapse or failure.

The National Structural Code of the Philippines (NSCP) defines soft story irregularity by the difference of stiffness (resistance to deformation) of one storey with an adjacent storey or the combined average stiffness of three upper adjacent storeys in the same building.

Figure 1.1 Soft Story Collapse/Failure (Dy, 2014)

Wherein, due to the modern architectural base floor plans of buildings being garages, offices, or building entrances that make use of mezzanine floors or overhangs, soft story irregularity becomes a highly probable structural issue, especially when the upper floors of those types of architectural plans are designed for residential use (Guevara-Perez, 2012; Durak & Aydin, 2016). Entailing that those upper floors; compared to the base floors, would contain more walls and columns to separate rooms from each other for residential use, causing those floors to be more rigid than their soft story base floors. Resulting in the seismic behavior of the base and upper floors to be significantly different from each other, as the soft story base floors are subjected to larger lateral loads and deformations compared to the other floors as exemplified by figure 1.1 (Kirac et al., 2011; Dy, 2014).

Figure 1.2. Chuzon Supermarket Collapse (Philstar, 2019)

Furthermore, the traditional analysis process for the CHB infill walls in reinforced concrete (RC) frames is to consider them as nonstructural as they are not expected to contribute to the structural capacity of the building. Hence, the common RC frame models are bare framed buildings, with the analysis only considering the weight of the CHB infill walls, which can prove to be a problem in determining an accurate seismic performance of an RC building as disregarding the interactions between the masonry infill walls and RC frame members can lead to a significantly different seismic behavior for the RC building such as a soft/weak story; which can cause a structural collapse like what occurred to the Chuzon Supermarket during the Luzon 2019 earthquake as seen in Figure 1.2 (Sia et al., 2022).

Therefore, the objectives of this study are to numerically investigate the seismic performances and behaviors of the soft story irregular RC buildings via modeling them through SAP2000, and to observe the effect of including the masonry CHB infill walls in the RC structural models on the development and behavior of the vertically irregular soft stories. The findings of this study could serve to find new ways to strengthen and make the buildings here in the Philippines less susceptible to earthquakes, which due to its location is quite a common occurrence, contributing to the sustainability of the modern structures around us by giving them a new enhanced lifespan by directly addressing the structural weaknesses of the buildings.

2. METHODOLOGY

2.1 Research Design

This study makes use of the SAP2000 software, a structural analysis and design software by csiamerica, for the modeling and application of the nonlinear pushover analysis, where the models would follow the modeling requirement of the NSCP and FEMA 356 to consider the effects of cracked section, where the flexural rigidity is taken as 0. $7E_cI_g$ for columns, and $0.5E_cI_g$ for beams from FEMA 356 (2000). Meanwhile, the design loads to be applied in the models were taken from the minimum design dead load tables of 204-1, 204-2, and minimum design live load table of 205-1 of the NSCP, where the earthquake load to be applied in either the x or y direction would make use of a total seismic weight composed of the full total dead load and 25% of the total live load with 5% accidental torsion considered. After the computation of the design loads present or acting on the structural models, they would be inputted in the factored or ultimate load combinations provided in NSCP Section 203.3.1, where load effect due to the vertical component of the earthquake was considered along with considering the orthogonal effects in the horizontal component of the earthquake.

2.2 Soft Story Irregularity Checks And Masonry Wall Equations

Following the NSCP, soft story is considered to exist in a building using the following conditions:

$$k_i \leq 0.70(k_{i+1}) \qquad \text{(Eq. 1)}$$

$$k_i \leq 0.80\left(\frac{k_{i+1}+k_{i+2}+k_{i+3}}{3}\right) \qquad \text{(Eq. 2)}$$

where

k_i = Lateral stiffness of the chosen story (kN/m)
k_{i+1} = Lateral stiffness of adjacent upper story (kN/m)
$\frac{k_{i+1}...k_{i+3}}{3}$ = Average lateral stiffness of 3 adjacent upper stories (kN/m)

Where in this study there would be two soft story irregularity checks done for each model. The 1st method would be using the equation for the lateral stiffness of the rigid reinforced concrete columns as follows:

$$k = \frac{12EI}{L^3} \qquad \text{(Eq. 3)}$$

where:
k = Lateral stiffness of the concrete column (kN/m)
E = Modulus of Elasticity (MPa)
I = Moment of Inertia (mm^4)
L = RC Column Height (mm)

In the 2nd method, the calculation of the story stiffness would be done by dividing the total story shear present in the story with the resulting story drift of the chosen story. The following equations would be used, where the story shear and story displacement data would be obtained by running the Static Lateral Force Procedure on the models through SAP2000.

$$Story\ Stiffness_{Level\ i} = \frac{Total\ Story\ Shear\ at\ Level\ i}{Story\ Drift} \qquad \text{(Eq. 4)}$$

where:

$$Story\ Drift = Story\ Displacement\ of\ Level\ i - Story\ Displacement\ Below\ Level\ i \qquad \text{(Eq. 5)}$$

Meanwhile, the masonry CHB infill walls that would be applied in the models would be represented by equivalent pin-jointed compression struts modeled as a cross-bracing system that would make use of the masonry infill equations of FEMA 356 & IS 1893:2016 to get the width of the equivalent compression strut "a" to represent the elastic in-plane stiffness of a solid unreinforced masonry infill panel prior to cracking. The following equations would be followed:

$$a = 0.175(\lambda_1 h_{col})^{-0.4} r_{inf} \qquad \text{(Eq. 6)}$$

where:
a = width of the equivalent compression strut (mm)
λ_1 = coefficient to determine the equivalent width of the infill strut
h_{col} = column height between centerlines of beams (mm)
r_{inf} = diagonal length of the infill panel (mm)

The coefficient (λ_1) has its own equation which can be seen below:

$$\lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4E_{fe} I_{col} h_{inf}}\right]^{1/4} \qquad \text{(Eq. 7)}$$

where:
E_{me} = Modulus of Elasticity of the infill material
E_{fe} = Modulus of Elasticity of the frame material
t_{inf} = thickness of the infill panel (mm)
h_{inf} = clear height of infill wall (mm)
I_{col} = moment of inertia of the column (mm^4)

Due to this paper opting to use equivalent pin-jointed compression struts to represent the existence of masonry infill walls in the models, the equivalent stiffness of the masonry infill walls would be computed using the equation provided by the Masonry Standards Joint Committee Code (2011):

$$Masonry\ Wall\ Stiffness = \frac{w_{inf} t_{inf} E_m l_{inf}^2}{d^3} \qquad \text{(Eq. 8)}$$

where:

w_{inf} = width of equivalent strut (mm)
E_m = Modulus of Elasticity of masonry in compression (MPa)
l_{inf} = clear length of infill wall (mm)
d = diagonal length of infill (mm)

Structural performance level for the masonry infill wall was monitored using the FEMA 356 (2000) drift criteria given as 0.2% for Immediate Occupancy (IO), 0.6% for Life Safety (LS), and 1.5% for Collapse Prevention (CP), where the struts were modeled as axial elements with non-linear axial hinges at the endpoints.

2.3 Building and Wall Configurations

The regular building model, which would have no irregularity, would be modeled in the simulation as a 5-story mid-rise mixed-use office and commercial building with a constant 3 meter story height for all floors. The bay design of the regular building would make use of a 3 by 3 bay design with each being 6 meters in length, leaving us with a symmetrical model, which was purposefully done so as to prevent other irregularities types; other than soft story irregularity, from forming in the regular building as much as possible. The limitation of 5-storeys with the 3-meter story heights are based on NSCP section 208.4.2, since this model would undergo both linear static and nonlinear static procedure; or static lateral force and pushover analysis. Shown in table 2.1 are the Regular model's structural specifications:

Table 2.1 Regular model's structural specifications

Property	Value
Column Dimension	600 mm x 600 mm
Column Longitudinal Reinforcements	12 - ø 25 mm (or approx. #8 rebars)
Column Transverse Reinforcements	ø 12 mm (or approx. #4 rebars) @ 100 mm spacing
Beam Section Dimensions	400 mm x 500 mm
Beam Longitudinal Reinforcements	8 - ø 25 mm (or approx. #8 rebars)
Beam Transverse Reinforcements	ø 12 mm (or approx. #4 rebars) @ 100 mm spacing
Compressive Strength of Concrete	28 MPa
Yield Strength of Longitudinal Rebars	420 MPa
Yield Strength of Transverse Rebars	280 MPa
Floor Slab Thickness	150 mm

The masonry CHB infill walls would also have specifications that would follow Mendoza et al. 's (2011) study about investigating the influence of CHB walls using the equivalent strut theory and SAP2000, where the height of the CHB unit is 200 mm with thickness being 150 mm, a mortar thickness of 10 mm, and a compressive strength of masonry unit and mortar of 10 MPa and 2.6 MPa; respectively.

2.4 Case Studies and Varied Parameters

Following the study of Dy & Oreta (2015), only the first story heights would be increased in order to create soft story irregular models. Where for the investigation of the seismic performances of the regular and soft story irregular models, and the effect of CHB masonry infill walls, there would be 3 case studies.

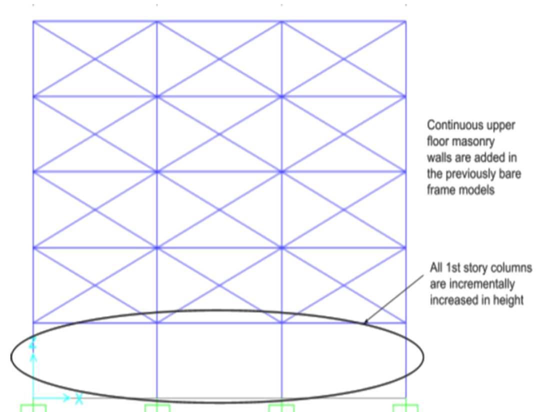


Fig 2.1. Sample sketch of a case study 2 model

Case study 1 is about increasing the 1st story height of the bare frame **Regular** model by 1m each time, where starting at the Regular model with a constant 3m height in all of its 5 stories, the **HI-1** model would increase the regular 1st story column height from 3m to 4m, with the **HI-2** model increasing the regular 1st story column height from 3m to 5m, and model **HI-3** is about increasing the regular 1st story from 3m to 6m. All of the models in Case study 1 are bare framed, hence only considers the weight of the continuous masonry walls on the exterior beams of the building's stories.

Case study 2, on the other hand, is about making use of the bare frame Case study 1 models and applying the equivalent struts as a cross braced system to represent the existence of continuous masonry infill walls on the upper floors only with the base floor remaining bare. Hence, the **IP-1 (Reg)** model is about using the case study 1 models in the parenthesis beside its model code as basis for the application of continuous infill walls on the upper floors only to make the previously bare frame models to infilled models; as shown in figure 2.1. Similar process is done for models **IP-1 (HI-1)**, **IP-1 (HI-2)**, and **IP-1 (HI-3)**.

Lastly, for Case study 3, the parameters to be enacted is similar as what occurred in Case study 2, but this time the continuous masonry wall equivalent struts would be applied in all floors; instead of just the upper floors. Hence, Case study 3 is composed of the models **IP-2 (Reg)**, **IP-2 (HI-1)**, **IP-2 (HI-2)**, and **IP-2 (HI-3)**.

3. RESULTS AND DISCUSSION

The seismic behavior of soft story irregular buildings with masonry infill walls would be analyzed using 4 bare frame models [Regular and HI Models] and 8 infilled frame models [IP Models]. Where it must be noted that the "Low" and "High" grade given for the soft story irregularity check does not indicate the severity of the irregularity, but is there to designate if the model in question is agreed by either one or both of the two different soft story irregularity check methods; shown previously, to have a soft story.

Table 3.1. Soft story irregularity check results

Model Code	Varied Parameter	Soft Story Check
Regular	None	None
HI-1	Increased 1st story column height with varying heights of 4m, 5m, and 6m; respectively (no infill walls)	Low
HI-2		High
HI-3		High
IP-1 (Reg)	Continuous masonry CHB infill wall placement on upper floors (2nd to 5th floors)	None
IP-1 (HI-1)		Low
IP-1 (HI-2)		Low
IP-1 (HI-3)		High
IP-2 (Reg)	Continuous masonry CHB infill wall placement on all floors	None
IP-2 (HI-1)		Low
IP-2 (HI-2)		High
IP-2 (HI-3)		High

As observed in table 3.1, increasing the 1st story column height did consistently induce a soft story irregularity on the Regular model, where the introduction of masonry CHB infill walls in the models had minor effect on the irregularity check results; be it continuous placement on the upper floors or on all floors, due to the similar "Low" and "High" soft story grades experienced by most of the case study models; except model IP-1(HI-2) that got a "Low" soft story grade compared to the other HI-2 configurations of case studies 1 and 3 that got a "High" grade.

Table 3.2. Resulting capacity curve data

Model Code	Highest Base Force (kN)	Highest Displacement (m)
Regular	9103	0.222
HI-1	6954	0.232
HI-2	5616	0.262
HI-3	4719	0.286
IP-1 (Reg)	9342	0.600
IP-1 (HI-1)	7108	0.600
IP-1 (HI-2)	5737	0.600
IP-1 (HI-3)	4813	0.600
IP-2 (Reg)	9435	0.109
IP-2 (HI-1)	7871	0.600
IP-2 (HI-2)	6414	0.600
IP-2 (HI-3)	5439	0.600

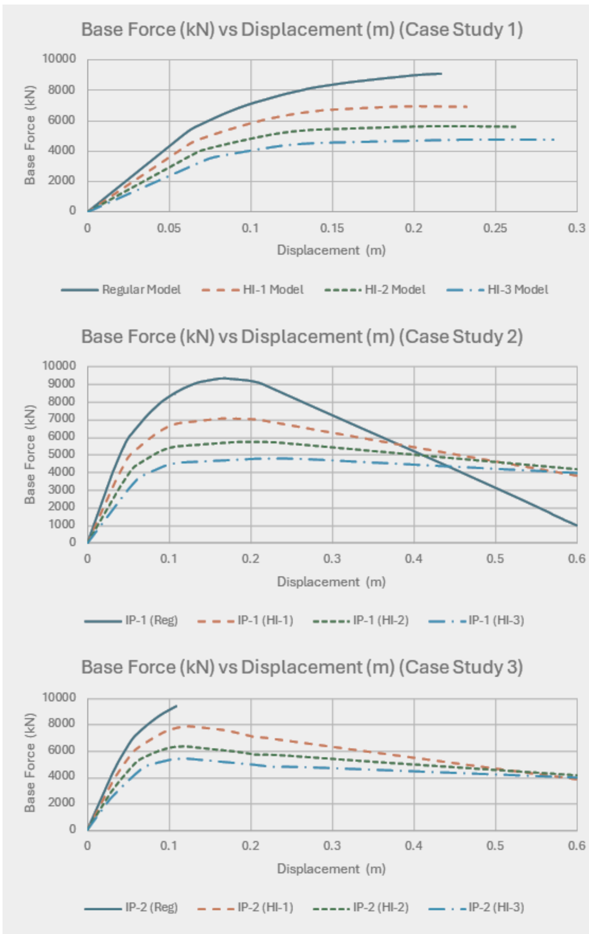


Fig 3.1. Capacity curves of Case studies 1 [top], 2 [middle], and 3 [bottom]

After the application of the nonlinear static pushover analysis using 0.6 m target displacement, it can be observed in table 3.2 that the placement of the continuous infill walls; on all floors or upper floors only, has significantly improved the base shear capacities of their bare frame counterparts, with the continuous on all floors wall configuration giving the highest improvement. Moreover, as shown in table 3.2 and figure 3.1, the ductile behavior of the regular model significantly increases with the continuous upper floor wall placement, but becomes stiff and brittle when it comes to the continuous in all floors wall placement. Whereas, the ductile behavior of soft story irregular HI models always increased with the consideration of the infill walls, which means that the continuous on all floors masonry infill wall placement was not enough to counteract the high deflection caused by the soft story.

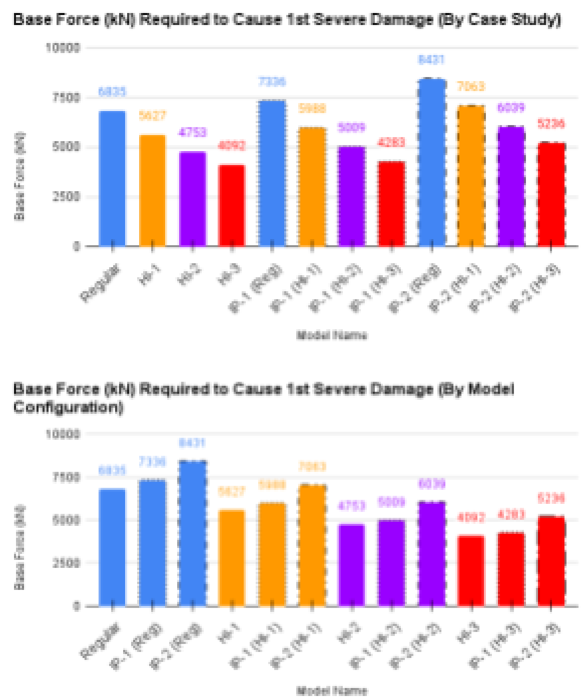
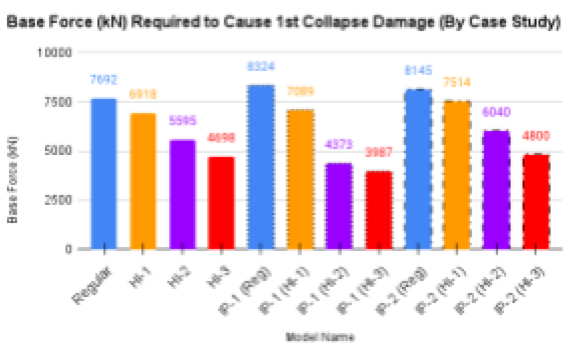


Figure 3.2. Base force required to cause 1st plastic hinges [1st severe damage in the model/building]

Table 3.3. 1st plastic hinge [severe damage] location

Model Code	1st plastic hinge development location
Regular	1st story corner and edge columns (left side) and center columns
HI-1	
HI-2	
HI-3	1st story corner columns (left side)
IP-1 (Reg)	1st story corner columns (left side) and center columns
IP-1 (HI-1)	
IP-1 (HI-2)	1st story corner columns (left side)
IP-1 (HI-3)	
IP-2 (Reg)	1st story center columns
IP-2 (HI-1)	1st story corner columns (left side)
IP-2 (HI-2)	
IP-2 (HI-3)	

Due to the nonlinear static pushover force being applied in the positive x-direction of the SAP2000 models, it was designated that the compression side of the building would be the right side, while the tension side would be the left side. As seen in figure 3.2 and table 3.3, after the application of pushover analysis on the case study models, the case study 1 models had their 1st plastic hinge always develop at **tension side (left side)** first, with this behavior worsening in the case study 2 models as by the IP-1(HI-2) model, it was having a similar 1st plastic hinge development behavior as the HI-3 & IP-1(HI-3) models; the highest soft story irregular models of case studies 1 & 2. Meanwhile, for the case study 3 models, the IP-2 (Reg) has developed its 1st plastic hinge in the 1st story critical Center columns, while the soft story irregular models of IP-2(HI-1) to IP-2(HI-3) developed their 1st plastic hinge in the 1st story Corner columns **(left side)**. Moreover, it can be observed in figure 3.2 (By Case Study) that as the 1st story height increases, the base shear force required to cause the 1st plastic hinge always decreases. The 1st story center columns are designated as the critical columns as they carry the heaviest load in the entire building in its original state.



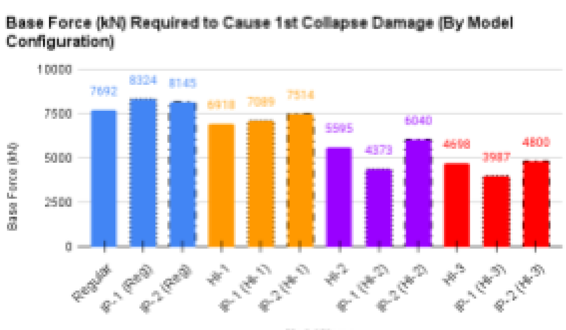


Figure 3.3. Base force required to cause 1st CP hinge [1st structural element collapse in model/building]

Table 3.4. 1st collapse hinge [collapse] location

Model Code	1st plastic hinge development location
Regular	1st story edge columns (right side)
HI-1	1st story edge columns (right side) and center columns
HI-2	
HI-3	1st story center columns
IP-1 (Reg)	1st story corner columns (right side)
IP-1 (HI-1)	1st story edge columns (right side)
IP-1 (HI-2)	1st story edge columns (left side)
IP-1 (HI-3)	
IP-2 (Reg)	1st story corner columns (right side)
IP-2 (HI-1)	
IP-2 (HI-2)	1st story corner column (left side)
IP-2 (HI-3)	1st story edge columns (left side)

Based on figure 3.3 and table 3.4, it can be observed that like the 1st plastic hinge development, the base shear force required to cause the 1st CP hinge always decreases as 1st story height increases (soft story severity), where this time the 1st CP [collapse damage] hinge gradually went from developing at the **compression side (right side)** first to only developing at the critical center columns as soft story severity increased in case study 1; which is unlike the 1st plastic hinges that had a tendency to develop at the **tension side (left side)**. In comparison, the most notable difference in case study 2 compared to case study 1, is that the 1st CP hinge behavior for the IP-1(HI-2) and IP-1(HI-3) models compared to their bare frame counterparts developed their the 1st CP hinge at the **tension side (left side)** rather than compression side and critical columns like their bare frame counterparts. This CP hinge development behavior of the mentioned case study 2 models can be attributed to the fact that the 1st CP developed first rather than a plastic hinge developing first; as seen by comparing the force required to cause the hinge developments between tables 3.3 and 3.4. Similar behavior could be observed in the 1st CP hinge development of the case study 3 models.

4. CONCLUSIONS

Based on the results of this numerical and analytical study, the following conclusions were drawn,

- As severity of soft story increases in a structure, its resulting base shear capacity would continue to significantly decrease, which therefore also causes the base shear force needed to cause the 1st severe and collapse damage in the building to also significantly decrease.
- The usage of masonry infill walls is an improvement for the building in terms of preventing the first significant structural damages and overall base shear capacity; be it continuous placement on upper floors or on all floors. However, in terms of first structural collapse development, it is always a detriment if masonry walls are only placed continuously in the upper floors, but is always an improvement if the continuous masonry wall is placed starting at the base floor.
- In terms of the structural analysis modeling, considering the presence of masonry walls in the bare frame models not only did it always change the ductile behavior of the structure when it was bare frame, but also significantly changed the seismic behavior or failure pattern of the previously bare frame regular and soft story models. As in this study, the location of the 1st CP hinges notably differ with the presence of masonry walls, as it went from having a tendency to develop on the **compression side (right side)** and critical center columns in the bare frame case study 1 models, to being a mix between developing on the **compression side (right side)** external columns for the Regular and lowest soft story severity HI-1 model configurations, while developing on the **tension side (left side)** external columns for the high soft story severity of the HI-2 and HI-3 model configurations of case studies 2 and 3.

5. REFERENCES (use APA style for citations)

Coburn, A. W., Spence, R. J., & Pomonis, A. (1992). Factors determining human casualty levels in earthquakes: Mortality prediction in building collapse. In Proceedings of the tenth world conference on earthquake engineering, 10, 5989-5994.http://www.iitk.ac.in/nicee/wcee/article/10_vol10_5989.pdf

Durak, U., & Aydin, K. (2016). Numerical Study of Influence of Infill Walls on the Vertical Irregularity Limit of Turkish Seismic Code. In Proceedings of the World Congress on Civil, Structural, and Environmental Engineering. https://doi.org/10.11159/icsenm16.111

Dy, A.F.C. (2014). Development of a brief code-based seismic diagnostic tool for existing RC buildings considering vertical irregularities [Master's thesis, De La Salle University]. animosearch. https://animosearch.dlsu.edu.ph/permalink/63DLSUL_INST/1ibggbk/alma991000693689706351

Dy, A.F.C., & Oreta, A.W.C. (2015). Seismic vulnerability assessment of soft story irregular buildings using pushover analysis. Procedia Engineering, 125, 925-932.https://www.sciencedirect.com/science/article/pii/S1877705815034207

Guevara-Perez, L. T. (2012). Soft story and weak story in earthquake resistant design: A multidisciplinary approach. In 15th world conference on earthquake engineering, 2, 856-865. https://www.iitk.ac.in/nicee/wcee/article/WCEE2012_0183.pdf

Kirac, N., Dogan, M., & Ozbasaran, H. (2011). Failure of weak-storey during earthquakes. Engineering Failure Analysis, 18(2), 572-581. https://doi.org/10.1016/j.engfailanal.2010.09.021

Mendoza, R. P., Cruz, E. S., & Senoro, D. B. (2011). Investigation of the influence of CHB walls in the seismic performance of low-rise reinforced concrete frames using the equivalent strut theory and SAP2000. Retrieved from https://www.researchgate.net/publication/299745623

Mendez, C. (2019, April 24). Supermarket owner surfaces, faces raps, *The Philippines Star*. https://www.philstar.com/headlines/2019/04/24/1912127

Sia, G.C., Mendoza, R.P., & Oreta, A.C. (2022). Numerical investigation of the infill-induced short column effect in reinforced concrete frames. In 3rd International Conference on Concrete and Steel Technology, Engineering and Design.

Soni, D. P., & Mistry, B. B. (2006). Qualitative review of seismic response of vertically irregular building frames. ISET Journal of Earthquake Technology, Technical Note, 43(4), 121-132.