EFFECTS OF INFILL BREAKAGE ON STORY BUILDINGS

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ABSTRACT

Soft Story is a type of irregularity due to the difference in floor-to-floor stiffness. This is very common when the ground story is kept open, and other stories fill in between the columns. However, while designing a soft-story building, the breakage of infill is not usually considered. When the building encounters a higher amplitude of seismic load, the breakage in infill occurs before the damage in columns. Consequently, the stiffness, as well as the dynamic characteristics of the building, change. The response of soft story buildings differs when wall breakage is considered compared to the traditional approach. Sometimes, it might be too conservative if we do not consider infill breakage. Therefore, it is necessary to consider the effect of infill breakage in analysis. This paper considers the impact of infill breakage in soft story frames and frames with complete infill. The deflections and inter-story drift of high-rise buildings for different magnitudes and frequencies of cyclic load were observed using a state-space approach considering breakage condition and no breakage condition. Subsequent changes in results for breakage and no breakage condition for soft story and fully infilled frame were noted. First, a design for a 6-story building was done using ETABS. Then, using the data, the stiffness was calculated using a document produced by the Federal Emergency Management Agency (FEMA), FEMA 365. Later, using a code in MATLAB, the natural frequency of the building was calculated. The frequency variation for the bare frame, frame with infill, and soft story frame was seen for different earthquake frequencies from minimum to near the natural frequency above it. For a bare frame, the resonance occurs at the external loading of natural frequency; however, as walls are added, and a soft story frame is created, the behavioral pattern changes due to the breakage, and the resonance point also changes. However, at the lower amplitude, the resonance point remained the same. Using the equivalent frame method, the stiffness was calculated, and later, by varying the stiffness according to the building classification of bare frame, complete infill, or soft story, the natural frequency was calculated. Then, varying amplitude for various frequencies and amplitude, the behavior was observed. For strut width calculation, FEMA was used. Usually, in analysis, it is considered that the wall goes back to its standard form, but once a wall is broken, it can never return to its normal situation. In this case, the effect of the wall is to be considered, thinking there is inelastic breakage.

Keywords: *Infill Breakage, Soft Story, State-Space Approach, Cyclic Load*

1. INTRODUCTION

Multistoried building frame structures are frequently used because of their ease of construction and rapid work progress. As infill material in the frame, panels of brickwork, blockwork, cast-in-place, or pre-cast concrete are used in column and girder framing of reinforced concrete and steel. The infills behave effectively as struts along its compression diagonals to brace the frame when an in-filled frame is subjected to lateral loading. As a result, the infills used as external walls or internal partitions contribute to the stiffness of the framing system FEMA 365 (2000). This contribution to the stiffness of the wall is dependent on the properties of infilled materials and openings, according to the Bangladesh National Building Code, BNBC (2020). The strengths of infills can be calculated in different ways according to different codes, including BNBC (2020) and FEMA 365 (2000). The stiffness of a frame is significantly increased using infills (Papia et al., 2003). Therefore, a bare frame has lower stiffness than a frame with infill. Usually, in strength calculation, the contribution of infill is ignored, but as infill provides stiffness, it should be calculated.

When a sudden reduction of stiffness occurs in a story in multi-storeyed buildings, it is called a soft story (BNBC, 2020). The soft story can happen due to the lack of infill materials. The response of frames with soft stories during an earthquake will differ from those without soft stories (Manos et al., 2022). During design, a soft story is also usually ignored so that variation can be seen here compared to the designed ones. Different approaches can be used to analyze the frame in lateral load. Here, a state space model is used. Dynamic models can be easily solved in MATLAB programs using state space approaches.

1.1 Soft Story

When the stiffness of the first floor is significantly lower than that of the upper floors, it results in a soft story in the building. This is caused by fewer and shorter partition walls on the first floor than on the upper floors. In buildings with soft stories, during an earthquake, the deformation in the building is concentrated in a single story. Soft stories are widespread in buildings and are found in areas such as car parking in office or residential buildings, large retail spaces, or floors with many windows. Despite their certainty, it is necessary to perform behavior analysis for soft stories to design a safe building structure.

1.2 Review of the Definition of Soft Story from Codes

According to ASCE 41 (2017), a seismic force-resisting system's story must have a stiffness greater than seventy percent of the adjacent story above and more excellent than eighty percent of the average seismic force-resisting system of the above three stories. It is considered a soft story if it fails to meet these criteria. In BNBC (2020), a soft story is also referred to as stiffness irregularity and is defined in the same way as in ASCE 41 (2017).

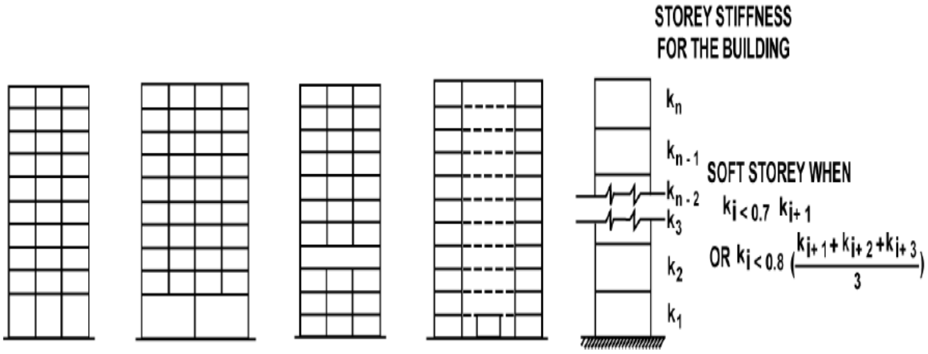

Figure 1 Soft Story (BNBC, 2020)

1.3 Equivalent Strut Width

The analysis of in-plane strength prediction of infilled frames is a statically indeterminate problem. It is not as simple as adding the properties of the infill and the frame to calculate the strength of a composite-infilled frame system. Over the years, a lot of analytic and experimental research has been conducted to understand better and predict the composite behavior of masonry-infilled frames. Researchers like Polyakov (1960), Stafford-Smith (1962, 1966, 1969), Mainstone (1971), Klingner and Bertero (1976, 1978), and many others have contributed to this field. These studies have shown that diagonal cracks appear in the center of the panel and between the frame and the infill. Gaps are formed in the non-leaded diagonal corners of the specimens, but complete contact is observed in the two loaded diagonal corners. Polykov first made this observation, simplifying infilled frame analysis by replacing the masonry infill with an equivalent compressive masonry strut. The equivalent masonry strut has the same thickness and mechanical properties as the infill and is assumed to be pinned at both ends. Calculating the equivalent width of the strut varies from one reference to the other. Some researchers, like Paulay and Priestley (1992) and Angel (1994), have assumed constant values for the strut width a. This approach considers the infill’s properties. It assumes that 'a' is between 12.5 to 25 percent of the diagonal dimension of the infill. Others, like Stafford-Smith and Carter (1969) and Mainstone (1971), have used complex expressions to estimate the equivalent strut width, a. They have considered parameters like the length of contact between the column/beam and the infill and the relative stiffness of the infill to the frame. According to FEMA 41 (2017), the equations used are (1) and (2).

Figure 2 shows the equivalent strut width of the infill, a.

$$\boldsymbol{a = 0.175(\lambda_1 \mathbf{h_{col}}) – 0.4\, \mathbf{r_{inf}}} \tag{1}$$

$$\boldsymbol{\lambda_1} = \left[\frac{\mathbf{Eme\ tinf\ \ sin\, 2\theta}}{\mathbf{4Efe\ tcol\ hinf}}\right]^{1/4} \tag{2}$$

The details of the calculation of Efe and Eme are shown in the calculation section.

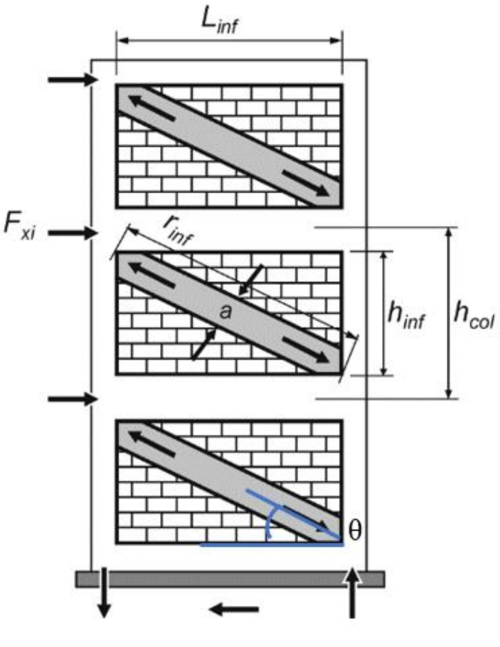

Figure 2 Equivalent strut (FEMA, 2015)

Where: hcol = Column height between centerlines of beams, in.,hinf = Height of infill panel, in., Efe = Expected modulus of elasticity of frame material, ksi, Eme = Expected modulus of elasticity of infill material, ksi, Icol = Moment of inertia of column, in 4., Linf = Length of infill panel, in., rinf = Diagonal length of infill panel, in., tinf = Thickness of infill panel and equivalent strut, in, θ = angle whose tangent is the infill height-to-length aspect ratio, radians, λ = Coefficient used to determine equivalent width of infill strut.

1.4 State Space Approach

Ogata (2004, 1998, 1992, 1978) showed the state space approach to model dynamic systems. Models are formed in the modeling chapter using this system. Analysis of multi-degrees of freedom was done. The number of degrees of freedom equals the number of stories. Floor mass was considered as lumped mass. Let us first consider a three degrees of freedom system. By taking the free body for each part, we get the following equations: 3a, 3b, 3c,

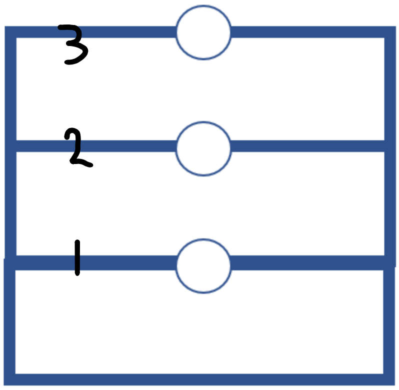

Figure 3 Free body

$$\dot{x}_1 = \dot{x}_1 \ ; \ m_1 \ddot{x}_1 + c\dot{x}_1 + c(\dot{x}_1 - \dot{x}_2) + k_1 x_1 + k_2 (x_1 - x_2) = -m_1 \ddot{x}_g$$

$$\Rightarrow \ddot{x}_1 = -\frac{k_1 + k_2}{m_1} x_1 - 2\frac{c}{m_1}\dot{x}_1 + \frac{k_2}{m_1} x_2 + \frac{c}{m_1}\dot{x}_2 - \ddot{x}_g \tag{3}$$

$$\dot{x}_2 = \dot{x}_2 \ ; \ m_2 \ddot{x}_1 + c(\dot{x}_2 - \dot{x}_1) + c(\dot{x}_2 - \dot{x}_3) + k_2 (x_1 - x_2) + k_3 (x_2 - x_3) = -m_2 \ddot{x}_g$$

$$\Rightarrow \ddot{x}_2 = \frac{k_2}{m_2} x_1 + \frac{c}{m_2}\dot{x}_1 - \frac{k_2 + k_3}{m_2} x_2 - 2\frac{c}{m_2}\dot{x}_2 + \frac{k_3}{m_2} x_3 + \frac{c}{m_2}\dot{x}_3 - \ddot{x}_g \tag{4}$$

$$\dot{x}_3 = \dot{x}_3 \ ; \ m_3 \ddot{x}_3 + c(\dot{x}_3 - \dot{x}_2) + k_3 (x_3 - x_2) = -m_3 \ddot{x}_g \Rightarrow \ddot{x}_3 = \frac{k_3}{m_3} x_2 + \frac{c}{m_3}\dot{x}_2 - \frac{k_3}{m_3} x_3 - \frac{c}{m_3}\dot{x}_3 - \ddot{x}_g \tag{5}$$

Using equations (3), (4) and (5) equation (6) is derived.

$$\begin{bmatrix} \dot{x}_1 \\ \ddot{x}_1 \\ \dot{x}_2 \\ \ddot{x}_2 \\ \dot{x}_3 \\ \ddot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{k_1+k_2}{m_1} & -2\frac{c}{m_1} & \frac{k_2}{m_1} & \frac{c}{m_1} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{k_2}{m_2} & \frac{c}{m_2} & -\frac{k_2+k_3}{m_2} & 2\frac{c}{m_2} & \frac{k_3}{m_2} & \frac{c}{m_2} \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{k3}{m3} & \frac{c}{m3} & \frac{-k3}{m3} & \frac{-c}{m3} \end{bmatrix} \begin{bmatrix} x1 \\ \dot{x}_1 \\ x2 \\ \dot{x}_2 \\ x3 \\ \dot{x}_3 \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \\ 0 \\ -1 \\ 0 \\ -1 \end{bmatrix} \ddot{x}_g \tag{6}$$

2. METHODOLOGY

At first, a design was done in ETABS for a 6-story bare frame. Then, equivalent strut thickness was calculated, infill diagonal stiffness was calculated, and the stiffness of the whole floor was calculated; in a MATLAB program, the natural frequency of the building was calculated, and for different frequencies and different magnitudes, the behavior of the building was observed.

3. MODELLING

At first, in ETAB, a design for a six-story frame was done. From there, the column size was found to be 15-inch square, beam 8inch x 16 inches, slab 4.5-inch

3.1 Calculations

Equivalent Strut Thickness from using equation (1) and (2): col =3m=9.84 ft=118 inch, h_{inf}= 118 inch (infill height is equal to the column height assumed), E_{fe} = 3600 ksi, E_{me} = ksi=820 ksi (calculation details are shown), I_{col} = $bh^{3/}12$=4200 in4, L_{inf} = 20ft=240 inch, ring =$(20^2+9.84^2)^{.5}$ =267 inch, t_{inf} = 10 inch (assumed), θ= $\tan^{-1}(9.84/20)$= 0.457 radian,λ_1= Coefficient used to determine the equivalent width of infill strut, Specified Compressive Strength of Masonry, f'm.

Calculation of Expected modulus of elasticity of infill material, Eme from equation (3) from BNBC (2020)

E_{me}=750 fm'≤ 15000 Mpa (7)

[Specified Compressive Strength of Masonry, fm'. In Bangladesh, the Cement sand ratio used is generally 1:4, for which fm' is 7.5Mpa]

=750 x$7.5\text{x}10^6$ N/ m2 =750 x$7.5\text{x}10^6$ x$(.225/ 39.37^2)$ [1N = .225 Ibs ; 1m =39.37 inch] =816,533.89 psi =820 ksi

Properties of column, I_{col}:

Elastic modulus of concrete is given by equation (4): $\mathbf{I_{col}}$ = $15^4/12$ = 4200 in^4

Efe=E_c= 57000fc'^.5 (8)

fc' is the compressive strength of concrete after 28 days of curing

Efe=E_c =57000(4000) ^.5= 3600 ksi,

$\lambda_{1=}$ 0.0336a =.175 $(\lambda_1 x h_{col})^{\wedge 1/4}$ ring =.175 (.0336 x118)$^{\wedge 1/4}$ x 267 =27.85=28inch

Calculation of lambda (ratio of stiffness with infill and without infill):

Diagonal Stiffness and the lambda value are calculated using equations 3.5 and 3.6.

Diagonal stiffness= (AE/L) $\cos^2$ (theta) (9)

Diagonal stiffness = (atE/L) $\cos^2$ (theta) = (27 x10x 820/267) (cos (.457))^2 =667 k/ inch

Natural Frequency: An existing program determines Natural frequency later (Reza,2006).

Additional damping coefficient c: For the previously mentioned hysteretic loop, damping is considered for column and infill. Here, damping in the ground, beam, and joints is not considered. For these parameters, an additional damping coefficient has been considered.

$$c= 4Dm\pi f_n \tag{10}$$

3.2 Determining Stiffness for Specific Time

The behavior of elasticity and inelasticity is illustrated in Figures 3a and 3b. Initially, the material follows path one until a higher force is applied, and then moves to path 2. Upon reversing the force, it follows path 3. However, the material does not return to its original state at no load due to inelasticity. Instead, it follows path four at a certain point as deformation decreases. When deformation is given in the original direction, the material follows path one again.

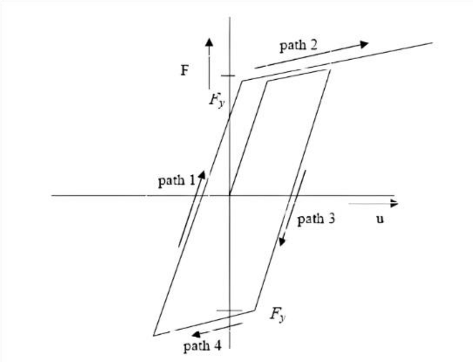

Figure 4 Hysteresis Loop (Reza,2006)

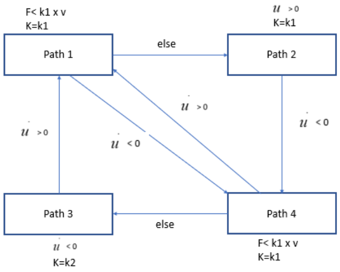

Figure 5 Hysteresis Loop

The behavior of elasticity and inelasticity is illustrated in Figures 3a and 3b. Initially, the material follows path one until a higher force is applied, and then moves to path 2. Upon reversing the force, it follows path 3. However, the material does not return to its original state at no load due to inelasticity. Instead, it follows path four at a certain point as deformation decreases. When deformation is given in the original direction, the material follows path one again.

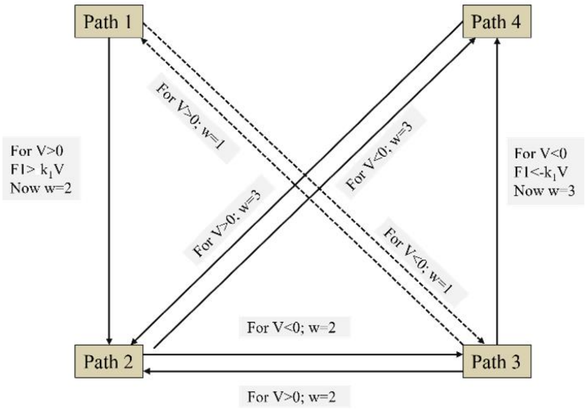

Figure 6 Loop for breakage

Here, w=1 means no breakage, w=2 means breakage on one side, and w=3 means to break on both sides. . this loop is used in the MATLAB logic. At first, when the deflection occurs, the walls have w=0, and the force goes above the elastic limit; one side of the wall breaks and becomes w=2. Moreover, if the force keeps increasing, path two will continue. However, if the deformation direction changes, the path will jump to path 3. Moreover, one in that path, the other side gets broken. It will never get back to path 1 or 3. It will keep on bouncing between 2 and. When there is a deflection that is v>0

3.3 Mathematical Model

Analysis of multi-degrees of freedom was done. The number of degrees of freedom equals the number of stories. Floor mass was considered as lumped mass. Let us first consider a three degrees of freedom system. By taking the free body for each part, we get the following equations: First, start m1, k1. A program was developed using the ‘ss’ .’lsim’ functions in MATLAB to solve the equation in the state space approach

4. RESULT AND DISCUSSION

The natural frequency of the bare frame is 1.92 Hz, the frame will fully infill in 4.55 Hz, and the soft storied frame will be 2.78 HZ. For each case, the behavior of the fame was observed in varying amplitude and frequency.

4.1 Bare Frame (Natural Frequency 1.92 Hz)

A bare frame for an amplitude of 0.01 ms^{-2} is applied for 20 seconds till a frequency of 1.5Hz, there is no breakage, and the maximum deflection is 3.6912e-04 m at a frequency of 1.92 Hz. There is a clear resonance, and the deflection drastically increases. However, at a frequency of 4, the deflection decreases. For higher amplitudes, the same phenomena can be seen. However, there is no breakage as there is no wall, as shown in Figure 5,6,7.

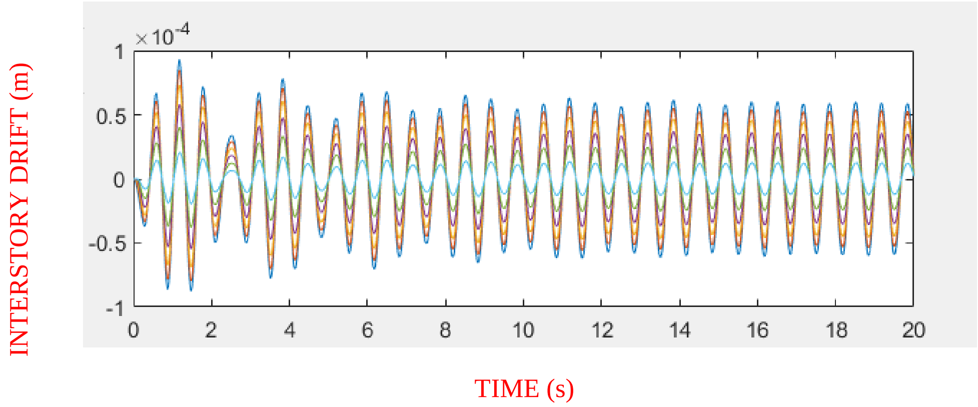

Figure 7: Inter-story drift for Bare frame a=0.01 ms^{-2}; f=1.5 Hz

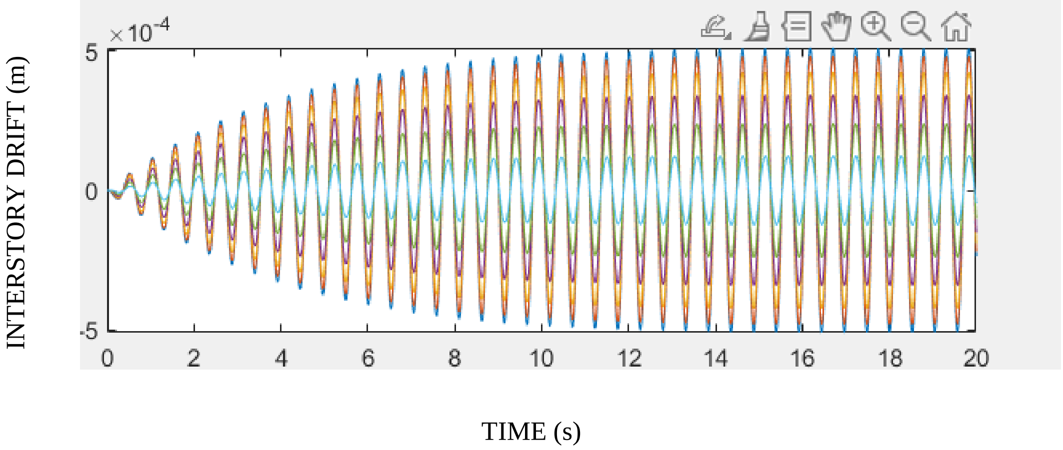

Figure 8 Interstory drift for Bare frame a=0.01 ms^{-2}; f=1.92 Hz

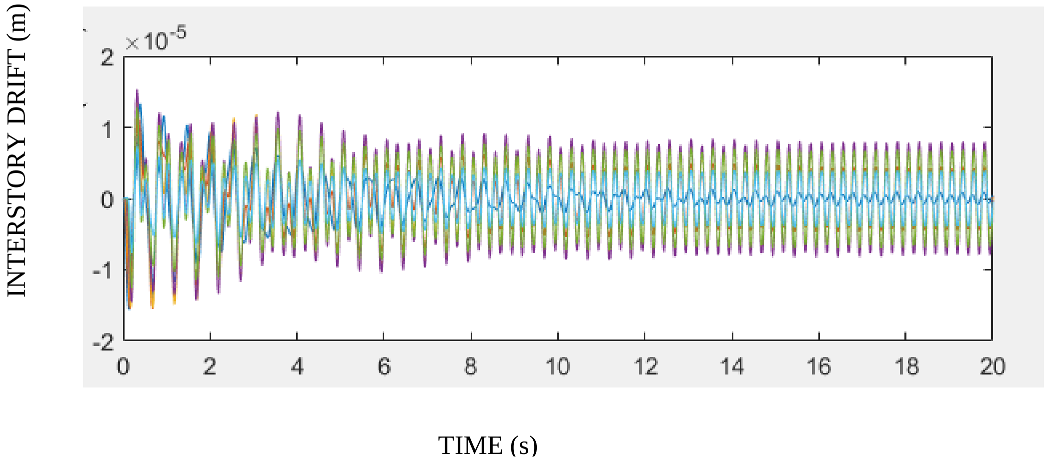

Figure 9 Interstory drift for Bare frame a=0.01 ms^{-2}; f= 4 Hz

4.2 Frame with Full Infill (Natural Frequency 4.55 Hz)

For complete infill with an amplitude of .01 ms^{-2}, here the resonance occurs at 4.55 Hz, and after 10s, there is a breakage in the wall, but at 4Hz, unique behavior can be observed; however, at 5 Hz loading, there is no brake. For a=.01 ms^{-2} at a frequency of 4hz, breaks occur just before 4s; for f=4.55, the breakage occurs before 2s. However, breakage occurs for an amplitude of 1 ms-2 at a frequency of .01 Hz.

as observed in Figure 8-13

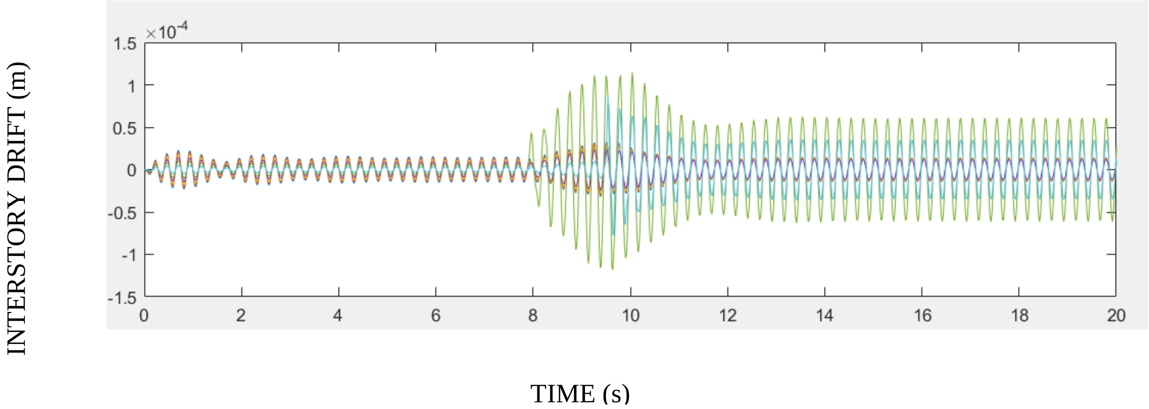

Figure 10 Interstory drift for Infilled frame a=0.01 ms^{-2}; f= 4 Hz

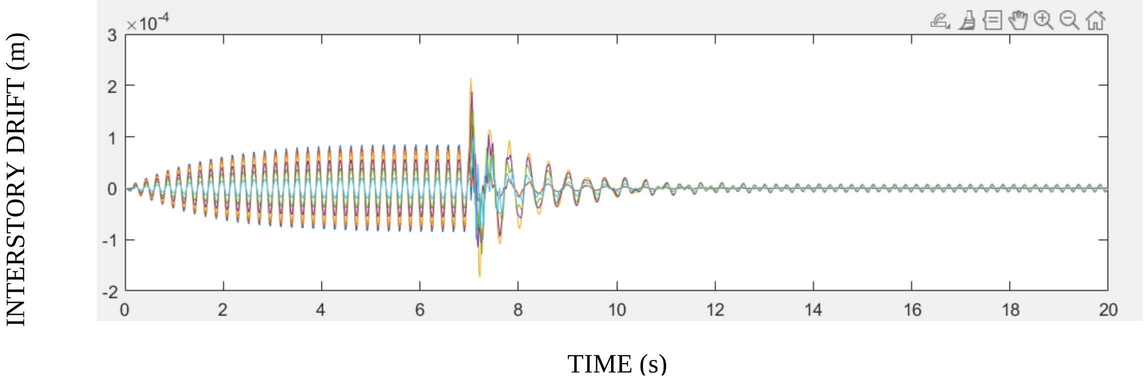

Figure 11 Interstorydriftfor Infilled frame a=0.01 ms^{2}; f= 4.55 Hz

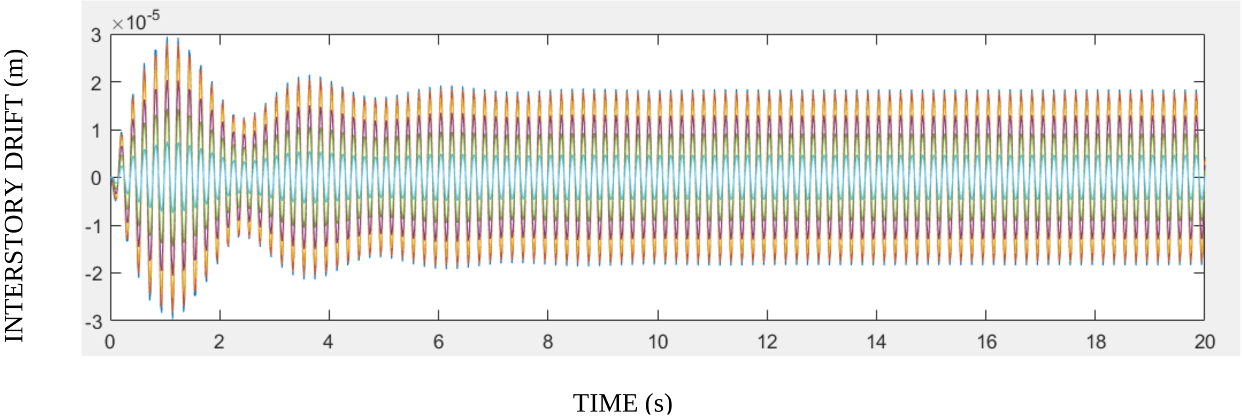

Figure 12 Interstory drift for Infilled frame a=0.01 ms^{-2}; f= 5 Hz

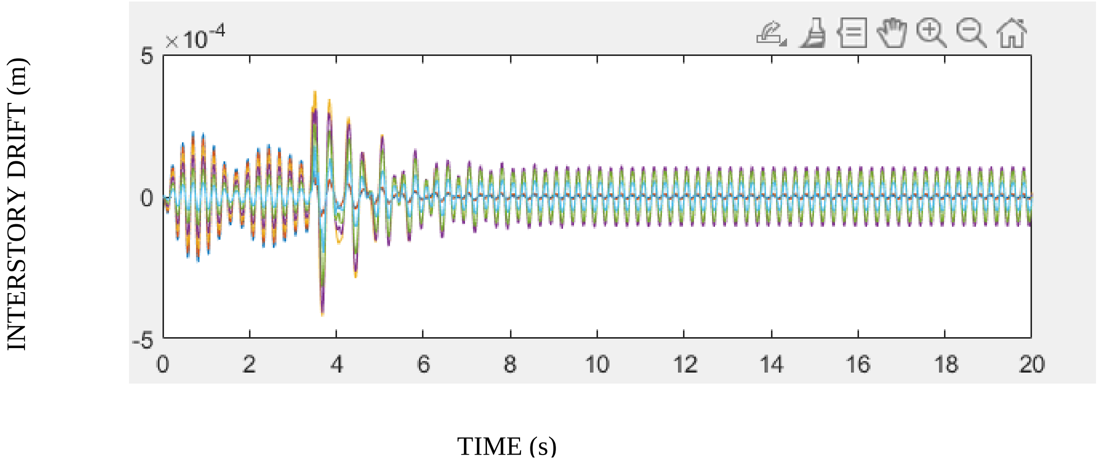

Figure 13 Interstory drift for Infilled frame a=0.1 ms^{-2}; f= 4 Hz

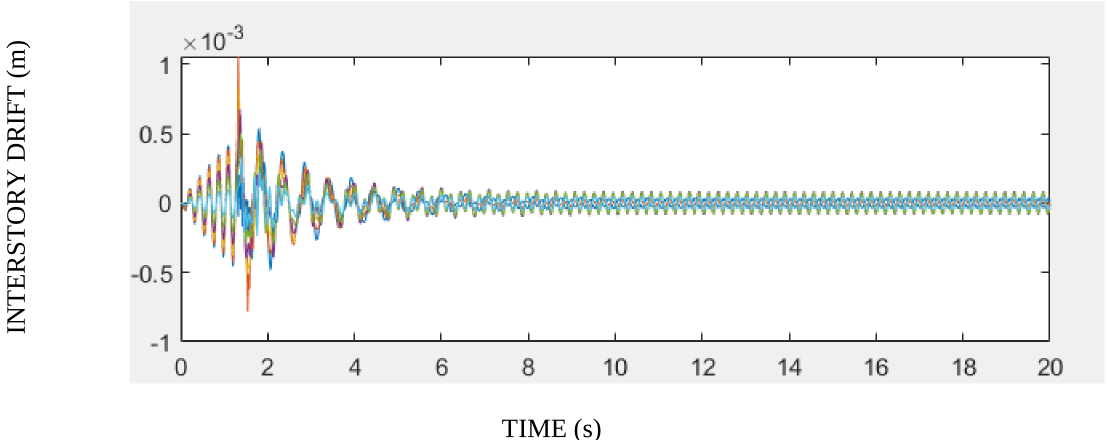

Figure 14 Interstory drift for Infilled frame a=0.1 ms^{-2}; f= 4.55 Hz

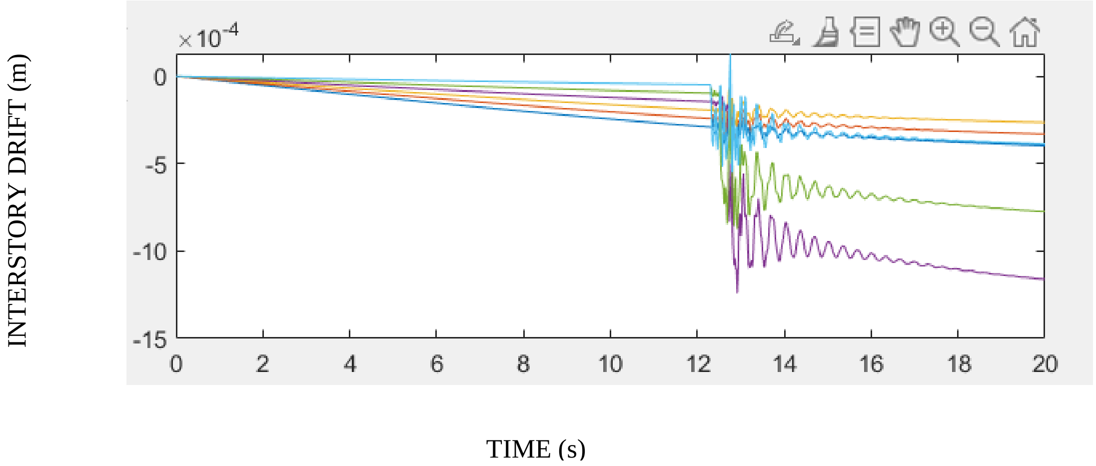

Figure 15 Interstory drift for Infilled frame a=1 ms^{-2}; f= .01 Hz

4.3 Soft Story (Natural Frequency 2.78 Hz)

However, for a soft story, the analysis is not that straightforward; however, for a higher amplitude of 0.1 ms^{-2}, the resonance is not clear as the breakage of the wall happens, as shown in Figures 14 and 15.

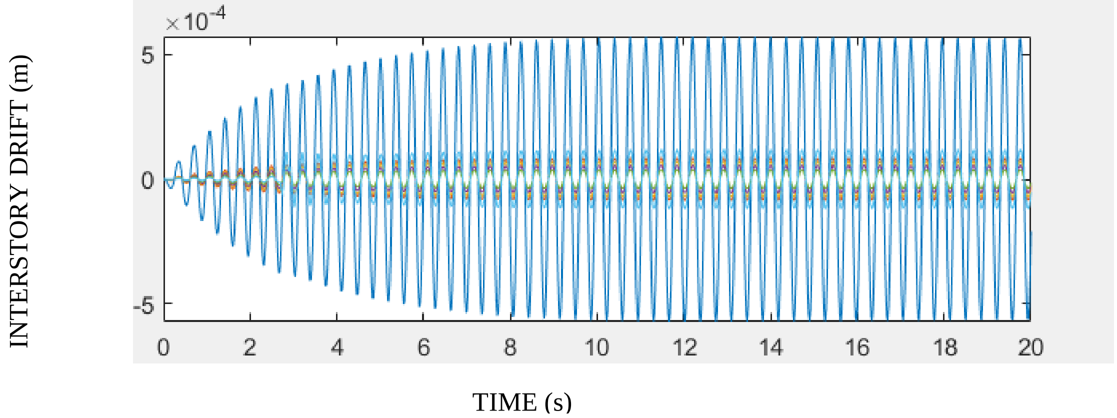

Figure 16 Interstory drift for Soft Storied frame a=.01 ms^{-2}, 2.78 Hz

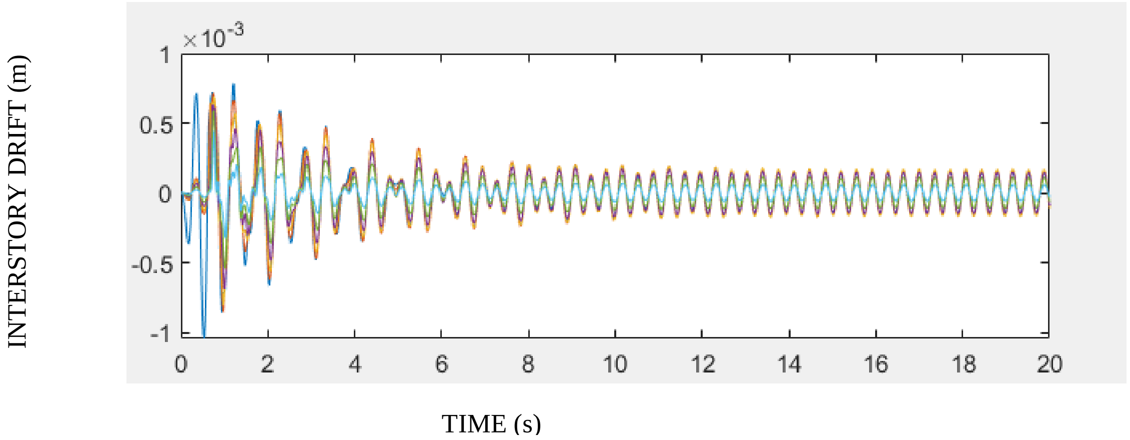

Figure 17 Interstory drift for Soft Storied frame a=.1 ms^{-2}, f=2.78 Hz

5. CONCLUSION

- For a bare frame, the resonance occurs at the external loading of natural frequency.
- As walls are added, a soft story frame is created, the behavioral pattern changes due to the breakage, and the resonance point also changes.
- However, the resonance point remained the same at the lower amplitude.

6. ACKNOWLEDGEMENT

Firstly, I want to express my heartfelt gratitude to my want to acknowledge Reza S. M., 2006, whose “Study of Dynamic Behavior Of Nonlinear R.C. Frames With Infills” worked as my go-to reference for me, moreover. I want to show my gratitude to my family and friends who helped me while I ran out of time; they assisted me and motivated me to keep going.

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