Response of Armature Type Infill Wall Panels in Intermediate Moment Resisting Frames Subjected to Earthquakes

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***Abstract*: The objective of this research is to study the planar behaviour of simple intermediate moment resisting frames (IMRFs) infilled with brick masonry when subjected to earthquakes. The various types of infill walls in IMRFs show a distinct response to lateral loads. In the 2005 Kashmir earthquake, about half of the structures that were damaged beyond repair were load-bearing buildings. But, the buildings that used armature type walls in construction were seen to be less affected by the earthquake. This study is carried out by simulating the various cases on SAP2000, a finite element analysis package. The forcing function taken is in the shape of response spectrum, the material properties and the mechanical behaviour have been taken from recent experimental studies in Pakistan. This study concludes that the performance of IMRFs is improved to a great extent if armature type infill wall panels are used in place of conventional infill walls.**

***Keywords*: Armature cross-walls, Earthquake, IMRF, Infill walls, Response Spectrum, SAP2000.**

I. INTRODUCTION

Since the dawn of mankind, masonry has been the oldest form of construction as evident from the ancient constructions in Rome, Egypt and Sindh [1]. It has also remained the most used construction material in Pakistan [2]. It is as such because of its low construction cost, and therefore it is still widely used in Reinforced Cement Concrete (RCC) frames too. However, it has been recorded that masonry is not strong against earthquakes, either load-bearing or infilled. In a recent study it was shown that one of the two identical frames having the same dimensions and properties collapsed because it was infilled with masonry and the other remained intact because it was not infilled [3]. This shows that the infill walls have a structural response to the RCC frames. The same study takes “Dhajji” into account, a special type of construction in which wood planks are used with stones to make armatures. The said construction was seen to be strong against earthquakes and during the Kashmir earthquake of 2005, almost all of the Dhajji constructions remained intact. This sparked an idea for the use of armature type infill walls in IMRFs. Recent studies have already modeled the brick masonry used, now the numerical modeling of IMRFs infilled with armature walls is studied.

II. THE 2005 KASHMIR EARTHQUAKE

The geodynamics of central and South Asia is controlled by the Eurasian and the Indian plate. The northern mountain ranges of South Asia are the result of the northward subduction of the Indian plate under the Eurasian plate. The rate of subduction as recorded by the USGS is found out to be 40 mm/year which causes many earthquakes in the region [4].

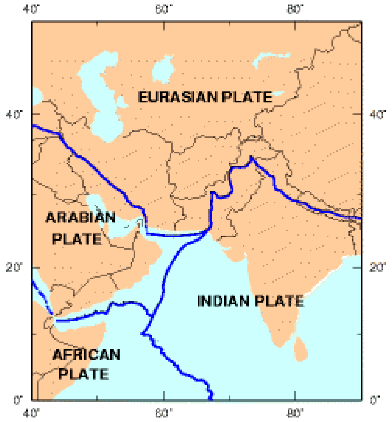

Fig. 1: Plate tectonics of South Asia

Fig. 1 depicts the tectonic details of South Asia, showing that the fault line passes through Pakistan, and that this region has the potential to produce significant earthquakes.

On the 8th of October, 2005, an earthquake with a peak moment Magnitude of 7.6 hit the Kashmir valley, leaving 150,000 people injured along with 75,000 casualties. 3.5 million people were left homeless. It is seen that an earthquake magnitude of around 8 is recurrent in this area, which makes it easy to predict the earthquake trends [5].

It is estimated that 780,000 buildings were either destroyed or damaged beyond repair in this earthquake. Around 17,000 schools and hospitals near the epicenter of the earthquake were completely destroyed which affected the life in this zone [6].

Most of the buildings that were destroyed were low-rise brick masonry and stone masonry buildings, either with pitched flexible roofs or mixed flexible and rigid concrete floors and roofs [7].

III. BUILDING TYPES IN PAKISTAN

According to a recent study, it is seen that about 60% of the built environment in Pakistan consists of load-bearing brick masonry structures [2, 8]. Such a construction is weak against lateral forces and ground accelerations, and thus needs reinforcement to withstand such forces. In the northern areas of Pakistan, timber laced masonry is used to resist the lateral loads whereas in the southern areas rice straw is used.

IV. BEHAVIOUR OF MASONRY INFILLED WALLS IN IMRFs

The beahviour of brick masonry is dependent on the behaviour of all the units of brick masonry viz. the dimensions and consistency of the brick units and the mortar bond. The behaviour of local brick masonry of central Pakistan has been modeled for numerical simulation on SAP2000 by [9] with the usage of experimental data as shown in figures 2a & b:

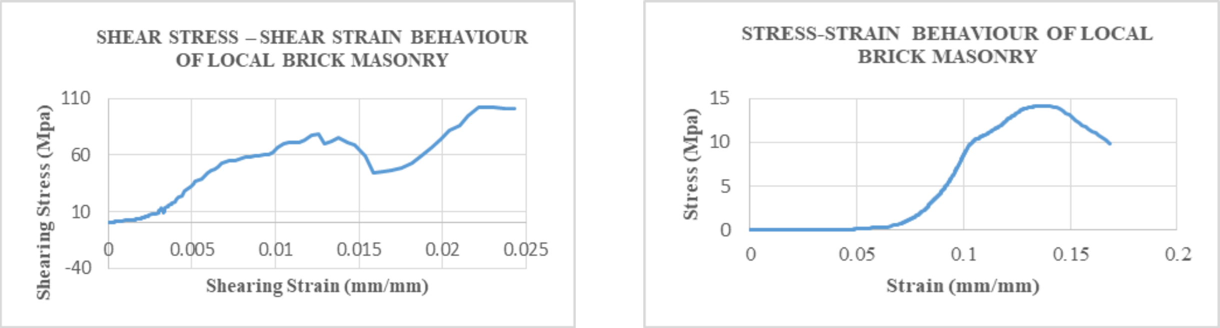

Fig. 2a & 2b: In-plane and axial compressive behaviour of local brick masonry

The behaviour of brick masonry as a whole changes when it is used as an infill material in RCC moment resisting frames. The infilled walls were once considered to be non-structural elements, but recent research shows that it's infact a structural element, and its behaviour depends on all the parameters of brick masonry [10].
A recent study shows the response of infill wall panels on RCC IMRFs by these two buildings, depicted in figure 3, that were meant to be identical when finished but an earthquake hit when one building was finished [11].

Fig. 3: Buildings in India that were meant to be identical.
Photo by: Randolph Langenbach

These infill walls are modeled by considering them as diagonal struts along the direction of force. Recent researches provide with models that ease the modeling of infill wall panels. [12] has carried out extensive experimental study on in-plane behaviour of brick masonry infill wall panels and consequently presented a mathematical model for the modeling of infill walls as diagonal struts.

A study in the northern areas of Pakistan reveals that timber studs resist the progressive destruction of the wall and prevent propagation of diagonal shear cracks and out-of-plane failure. The "Dhajji" and "Bhattar" types of construction in Kashmir are an example of this type of construction as researched by [11]. Dhajji and Bhattar are depicted in figures 4 & 5:

Fig. 4: Dhajji construction in Northern Pakistan

Photo by: Randolph Langenbach

Fig. 5: Bhattar construction in Northern Pakistan

Photo by: Randolph Langenbach

After a talk by Randolph Langenbach in 2006 at Islamabad, the ERRA and NESPAK approved Dhajji as compliant for government support and the following year, Bhattar was approved too [11]

V. ARMATURE TYPE INFILL WALL PANELS

It was observed by [11] that if infill walls are subdivided into many panels instead of just one, the in-plane capacity increases by a great magnitude. This is evident by the Dhajji and Bhattar construction methods that are known to withstand earthquakes better than RCC moment resisting frames. This type of construction of infill walls which uses small wall panels instead of just one is defined as armature type infill wall construction by [11] and is depicted in fig 6:

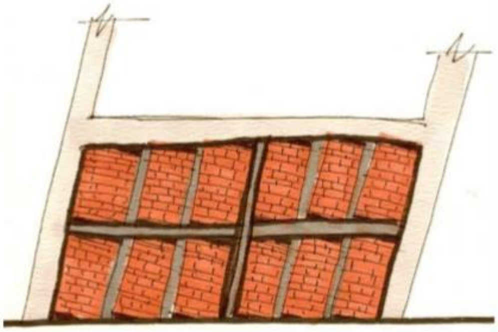

Fig. 6: Armature cross-wall concept showing the details of panels in wall.

Image by: Randolph Langenbach

VI. SIMULATION OF BRICK MASONRY IN SAP2000

The macro modeling of brick masonry was carried out by [9] on SAP2000, a Finite Element Analysis package. The results from the experimental investigations were compared to the numerical simulation and the results were found to be consistent as shown in fig 7.

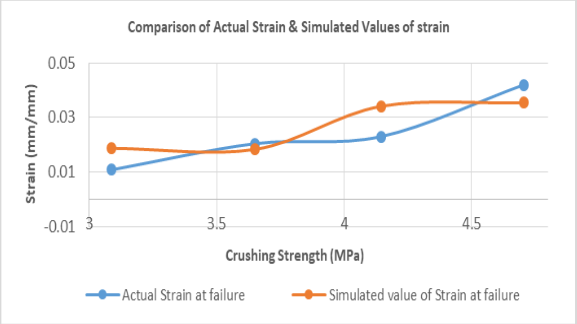

Fig. 7: Comparison of Experimental & Numerical results by [9]

The distribution of stress was also found out to be consistent with the actual scenario as shown in fig 8:

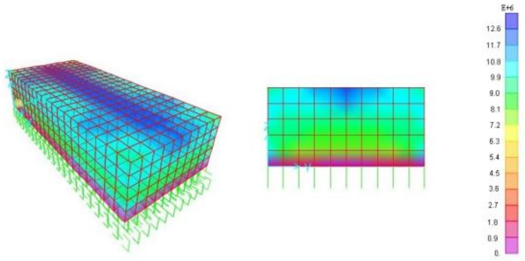

Fig. 8: Stress distribution in a single brick unit.

VII. SIMULATION OF INFILL WALL PANELS IN SAP2000

A. *Definition of element geometry.*

This study was conducted on SAP2000 using a simple single-storey single-span frame with two column elements (AD & BC) and two beam elements (AB & CD). The frame is defined in the x-z plane, with the member AB parallel to the x-direction. The frame was fixed at the base (Points A & B) as depicted in figure 9.

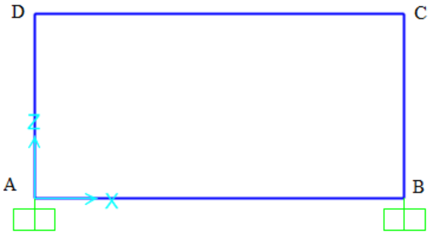

Fig. 9: The defined elements of frame

B. *Definition of material properties*

The infill material properties are taken from [9] as tabulated in table 1:

Table 1. The mechanical properties of masonry used in analysis

Property	**Value**
Modulus of elasticity	20.23kN/mm2
Poisson’s ratio	0.21
Specific weight	13.165kN/m3
Specific gravity	2.549

C. *The FEMA 356 provisions for strut definition.*

In this study, the infill wall panels are designed by macro modeling of brick masonry as suggested by [13]. This approach considers brick masonry infill walls as equivalent compressive diagonal struts. Macro modeling considers masonry as a continuum, and not as discrete elements.

FEMA 356 gives the following two formulae (1) & (2) to approximate the width of equivalent compressive diagonal strut:

$$\lambda_1 = \left(\frac{E_m t_{inf} \sin 2\theta}{4 E_{fe} I_{col} h_{inf}}\right)^{0.25} \qquad (1)$$

$$a = 0.175\,(\lambda_1 h_{col})^{-0.4} L_{diag} \qquad (2)$$

Where,

E_m and E_{fe} are the elastic moduli of the infill and the frame material respectively; t_{inf} is the thickness of the infill wall; I_{col} and h_{col} are the moment of inertia and the height of the column cross section of the surrounding frame; h_{inf} is the height of the infill wall panel; L_{diag} is the length of the equivalent compressive diagonal strut and ‘a’ is the width of the equivalent compressive diagonal strut.

D. *Cross-section of diagonal strut.*

For this study, the values tabulated in table 2 were used:

Table 2. The various geometric and mechanical properties used in analysis

Property	**Value**	**Property**	**Value**
E_m	$3\text{x}10^6$ psi	E_{fe}	$4\text{x}10^6$ psi
h_{col}	144 in	h_{inf}	144 in
I_{col}	0.2345 ft^4	Θ	26.565°
t_{inf}	9 in	L_{diag}	26.8328 ft

For the simulated case, the thickness and width of equivalent diagonal compressive strut as per FEMA 356 are found to be as under:

λ_1 = 0.0372 in^{-1}
t_{inf} = 9 in
a = 28.8 in
Thus, the diagonal strut was designed with cross-sectional dimensions of 9 in x 28.8 in.

E. Construction of plastic hinge properties.

The non-linear force-displacement relationships of members are modelled as plastic hinges. The relation contains a series of line segments differentiating between unloaded condition, yielding (Point A), nominal strength (Point B), ultimate strength (Point C), initial failure (Point D) and residual strength (Point E) as depicted in figure 10. The area between yielding and nominal strength is divided into three distinct points known as Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) that are used as defining parameters for the hinge.

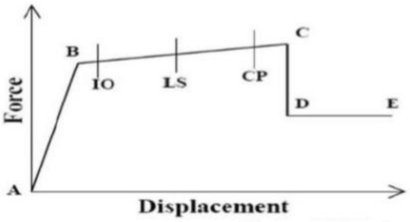

Fig. 10: The force-displacement relationship for plastic hinge as per FEMA 356

For this study, the force-displacement relationship was defined as studied by [9] as tabulated in table 3:

Table 3. The three defining parameters of plastic hinge.

Immediate Occupancy (IO)	50%
Life Safety (LS)	80%
Collapse Prevention (CP)	100%

F. Definiton of load case – Response spectrum.

The load case was defined as a response spectrum along the x-direction as defined in the Building Code of Pakistan Seismic Provisions 2007. As per the site conditions of Abbottabad, the Seismic zone is Zone 3, Therefore, the seismic zone factor is Z = 0.3. For a soil profile type of soft clay as mentioned in [14], the soil profile type is S_E^1. The values of C_a and C_v are thus found to be 0.36 and 0.84 respectively; As per the BCP SP 2007, g = 9.815 m/s^2; and the damping ratio is 0.05 since it is not explicitly defined. The number of modes in this analysis was limited to one only.

G. Finalized model of frame.

The finalized model consists of two beams AB & DC (24 feet long) and two columns AD & BC (12 feet long), with one diagonal strut BD as shown in figure 11.

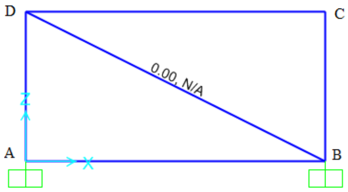

Fig. 11: Finalized Model

H. Assignment of tension/compression limits.

The diagonal strut was assigned a tension limit of zero that defines it as only capable of taking compressive loads.

VIII. RESULTS OF SINGLE-STOREY SINGLE-SPAN INFILL WALL FRAME ANALYSIS

The following results were obtained from the simulation of single-storey single-span infill wall frame analysis on SAP2000.

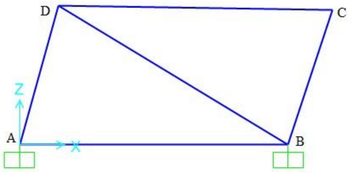

Fig. 12: The deformed shape of frame after analysis.

Figure 12 shows the deformed shape of the frame. The results obtained from the analysis are tabulated in table 4.

Table 4. The results obtained from the analysis of single-storey single-span infill wall frame.

Axial load on strut	57417.60 lbs
Horizontal reaction at joint A	2660.59 lbs
Vertical reaction at joint A	30794.42 lbs
Horizontal reaction at joint B	54275.73 lbs
Vertical reaction at joint B	27044.85 lbs
Horizontal Displacement at joint C	0.06 in
Vertical Displacement at joint C	2.4×10^{-5} in
Horizontal Displacement at joint D	0.052 in
Vertical Displacement at joint D	6.8×10^{-3} in

IX. SIMULATION OF FOUR-PANEL ARMATURE TYPE INFILL WALL PANELS IN SAP2000

In this case, the model was refined so that the same wall is composed of four panels in one wall instead of just one. The resulting wall is known as armature type infill wall as depicted in figure 13.

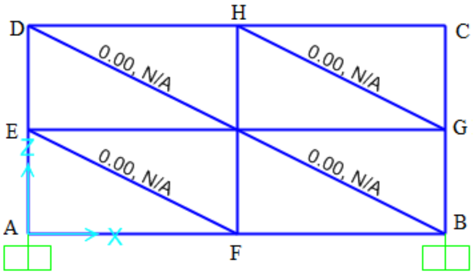

Fig. 13: Four-panel infill wall frame before analysis.

X. RESULTS FROM THE FOUR-PANEL ARMATURE TYPE INFILL WALL ANALYSIS IN SAP2000

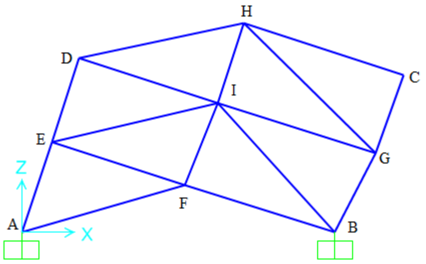

Fig 14: The deformed shape of frame

Figure 14 shows the shape of infill wall frame with four panels after running the analysis. The results obtained from the analysis are tabulated in table 5.

Table 5. The results obtained from the analysis of four-span infill wall frame.

For the panel AFIE		**For the panel IGCH**	
Axial load on strut	43716.03 lbs	Axial load on strut	1279.65 lbs
Horizontal reaction at joint A	28515.38 lbs	Horizontal displacement at joint C	0.0315 in
Vertical reaction at joint A	54770.21 lbs	Vertical displacement at joint C	3.73×10^{-4} in
For the panel FBGI		**For the panel EIHD**	
Axial load on strut	15685.26 lbs	Axial load on strut	36336.44 lbs
Horizontal reaction at joint B	41686.35 lbs	Horizontal displacement at joint D	0.0261 in
Vertical reaction at joint B	1816.02 lbs	Vertical displacement at joint D	8.05×10^{-3} in

XI. SIMULATION OF NINE-PANEL ARMATURE TYPE INFILL WALL PANELS IN SAP2000

In this case, the model was refined so that the same wall is composed of nine panels in one wall instead of just one. The resulting wall is as depicted in figure 15.

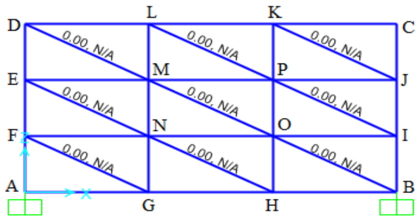

Fig. 15: Nine-panel infill wall frame before analysis.

XII. RESULTS OF NINE-PANEL ARMATURE TYPE INFILL WALL PANELS IN SAP2000

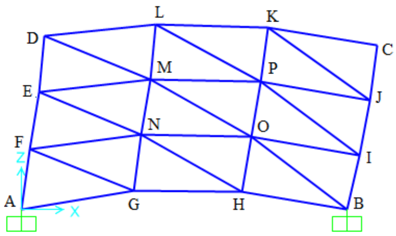

Fig. 16: Nine-panel infill wall frame before analysis.

Figure 16 shows the shape of nine-panel frame after running the analysis. Table 6 shows the data obtained from the analysis.

Table 6. The results obtained from the analysis of nine-panel frame.

For the panel AGNF		**For the panel HBIO**	
Axial load on strut	35177.65 lbs	Axial load on strut	10222.16 lbs
Horizontal reaction at joint A	46645.4 lbs	Horizontal reaction at joint B	47434.08 lbs
Vertical reaction at joint A	78961.14 lbs	Vertical reaction at joint B	7136.39 lbs
For the panel PJCK		**For the panel EMLD**	
Axial load on strut	7590.48 lbs	Axial load on strut	25771.66 lbs
Horizontal displacement at joint C	0.02628 in	Horizontal displacement at joint D	0.02 in
Vertical displacement at joint C	1.14×10^{-3} in	Vertical displacement at joint D	9.97×10^{-3} in
For the panel GHON		**For the panel OIJP**	
Axial load on strut	22432.08 lbs	Axial load on strut	712.34 lbs
For the panel MPKL		**For the panel FNME**	
Axial load on strut	7753.99 lbs	Axial load on strut	35728.69 lbs
For the panel NOPM			
Axial load on strut	19885.01 lbs		

XIII. RESULTS

The various results obtained from the analysis are as follows:

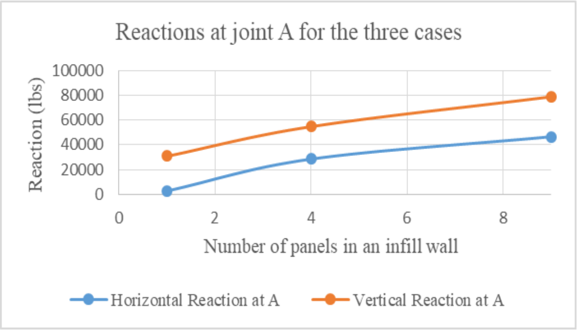

Fig. 17: The reactions at point A for the three cases analyzed.

Figure 17 shows the variation in support reactions at point A for the three cases analyzed viz. An infill wall with only one panel, an armature type infill wall with four panels and an armature type infill wall with nine panels. It is evident that with the increase in number of panels in an infill wall, the support reactions are also increasing. This is because to separate every panel, a reinforced concrete lintel is used, which increases the total load on the bottom beam. Same is the case with the reactions at point B as shown in figure 18.

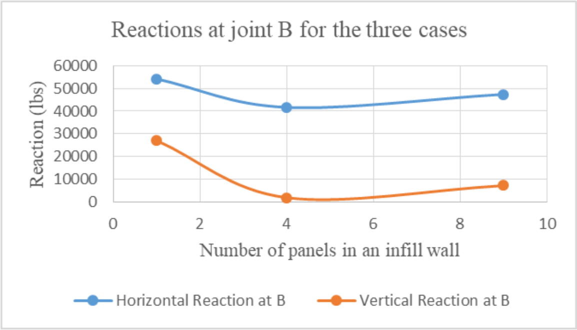

Fig. 18: The reactions at point B for the three cases analyzed.

As shown in figure 19, the net displacements at Joint C decrease as the number of panels in an infill wall increase.

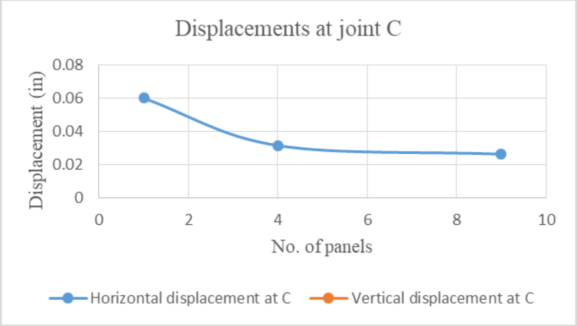

Fig. 19: The displacements at joint C for the three cases analyzed.

Same is the case for joint D as shown in figure 20 i.e. the net displacements at Joint D decrease as the number of panels in an infill wall increase.

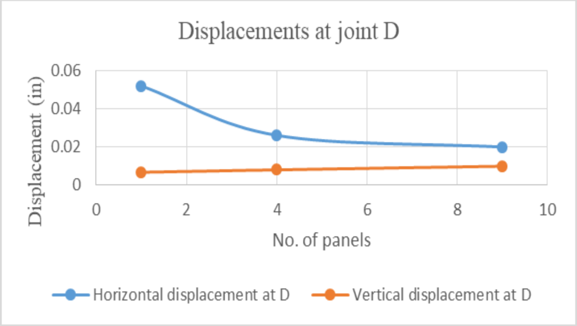

Fig. 20: The displacements at joint D for the three cases analyzed.

With increasing number of infill wall panels, the maximum axial compressive force in the diagonal struts decreases, which shows that if armature type infill walls are used in place of conventional masonry infill, the in-plane performance of frame increases. This is shown in figure 21.

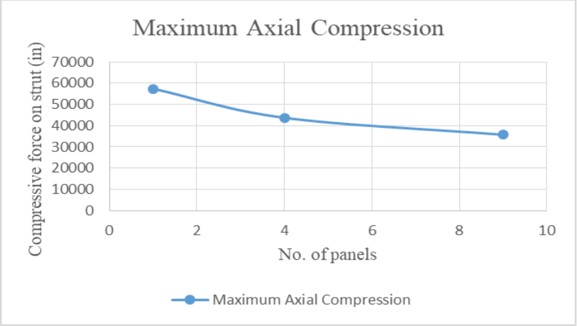

Fig. 20: The maximum axial compression for the three cases analyzed.

XIV. CONCLUSIONS

With the usage of armature type infill walls:

- The base reactions at joints A and B increase, this is because to convert a conventional infill wall into an armature type infill wall, additional members i.e. RCC lintels are used, that increases the overall load of the wall and consequently, the base reactions increase.
- The displacements of the joints C & D decrease, this is because with increasing number of panels, the number of unknowns increases, and that leads to the increased stability of the structure.
- The maximum axial force in the various equivalent diagonal compressive struts decreases, which shows that with increasing number of panels, the magnitude of in-plane forces decreases, that also adds to the overall stability of the structure.

This proves that in earthquake prone areas, the use of armature-type infill walls in RCC IMRFs will make structures more efficient against earthquakes, and will lead to a more sustainable built environment.

XV. RECOMMENDATIONS

The behaviour of armature-type infill wall panels in multi-storey multi-span, tall and high-rise buildings should also be studied so that the most efficient way of construction in these structures comes to be known.

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