American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-9, Issue-8, pp-194-204
www.ajer.org
Research Paper Open Access

Modal Analysis of Braced and Unbraced Steel Frames

Raqib Al Mahmood[1*], Amit C. Barman[2], Md. Hasnain Hossain[3], S. Khusru[4]
[1,2,3]Graduate Student, [4]Assistant Professor, Department of Civil Engineering,
Ahsanullah University of Science and Technology, Dhaka-1208, Bangladesh
Corresponding Author: raqib.nizu@gmail.com

ABSTRACT : *The inherent dynamic characteristics of a structure play a significant role in earthquake engineering for assessing seismic hazard. Modal analysis is the process of determining the inherent dynamic characteristics of a system and used to determine structure vibration characteristics. Steel structures are considered as most reliable in time of seismic activity and getting popularity in Bangladesh due to its less erection time. This paper is an attempt to assess, the efficacy of the bracing system in reducing the natural period of a steel frame and to find out the most effective bracing system in this regard. A comparative parametric study of the unbraced frame and the braced frame was carried out based on modal analysis. The parameters for the study were modal period and frequency, mode shape, joint displacement, story drift, base reaction, and moment distribution in column andtypical story beam. The investigation started with modeling of a three and a nine-storied moment resisting frames, following the SAC Seattle model buildings and Pre-Northridge designs as the base model. Two different braced model-concentrically braced and eccentrically braced, was then developed for each type of frame. Modeling and analysis were performed using SAP2000 V14 software. The parametric study report that the bracing system can reduce the natural period and the concentrically braced frame exhibits the best performance.*

KEYWORDS: *Modal analysis, Natural period, SAC Frame, Concentric bracing, Eccentric bracing.*

Date of Submission: 15-08-2020 Date of acceptance: 01-09-2020

I. INTRODUCTION

All objects have a natural period or frequency, at which they will move back and forth if they are given a horizontal push. When earthquake motion starts a building vibrating, it will tend to sway back and forth at its natural period [1].As seismic waves move through the ground, the ground also moves at its natural period [2]. If the natural frequency of a structure and the frequency of ground motion is close or equal, the structure may suffer greatest damage due to resonance [1-2].

Bangladesh, a South Asian country located between24°0'0" N latitude and 90°0'0" E longitude, lies in a seismically active zone making it extremely vulnerable to major earthquakes [3]. Two major fault lines run through Bangladesh, one 144 km and the other 370 km from its capital Dhaka. Bangladesh has had several fairly mild earthquakes in the last two decades [4] and two major ones in the past 100 years [3].The demand for steel buildings is increasing in the country as it needs low investment and less time, and provides high safety [5]. So, to ensure the safety of modern days steel structures from seismic hazard, it is important to find out their dynamic characteristics.

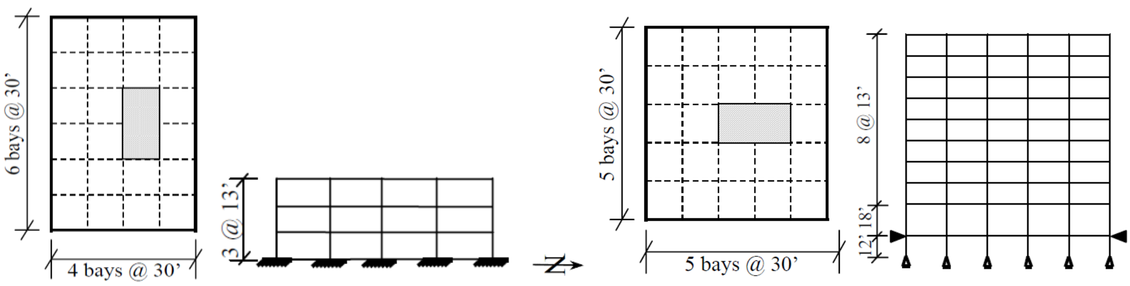
Modal analysis is the process of determining the inherent dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes, and using them to formulate a mathematical model for its dynamic behavior [6].In structural engineering, modal analysis is applied to find the various periods that the structure will naturally resonate at, by using the structure's overall mass and stiffness. The modal analysis is very important in earthquake engineering, because the periods of vibration evaluated helps in checking that a building's natural frequency does not coincide with the frequency of earthquakes prone region where the building is to be constructed [7].

Bangladesh being vulnerable to earthquake, dynamic analysis is a must for the future design of steel structures in major earthquake zones considering the best effective bracing patterns [8]. The concentric bracings increase the lateral stiffness of the frame, thus increasing the natural frequency and also usually decreasing the lateral drift. However, increase in the stiffness may attract a larger inertia force due to earthquake. Further, while the bracings decrease the bending moments and shear forces in columns, they increase the axial compression in the columns to which they are connected. Since reinforced concrete columns are strong in compression; it may not pose a problem to retrofit in RC frame using concentric steel bracings.Eccentric Bracings reduce the lateral stiffness of the system and improve the energy dissipation capacity. Due to eccentric connection of the braces to beams, the lateral stiffness of the system depends upon the flexural stiffness of the beams and columns, thus reducing the lateral stiffness of the frame. The vertical component of the bracing forces due to earthquake cause lateral concentrated load on the beams at the point of connection of the eccentric bracings [9].

This study is undertaken to analyze the response and behavior of steel frames under modal analysis in different bracing conditions, hence to find out the most effective bracing system in reducing the natural period.

II. METHODOLOGY

For this study we considered 3 and 9 storied SAC frames. SAC frame is a globally recognized moment resisting steel frame and all the section of this frames are predefined. The floor plans and elevation of 3 and 9 story SAC model buildings were preset.Theshaded area indicates the penthouse location.The column bases in the 3-story buildings are considered as fixed. The 9-story buildings have a single-level basement. Plan and the loading have been derived from the model used in the section FEMA 355C [10]. Design conditions for Pre-Northridge model building of Seattle (SE) structures have been followed. Pre-Northridge designs were based on design practices prevalent before the Northridge earthquake, i.e., without consideration of the FEMA 267 (1995) document. These designs had the standard beam-to-column welded connection details [10]. The 2D floor plan & elevation view of the 3 and 9 storied SAC SE buildings is shown below:



(a) (b)

Fig. 1: Floor Plans and Elevations for (a) 3 & (b) 9 storied SAC SE buildings.

Fig. 2 below shows the positions of NS moment resisting frame for Seattle model buildings in bold lines.

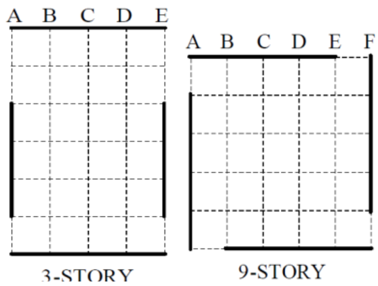


Fig. 2: Layout of moment resisting frame for 3 and 9 storied SE model buildings.

A572 Gr. 50 steel has been used for all column, beam, girder and bracing sections in this study. A metal slab had been provided as per FEMA 355C [10].The column and girder sizes of 3 and 9 storiedframe are shown in Table 2 and 3 respectively.Pipe section is used for bracing.All external frames are braced by bracing systems placed only at corner panelsin both directions. Bracing section property of 3 and 9 storied SAC frame are shown in Fig. 3. For modeling and modal analysis of the said structures SAP2000 V14had been used [11].The materialproperties are shown in the table below.

Table 1: Material Properties

Name	Type	Modulus of Elasticity, E (lb/in^2)	Poison's Ratio, v	Unit Weight lb/ft^3	Yield Strength, F_y lb/in^2
A572Gr50	Steel	29000000	0.3	490	50000

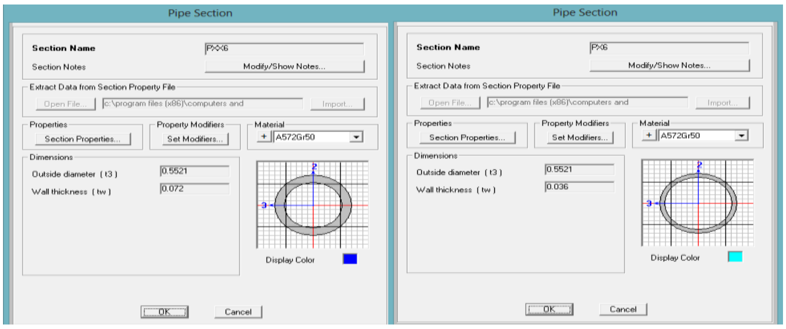
Table 2: Frame elements for 3 story SAC SE building

Story/Floor	Columns		Doubler Plates (in)	Girder
	Exterior	Interior		
1/2	W14X159	W14X176	0,1/4	W24X76

2/3	W14X159	W14X176	0,9/16	W24X84
3/Roof	W14X159	W14X176	0,0	W18X40

Table 3: Frame elements for 9 story SAC SE building

Story/Floor	Columns		Doubler Plates (in)	Girder
	Exterior	Interior		
-1/1	W24X229	W24X229	0,0	W30X108
1/2	W24X229	W24X229	0,0	W30X108
2/3	W24X229	W24X229	0,1/4	W30X116
3/4	W24X229	W24X229	0,0	W30X108
4/5	W24X229	W24X229	0,0	W27X94
5/6	W24X207	W24X207	0,0	W27X94
6/7	W24X207	W24X207	0,1/4	W24X76
7/8	W24X162	W24X162	0,1/4	W24X76
8/9	W24X162	W24X162	0,1/4	W24X62
9/Roof	W24X131	W24X131	0,1/4	W24X62



(a) (b)

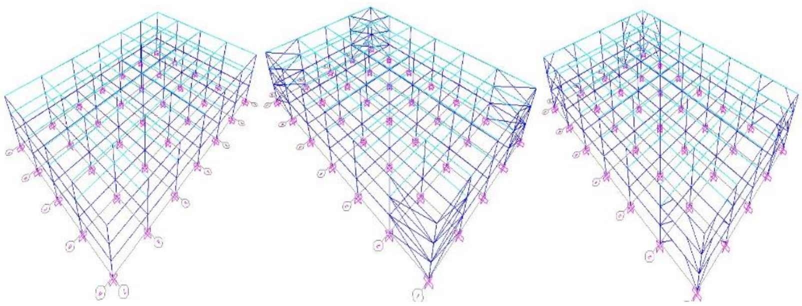
Fig. 3: Bracing section property for (a) 3 & (b) 9 storied SAC SE buildings.

AISC-LRFD method has been followed for member design.Loads are distributed as gravity load & lateral load. Gravity loads are distributed over the floor and the roof as per FEMA 355C [10].They are different for floor and roof. Lateral loads include wind load and earthquake load and for bothload UBC 94 auto lateralload pattern has been used.Wind load is considered in one direction but the earthquake load is considered in X & Ydirection. For calculating lateral load, the joint constraint has been provided as rigid diaphragm. They wereprovided at each joint of each floor.Following load combination are used to obtain the loads in this study [12]:

1. 1.4 (D+F)
2. 1.2 (D+F+T) + 1.6 (L+H) + 0.5 (L_r or S or R)
3. 1.2 D + 1.6 (L_r or S or R) + (L or 0.8 W)
4. 1.2 D + 1.6 W + L + 0.5 (L_r or S or R)
5. 1.2 D + 1.0 E + L + 0.2 S
6. 0.9 D + 1.6 W + 1.6 H
7. 0.9 D + 1.0 E + 1.6 H
8. Envelope

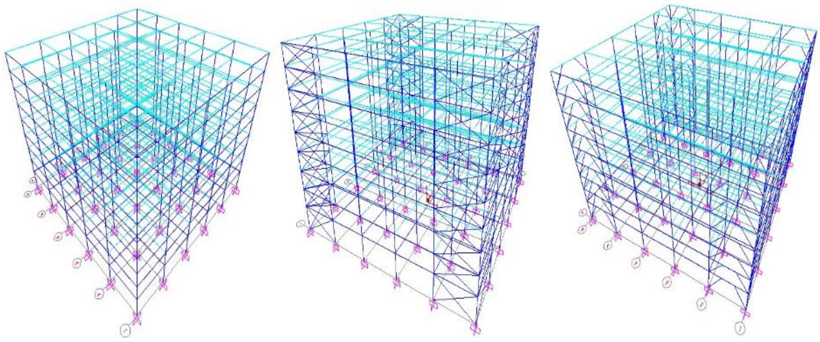
Where, D = dead load, E = earthquake load, F = load due to fluids with well-defined pressures and maximum heights, H = load due to lateral earth pressure, ground water pressure or pressure of bulk materials, L = live load, L_r = roof live load , R = rain load, S = snow load, T = self-straining force, W = wind load.

A 3-D view of the unbraced frame (UBF), concentrically braced frame (CBF) and eccentrically braced frame (EBF) for 3 and 9 storied SAC SE building is shown in Fig 4 and 5 respectively.



(a) (b) (c)

Figure 4: 3D view of 3 storied (a) UBF (b) CBF (c) EBF



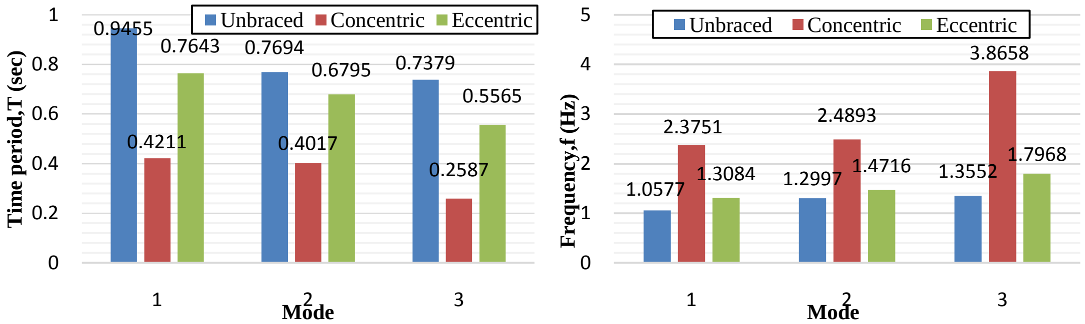
(a) (b) (c)

Figure 5: 3D view of 9 storied (a) UBF (b) CBF (c) EBF

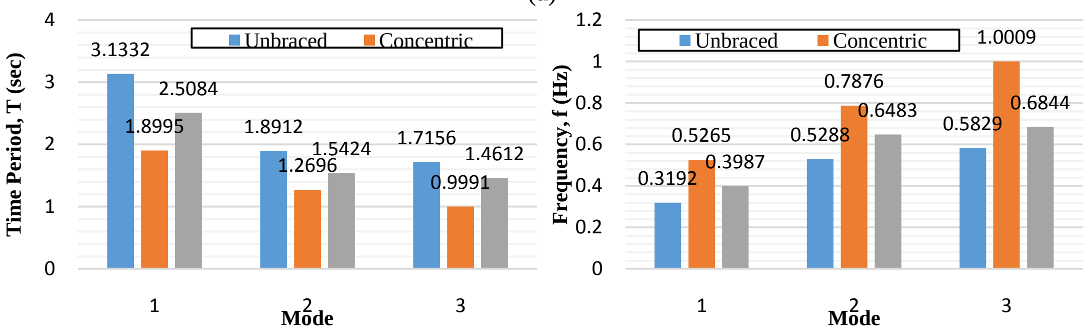
III. RESULTS AND DISCUSSIONS

a. Modal Period and Frequencies

The modal period and frequency of the analyzed frames for the first three mode are shown in Fig.6.



(a)



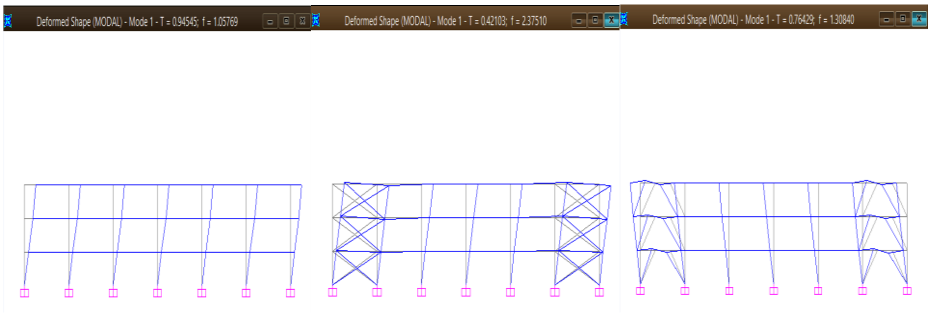
(b)

Fig. 6: Time period and frequency of (a) 3 storied and (b) 9 storied SAC frame for first 3 mode

After observing the modal period and frequency results from Fig. 6, it is clear that modal period of a structure can be minimized by providing bracing in that structure and concentric bracing is more effective to do so. The above table also indicate that modal frequency can be increased by providing bracing in the structure and concentric bracing is more effective to do so.

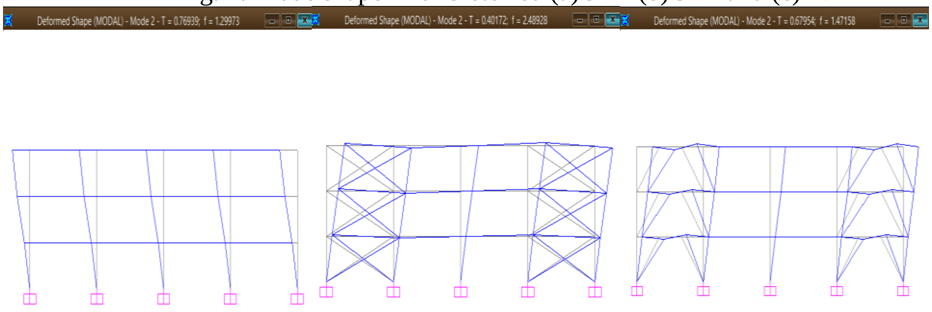
b. Mode Shape

The 1st 6 mode shape of 3-storied frame has been shown in following Figures for different types of bracing system.



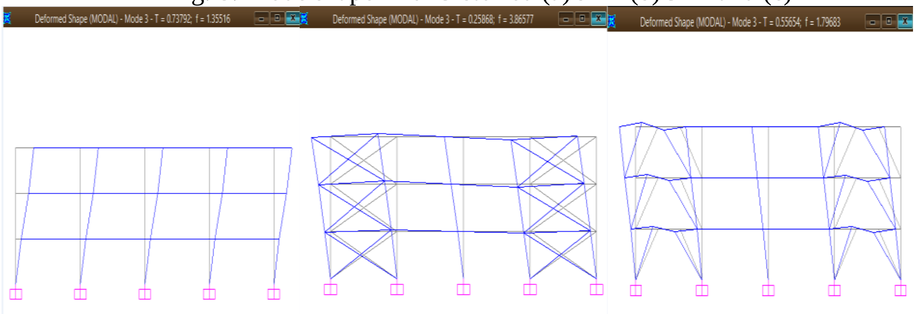
(a) (b) (c)

Fig. 7: Mode shape 1 for 3-storied (a)UBF (b)CBF and (c)EBF



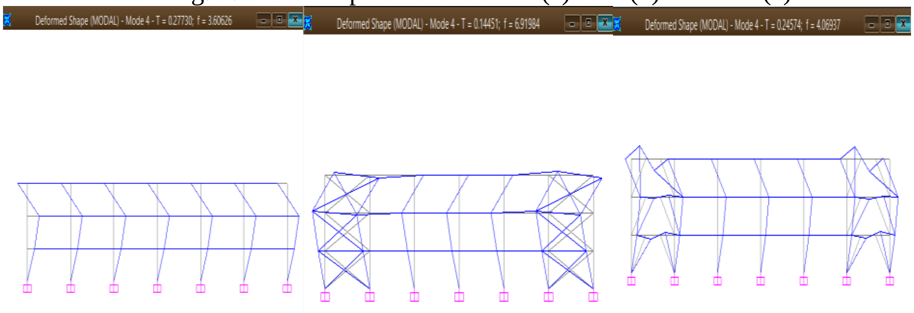
(a) (b) (c)

Fig. 8: Mode shape 2 for 3-storied (a)UBF (b)CBF and (c)EBF



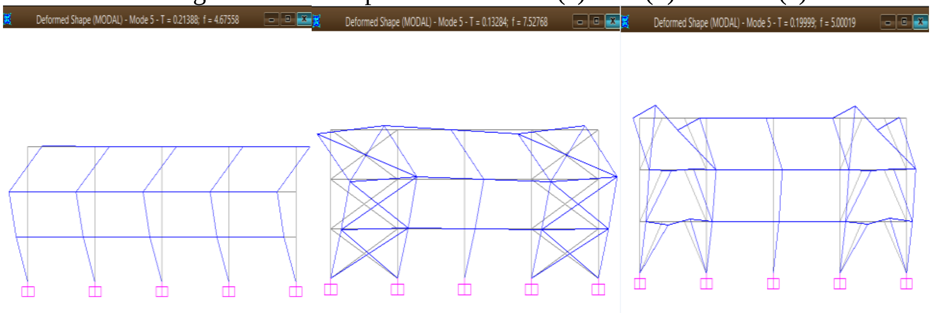
(a) (b) (c)

Fig. 9: Mode shape 3 for 3-storied (a)UBF (b)CBF and (c)EBF



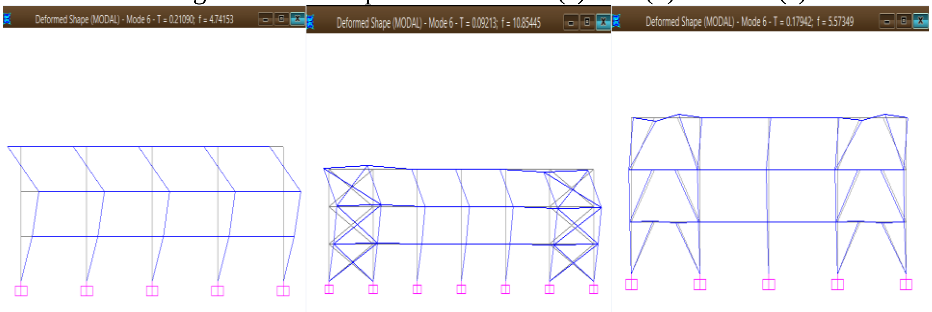
(a) (b) (c)

Fig. 10: Mode shape 4 for 3-storied (a)UBF (b)CBF and (c)EBF



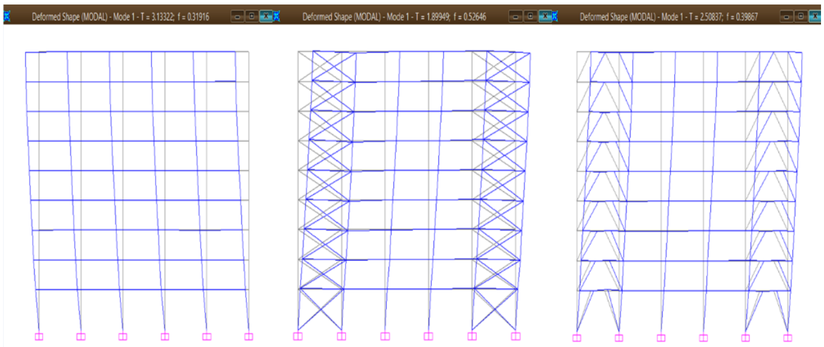
(a) (b) (c)

Fig. 11: Mode shape 5 for 3-storied (a)UBF (b)CBF and (c)EBF

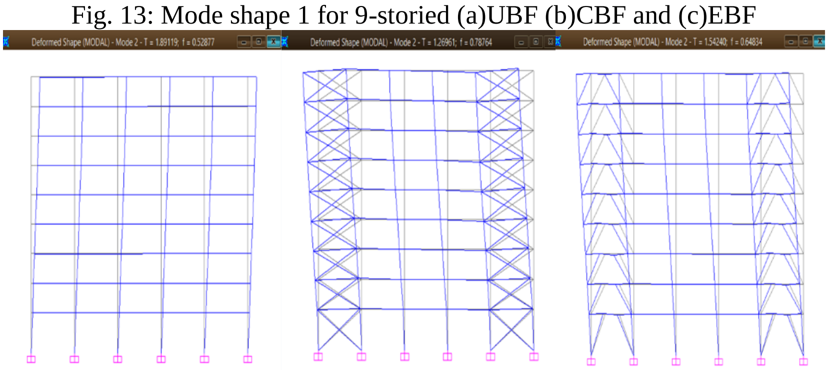


(a) (b) (c)
Fig. 12: Mode shape 6 for 3-storied (a)UBF (b)CBF and (c)EBF

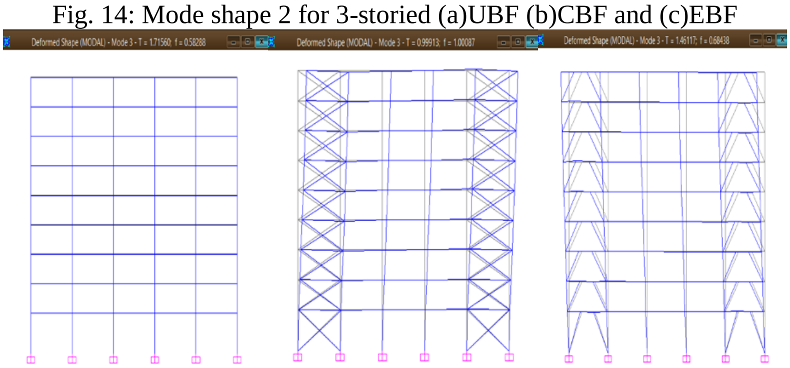
The 1st 6 mode shape of 9-storied frame has been shown in following figures for different types of bracing system.



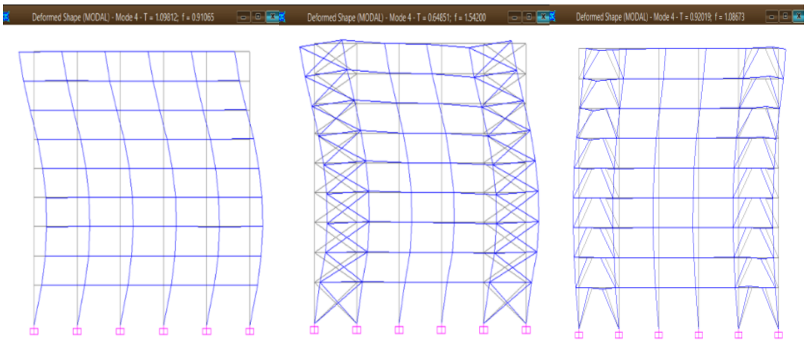
(a) (b) (c)
Fig. 13: Mode shape 1 for 9-storied (a)UBF (b)CBF and (c)EBF



(a) (b) (c)
Fig. 14: Mode shape 2 for 3-storied (a)UBF (b)CBF and (c)EBF

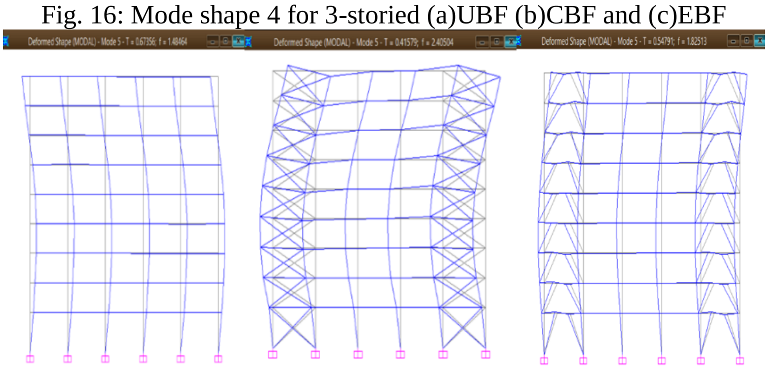


(a) (b) (c)
Fig. 15: Mode shape 3 for 3-storied (a)UBF (b)CBF and (c)EBF



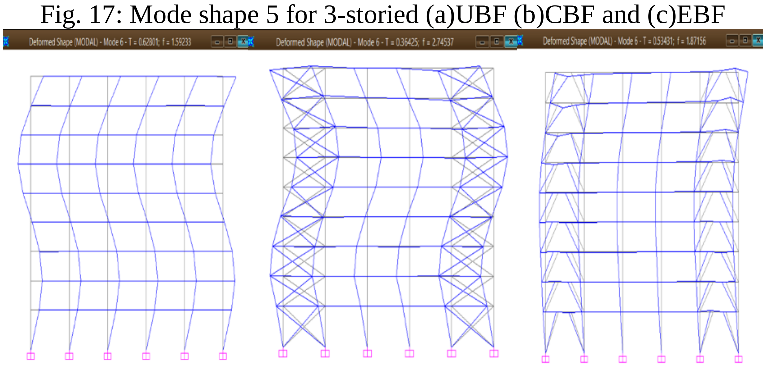
(a) (b) (c)

Fig. 16: Mode shape 4 for 3-storied (a)UBF (b)CBF and (c)EBF



(a) (b) (c)

Fig. 17: Mode shape 5 for 3-storied (a)UBF (b)CBF and (c)EBF

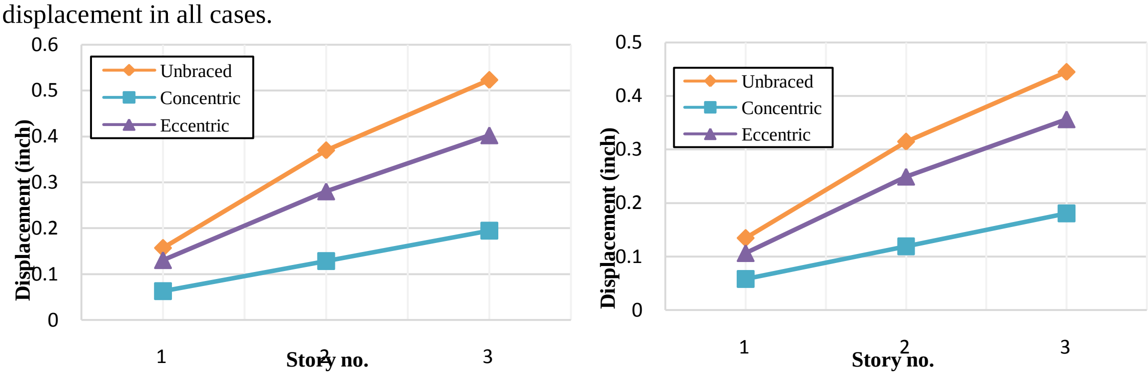


(a) (b) (c)

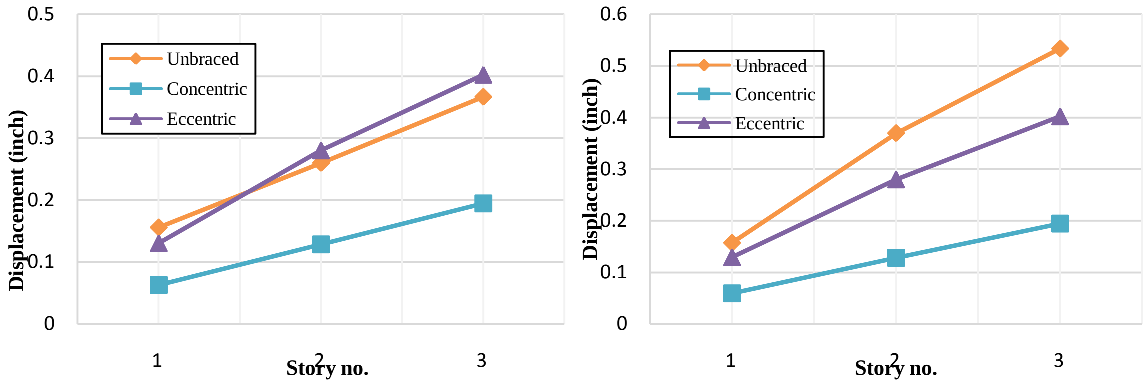
Fig. 18: Mode shape 6 for 3-storied (a)UBF (b)CBF and (c)EBF

c. Joint Displacement

The Joint displacement for different story levelsdue to envelope load for both 3 and 9 storied SAC frameshas been depicted in figures19 and 20 respectively. From the following figures, it is observed that CBF depicts less displacement in all cases.

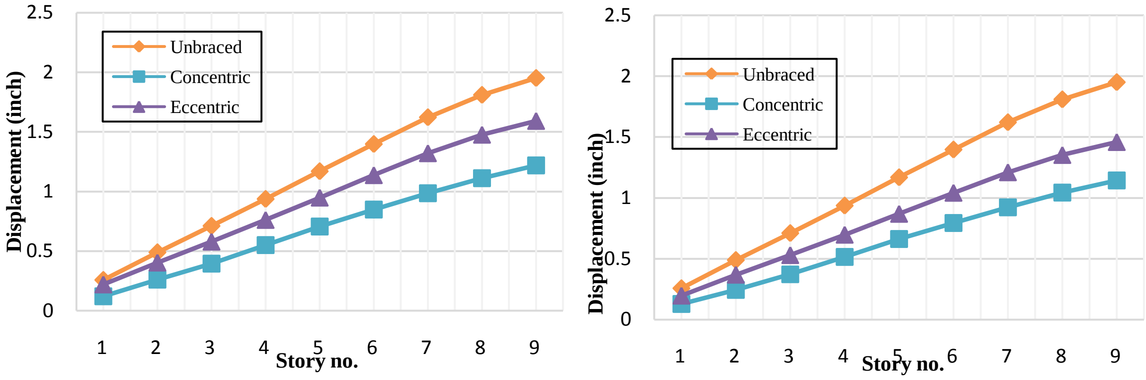


(a) (b)



(c) (d)

Fig. 19: Joint displacement of 3 storied SAC frame in the short direction (a) exterior (b) interior frame and in the long direction (c) exterior (b) interior frame.

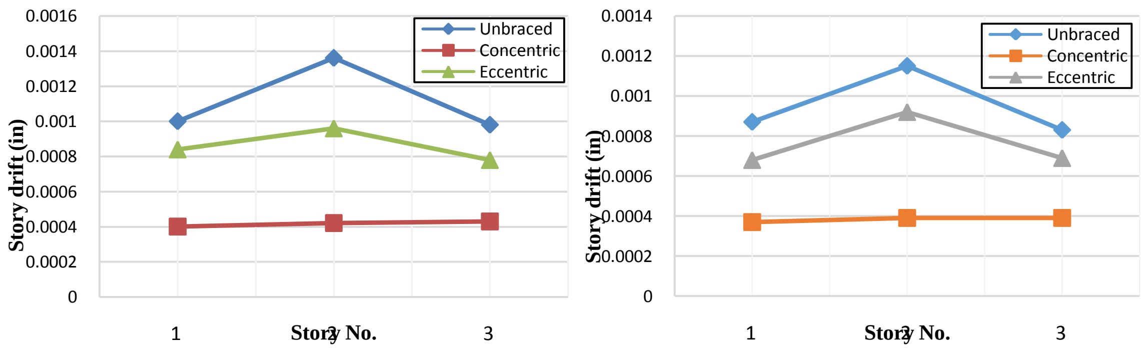


(a) (b)

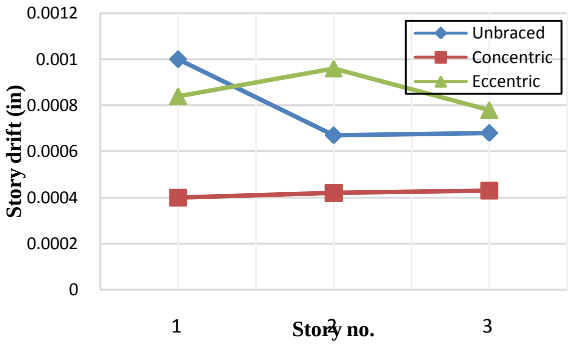
Fig. 20: Joint Displacement of 9 storied SAC frame in the (a) exterior and (b) interior frame.

d. Story Drift

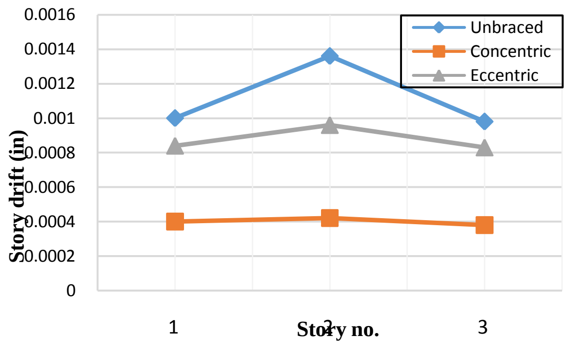
Story drift is the displacement of one story or floor relative to the story or floor above or below due to design lateral forces [13].The buildings were required to conform to a drift limit of h/400 as per FEMA 355C, where “h” is the story height [10].So for the 3 story SAC frame, the limit for all the story is (13*12)/400=0.39″ and for the 9 story SAC frame, thelimit for story 1 is (12*12)/400=0.36″ , for story 2 is (18*12)/400=0.54″ andfor the other stories are(13*12)/400=0.39″ .



(a) (b)

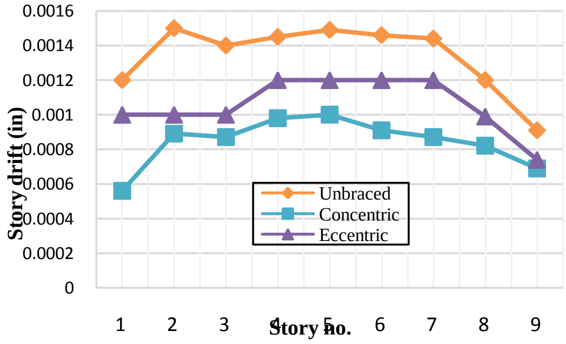


(c)

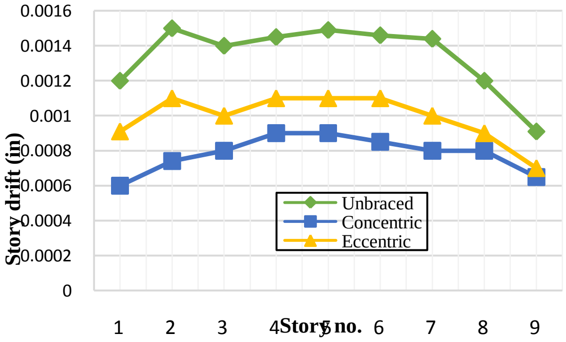


(d)

Fig. 21: Story drift of 3 storied SAC frame (a) exterior (b) interior (c) exterior (d) interior



(a)



(b)

Fig. 22: Story drift of 9 storied SAC frame (a) exterior (b) interior

From the above figures, it is observed that the story drift value was well below the maximum limit for both 3 and 9 storied frames. CBF structures produce the least story drift in all cases.

e. Base Reaction

The base reaction of both 3-storied and 9-storied SAC frame is shown in Fig. 23. From the following figure, it has been found that 9 storied frames produce much higher base reaction than the 3 storied frames and CBF shows higher values.

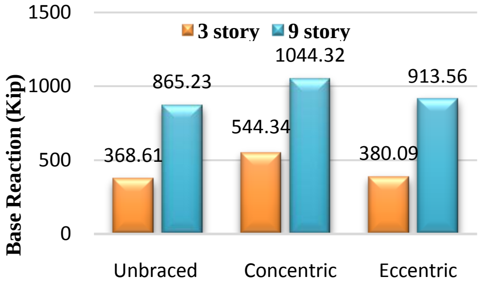
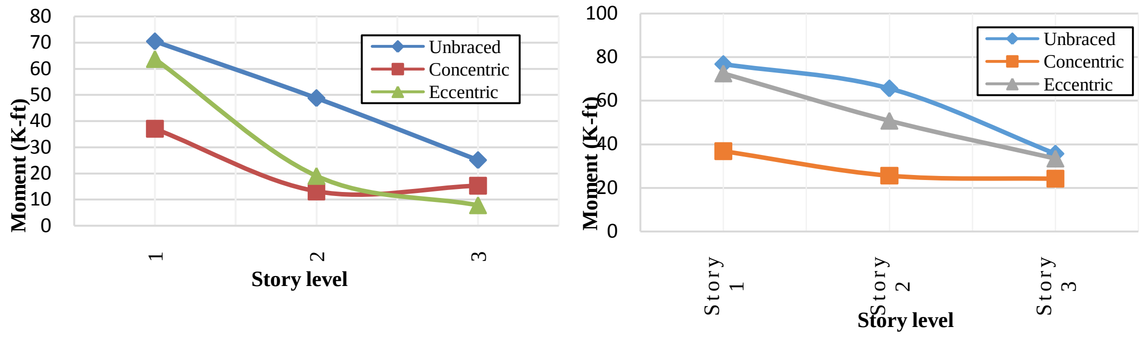


Fig. 23: Base reaction of 3 and 9 storied SAC frame

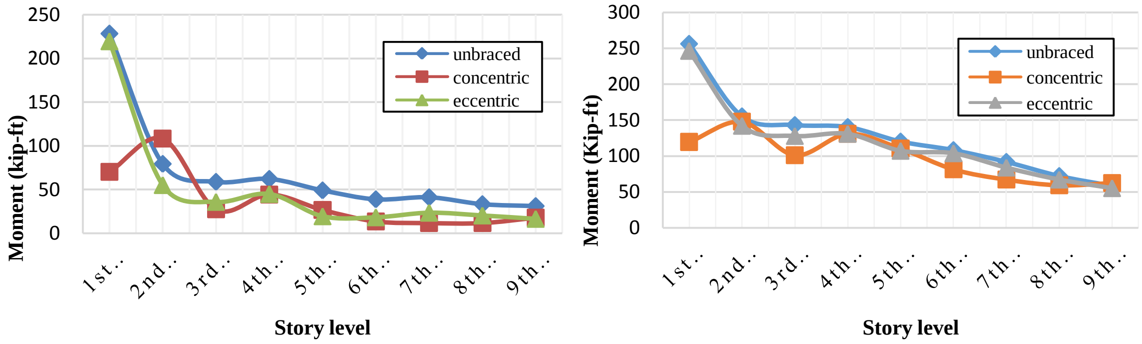
f. Column Bending Moment

The column bending moment for an exterior and interior column of both 3 and 9 storied SAC frame are shown in figure 24 and 25 respectively.



(a) (b)

Fig. 24: Column bending moment in the (a) exterior and (b) interior frame of 3 storied SAC frame



(a) (b)

Fig. 25: Column bending moment in the (a) exterior and (b) interior frame of 9 storied SAC frames

The above figures show that the braced frames produce less moment than the unbraced frame.

g. Typical Story Beam Moment

The typical story beam moment in both short and long direction of 3 storied SAC frame is presented in tables below:

Table 4: Typical story beam moment in short direction of 3 story SAC frame

Short direction	Moment(k-ft) at Beam	i End			j End		
		UBF	CBF	EBF	UBF	CBF	EBF
Exterior frame	1A1B	42.9432	10.9689	17.4518	50.0964	20.4109	6.49936
	1B1C	37.7768	16.0198	34.1841	49.2538	28.3529	43.7827
	1D1E	40.8973	9.7327	10.5348	58.7823	24.6012	14.8042
Interior frame	4A4B	50.1338	16.4039	38.8966	56.6787	25.9734	46.4482
	4B4C	44.125	15.6174	34.6286	57.5087	28.7489	47.9281
	4D4E	50.2024	19.4966	39.9764	68.5278	34.7974	57.2949

Table 5: Typical story beam moment in long direction of 3 story SAC frame

Long direction	Moment(k-ft) at Beam	i End			j End		
		UBF	CBF	EBF	UBF	CBF	EBF
Exterior frame	1A2A	54.0693	8.8632	10.3965	56.4557	16.7356	14.6219
	3A4A	39.5169	8.8532	21.8967	52.6278	21.2199	36.2857
	6A7A	45.8873	7.791	7.0594	67.2838	20.3588	6.9441
Interior frame	1C2C	52.6864	11.637	34.2058	55.6882	20.4612	39.8335
	3C4C	40.6807	8.9761	26.1712	53.8217	21.7477	39.3548
	6C7C	47.3805	12.1544	31.5015	67.9187	26.8696	49.419

The typical story beam moment of both i end and j end of 9 storied SAC frames is presented in table below:

Table 6: Typical story beam moment of 9 story SAC frame

Moment(k-ft) at Beam 1A1B	i End			j End		
	UBF	CBF	EBF	UBF	CBF	EBF
2nd floor	125.5665	67.7928	75.4901	131.3299	72.9199	61.1426
3rd floor	107.8781	42.8044	72.289	114.2218	50.628	60.3981
4th floor	82.3104	34.5759	33.6889	89.8036	42.2948	43.5625
5th floor	76.6161	23.3039	29.0378	83.5344	30.5256	41.9134
6th floor	49.0712	17.5363	19.4234	56.4969	17.0329	23.6169
7th floor	38.9832	17.9959	12.4404	45.9964	11.6073	22.324
8th floor	28.4741	15.2716	1.3932	25.6158	5.2617	12.9318

From the above tables, it has been seen that bending moment of the typical story beam in braced frame has been reduced in both i and j end from the unbraced frame.

IV. CONCLUSION

In this paper, a 3 and a 9 storied moment resisting steel frame in three different bracing condition-UBF, CBF and EBF, were constructed using SAP2000, following the SAC Seattle model building and Pre-Northridge design, to observe the efficacy of the bracing system in reducing natural period of a steel structure and to find out the most effective bracing system in this regard.

As the time period decreases, the frequency increases and 9-storied frames tend to have lower natural frequency than 3-storied frames. Both CBFs and EBFs has effectively reduced the time period for the analyzed frames and CBFs is more effective to do so. CBFs reduces time period up to 60 % and that of EBFs can reduce up to 20%. Braced frame shows less joint displacement and story drift than unbraced frames. CBFs reduced joint displacement from 30%-60% and EBFs reduced 10%-20% compared to UBFs. Story Drift has been reduced from 20%-65% in CBFs and 10%-25% in EBFs. Values of base reaction is higher in braced frames compared to unbraced frames. 9-storied frame shows higher base reaction compared to 3-storied frame. Among the bracing systems, CBFs produces highest base reaction forces for the analyzed frames. Bending moment in column for both 3 and 9 storied frames continuously decreases with the increase in story level. The columns in unbraced frames produces maximum moment compared to columns in braced frames. After all the analysis and comparison, we came to know that CBFs is the most effective system under given conditions.

For further studies it is recommend to use different types of bracings and section property available in Bangladesh. Time history analysis and Response spectrum analysis with different earthquake data, P-Δ effect and other analysis may give the best result. In this study bracing is installed only in the exterior frames, so in future study may involve bracing in both exterior and interior frames.

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