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Seismic Performance of Steel Frames with Inverted V-Braces for North Cyprus

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Abstract: ***Cyprus Island is located in a high-risk zone, in which the buildings should have lateral load-resistance systems to resist the lateral imposed loads. Bracings play a vital role in the structural behavior of buildings during an earthquake. There are many bracing systems that can be found thorough searching in the literature. However, there are insufficient studies regarding the inverted-V bracing system in accordance with the Northern Cyprus seismic code of NCSC-2015. In this study, the seismic performance of steel structures equipped with various types of inverted-V bracing systems is investigated for mid-rise and high-rise buildings in accordance with NCSC-2015 code. Several steel structure buildings having different lateral load-resistance systems are analyzed under different loading patterns applying ETABS2016 software. For this purpose, linear static equivalent lateral force method (ELFM), nonlinear static (Pushover) and nonlinear dynamic time-history (TH) analyses were adopted. The obtained results in this research indicate that the inverted-V bracing systems dramatically enhance the performance of the steel structures more particularly when the earthquake is applied perpendicular to the weak axis of the columns. This indicates that the inverted-V bracing system is an effective solution to resist the applied lateral loads while maintaining the functionality of the building. By applying the regression analysis some practical equations were submitted for the stiffness factor to be employed in similar cases as a guideline.***

Keywords: inverted-v steel bracing, equivalent lateral force method, pushover, time history, ncsc-2015 code.

I. INTRODUCTION

Earthquakes can result in a catastrophic event, which can lead to a large number of casualties and significant damages to structures. Thus, designing the structures to withstand these events is a major concern for engineers. There are plenty of systems that can enhance the ability of structures to resist the lateral forces such as base isolation, tuned mass damper, viscous and friction dampers. However, such a system requires skilled labors and is hard to apply in developing countries. Besides, it has a high cost of shipping and installation. Hence, cheaper and applicable systems such as shear walls or bracings are more desirable in such countries. Cyprus is located within the plate boundary between the Anatolian, Nubian and Sinai faults and is threatened by seismic activities. Thus, the development of applicable and inexpensive systems that can survive the severe ground motion is extremely vital. The main provision of the seismic design of structures is highly dependent on the structure lateral stiffness, ductility and strength. Lateral stiffness, ductility, and structural strength factors contribute to minimizing the failures of the structural elements [1]. Ultimately, the three mentioned phenomena are highly influenced by the structural system and the material properties [2]. Bracing system is one of the most important lateral load-resisting systems because of their major role in reducing the interstory drift ratios and for their high stiffness capability [3]. There are many different types of bracing systems. However, most of them minimize the ability to create openings along the elevation of the building, where openings are quite essential in Northern Cyprus for natural ventilation, unlike the inverted-V bracing systems, which have good flexibility in this aspect [4]. Steel structural systems equipped with inverted-V bracing systems are widely used in practice to resist the lateral loads created by seismic activity. However, the number of guidelines to design these bracing types is quite poor [5]. For this purpose, this paper aims to investigate the performance of various inverted-V bracing systems to resist the lateral loading that might be generated in the selected location of Northern Cyprus.

II. BUILDINGS SPECIFICATIONS

All the modeled buildings consist of a ground floor with an elevation of 3.5 m from the ground level and the heights of the other stories are 3 m. The steel modeled mid-rise and high-rise buildings consisted of both G+4 (5-story) and G+9 (10-story) structures, with 4 different types of bracing systems. They have both regular and irregular plans as shown in Figs. 1 and 2. The location of the modeled buildings is assumed to be at Famagusta city in Northern Cyprus. This location has characterized by a peak ground acceleration (PGA) ranging between 0.30g-0.35g. All structures are modeled as frames with rigid connection except the bracings and secondary beams, which they are hinged at both ends.

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The composite steel floor decks are modelled as one-way membrane element.

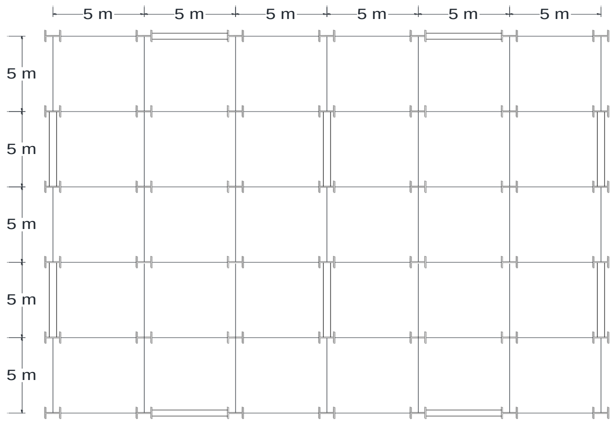

Fig 1. Floor plan for regular buildings.

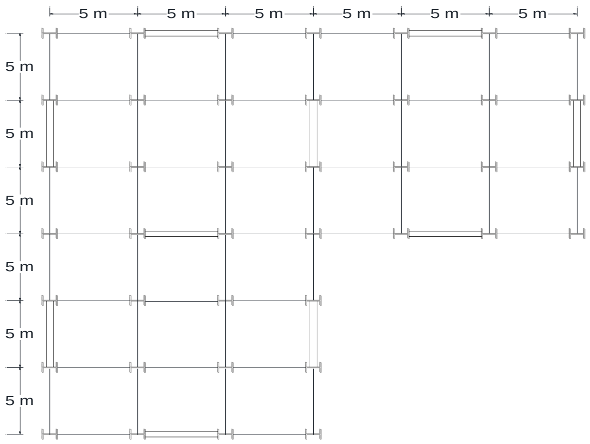

Fig 2. Floor plan for irregular buildings.

III. PROPERTIES OF THE MODELED INVERTED-V BRACING SYSTEMS

In this study, four different types of inverted-V bracing systems are selected that are widely used in practice. The circular steel hollow section is employed to model the bracing parts except for the knee elements where wide flange cross-section is used to overcome the exerted shear stresses. The studied systems are listed below:

- Concentric inverted-V (CIV) bracing system.
- Eccentric inverted-V (EIV) bracing system with a 15% linkage spacing out of the span length.
- Inverted-V bracing system with knees parallel to the frame diagonals (KIVD).
- Inverted-V bracing system with knees parallel to the bracing element (KIVB).

A schematic view of the adopted bracing systems is presented in Fig. 3.

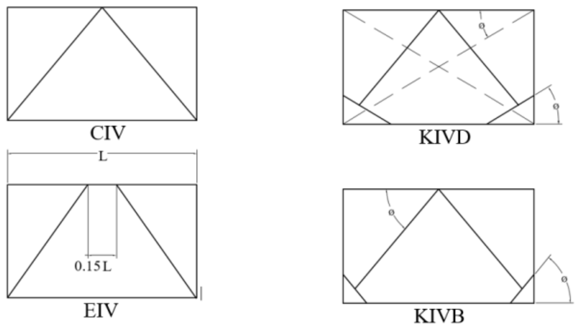

Fig. 3. Schematic view of the adopted bracing systems.

IV. STRUCTURAL MODEL DESIGN CRITERIA

The steel structural models were designed in accordance with Eurocode 3 [6, 7] applying ETABS2016 software [8-10]. The buildings were loaded up to the yielding of the smallest sections that can withstand the applied loads. The structures are subjected to various types of loading as listed in Table I [11]. The parameters used in the calculation of the seismic loads are presented in Table II.

Table I. Loading specifications.

Load Patterns	Magnitude
Dead Load	Self-weight of the structure
Live load	2 kN/m^2 according to(TS498)
Additional Dead Load	1.5 kN/m^2
Wind Load	15 m/s according to (TS498)
Earthquake load	10% exceedance within 50 years according to (NCSC2015)

Table II. Seismic load parameters.

Earthquake seismic parameters	Value
Effective ground acceleration coefficient, (A_o)	0.3 g
Site class	Z2
Importance factor (I)	1
Live load reduction factor	0.3
Damping ratio	5%
Structural behavior factor (R)	6 - 8

V. APPLIED METHODS TO ANALYZE THE STRUCTURAL PERFORMANCE OF THE BUILDINGS

The structural performance of the steel buildings under high-risk seismic zone is evaluated by means of pushover analysis and nonlinear time-history analysis.

A. Pushover Analysis

The nonlinear static pushover analysis is conducted in accordance with FEMA365 [12] where plastic hinges at both ends of the structural members are assigned. The properties of the plastic hinges are listed in Table III. Earthquake load case with an exceedance probability of 2% within 50 years is applied to push the building. The lateral forces are applied at the center of the semi-rigid diaphragm with an additional eccentricity of ±0.05. The lateral loads are applied in 200 steps until the target displacement is reached.

Table III. The properties of the plastic hinges.

Structural member	Stresses regarding hinge formation
Column	Axial stress and bending moments in both major and minor axes of the member's section (P, M3, M2)
Beam	Bending moment along the major axis of the member's section (M3)
Bracing	Axial stress (P)
Knee	Bending moment along the major axis of the member's section (M3)

B. Nonlinear Time-History Analysis

In order to perform the nonlinear time-history analysis, 3 different ground motion records are selected aiming to cover a large range of frequencies as suggested by NCSC2015 [13]. The details of the selected ground motion records are presented in Table IV and the ground acceleration resulted of these earthquakes are shown in Fig 4, where the data are collected from the Pacific Earthquake Engineering Research center (PEER) ground motion database [14]. The ground motion records are scaled so they have a similar behavior of earthquake spectra with an exceedance probability of 2% within 50 years. Plastic hinge properties are identical to the pushover analysis.

Table IV. The details of the selected ground motion records.

Earthquake Name	Kocaeli, Turkey	Duzce, Turkey	Erzincan, Turkey
Station Name	Duzce	Sakarya	Erzincan
Year	1999	1999	1992
Magnitude, Mw (Richter)	7.51	7.14	6.69
Shear-wave velocity ,Vs30 (m/sec)	281.86	414.91	352.05
Rjb (km)	13.6	45.16	0
Rrup (km)	15.37	45.16	4.38

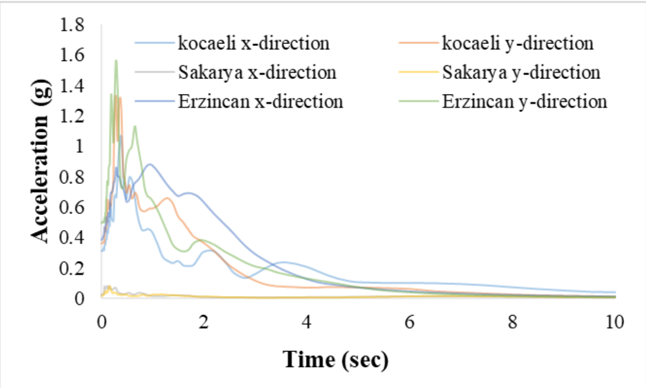

Fig 4. Ground acceleration records.

VI.RESULTS AND DISCUSSIONS

The behavior of the inverted-V bracing system in enhancing the seismic performance of steel structure building is presented in this section through the application of various types of inelastic analysis conducted applying ETABS2016 software. In order to meet this objective, some vital parameters that influence the seismic behavior of the structure are discussed. These parameters include the total mass of the structure, the initial lateral stiffness and its degradation, the roof drift, the ductility of the structural system, plastic hinge formations, roof acceleration and the total absorbed energy by the structure.

A. Total Weight of the Structure

Beyond the analysis of the steel structure building the cost of the employed systems is extremely important. The cost of the steel structure buildings is directly related to the weight of the steel, which is used. All buildings are designed using the optimum sections that can withstand the resulted internal stresses. The results show that moment-resisting frames (MRF) are heavyset although it has the least number of structural members compared to the buildings equipped with the bracing systems this can be clearly seen in Table V which presents the total weight of the steel structure buildings. The main reduction is observed in columns weights where the reduction in beams weights is insignificant.

Table V. Total weight of the structural systems.

Model name	5-story structures (ton)	10-story structures (ton)
R-CIV	1089.5	2204.4
R-EIV	1089.6	2202.4
R-KIVD	1090.2	2206.3
R-KIVB	1089.4	2204.3
R-MRF	1098.1	2224.5
IR-CIV	982.7	1988.5
IR-EIV	983.2	1987.1
IR-KIVD	984.0	1991.1
IR-KIVB	982.9	1988.2
IR-MRF	994.0	2004.8

B. Initial Lateral Stiffness

The results obtained from the nonlinear static pushover analysis show that at low monitored displacement the lateral stiffness is constant this can be linked to the fact that the structural members did not exceed their yielding stress and the behavior of the structure is rather linear. However, the lateral stiffness reduces the increment of the monitored displacement. This behavior indicates the initial formation of the plastic hinges where the internal stresses within some of the structural members exceed the yielding stress. The results also show that the CIV bracing system has the highest initial stiffness compared to the other systems. However, upon the formation of the plastic hinges, initial lateral stiffness is dramatically reduced, where lateral stiffness level becomes almost equal to the other systems. Ultimately, MRF has the least lateral stiffness and the drop in its stiffness is not as quite severe as the bracing system. This behavior is observed in all analyzed cases, which can be seen in Figs. 5 and 6 that presents the lateral stiffness against the monitored for 10-story buildings in x-direction. In addition, the results of the initial lateral stiffness of all models are summarized using the bar chart shown in Fig. 7. The enhancement of the buildings' lateral stiffness upon adding the bracing system is listed in Table VI.

It can be clearly seen that CIV system for both regular and irregular (R-CIV and IR-CIV) achieved remarkable improvement, especially in the y-direction. This can be linked to the column's major axis orientation since it is oriented parallel to the x-direction.

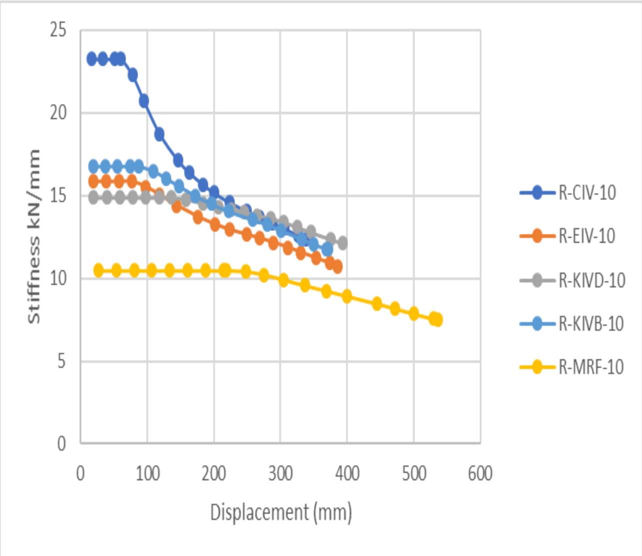

Fig 5. Stiffness in function of displacement in the x-direction for regular 10-story buildings.

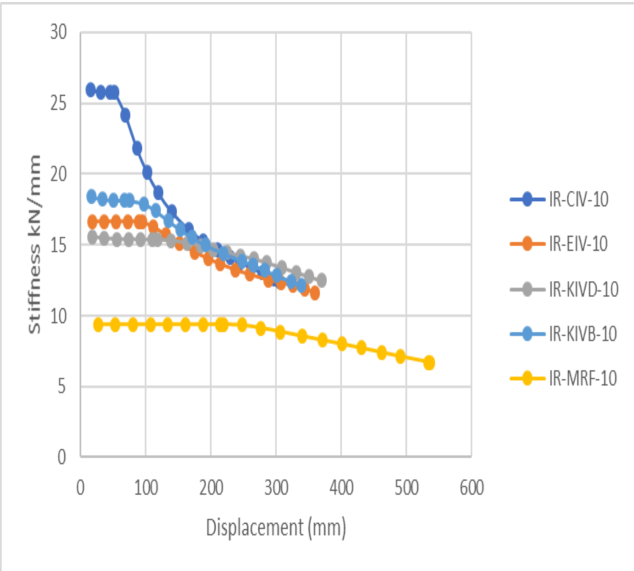

Fig 6. Stiffness in function of displacement in the x-direction for irregular 10-story buildings.

By applying the regression analysis, Eqs. (1) to (5) are found for the stiffness factor (K) in the x-direction for Regular 10-story buildings in function of lateral drift (related to the curves shown in Fig. 5):

$K = -8E\text{-}09d^4 + 6E\text{-}06d^3 - 0.0015d^2 + 0.0729d + 22.486$

With $R^2 = 0.996$ (For CIV bracing) (1)

$K = -1E\text{-}09d^4 + 1E\text{-}06d^3 - 0.0004d^2 + 0.0306d + 16.235$

With $R^2 = 0.9981$ (For EIV bracing) (2)

$K = -2E\text{-}09d^4 + 1E\text{-}06d^3 - 0.0004d^2 + 0.0279d + 15.398$

With $R^2 = 0.9982$ (For KIVD bracing) (3)

$K = 8E\text{-}11d^4 - 5E\text{-}08d^3 - 2E\text{-}05d^2 + 0.0035d + 14.777$

With $R^2 = 0.9983$ (For KIVB bracing) (4)

$K = 2E\text{-}10d^4 - 2E\text{-}07d^3 + 5E\text{-}05d^2 - 0.0034d + 10.524$

With $R^2 = 0.9978$ (For MRF) (5)

For Irregular 10-story buildings, Eqs. (6) to (11) (related to the curves shown in Fig. 6) are found for the stiffness factor (K) in the x-direction:

$K = -1E\text{-}08d^4 + 9E\text{-}06d^3 - 0.0019d^2 + 0.066d + 25.6$

With $R^2 = 0.9947$ (For CIV bracing) (6)

$K = -2E\text{-}09d^4 + 2E\text{-}06d^3 - 0.0005d^2 + 0.0415d + 15.872$

With $R^2 = 0.9971$ (For EIV bracing) (7)

$K = 4E\text{-}10d^4 - 3E\text{-}07d^3 + 4E\text{-}05d^2 - 0.0033d + 15.567$

With $R^2 = 0.9983$ (For KIVD bracing) (8)

$K = -2E\text{-}09d^4 + 2E\text{-}06d^3 - 0.0005d^2 + 0.0324d + 17.815$

With $R^2 = 0.997$ (For KIVB bracing) (9)

$K = = 2E\text{-}10d^4 - 2E\text{-}07d^3 + 4E\text{-}05d^2 - 0.003d + 9.4216$

With $R^2 = 0.9984$ (For MRF) (10)

In Eqs. (1) to (10), K is expressed in kN/mm, and d is expressed in mm. R^2 determines the determination factor.

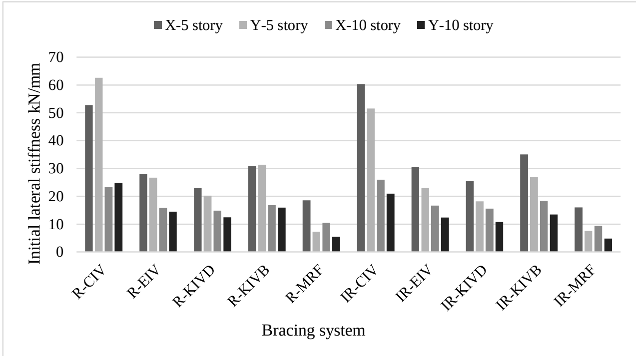

Fig 7. Initial lateral stiffness.

Table VI: Enhancement of the building lateral stiffness.

	5-story structures		10-story structures	
Bracing system	***(%) in x-direction**	***(%) in y-direction**	***(%) in x-direction**	***(%) in y-direction**
R-CIV	184.7	763.4	122.2	353.2
R-EIV	51.3	267.9	51.4	164.1
R-KIVD	23.8	179.2	42.0	126.4
R-KIVB	66.7	332.0	60.4	190.7
IR-CIV	276.6	578.8	176.7	336.7
IR-EIV	90.9	202.9	77.6	158.7
IR-KIVD	59.4	139.3	66.3	125.3
IR-KIVB	118.9	254.5	96.6	180.8

C. Roof Drift

The values of roof drift obtained by applying the nonlinear time-history analysis of three different ground motion records show that the MRF system has the highest roof drift especially along the y-direction, this is mainly related to the high ductility and low lateral stiffness of the MRF system. Resonance did not take place in the case of the MRF since all ground motion records produce similar displacement in both orthogonal directions regardless of their different frequencies. On the other hand, for the least roof drift, the results are inconsistent where CIV has the best performance in the case of 5-story buildings. However, for the 10-story buildings, KIVB resulted in a lower drift. This is valid for all the cases of the ground motion records.

The results of the maximum roof drift for all models are summarized using the bar chart illustrated in Fig 8. Ultimately, the percentages of the reduction of the roof drift when the bracings are added to the MRFs are presented in Fig 9.

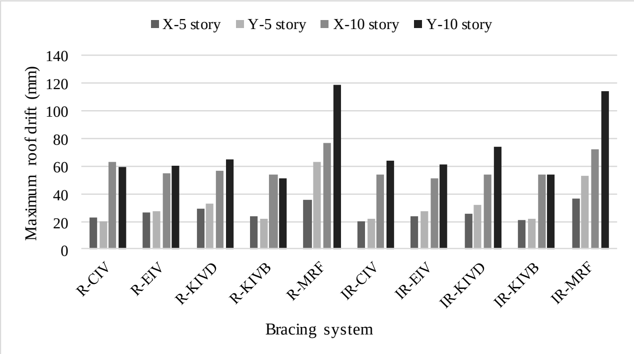

Fig.8 Maximum roof drift.

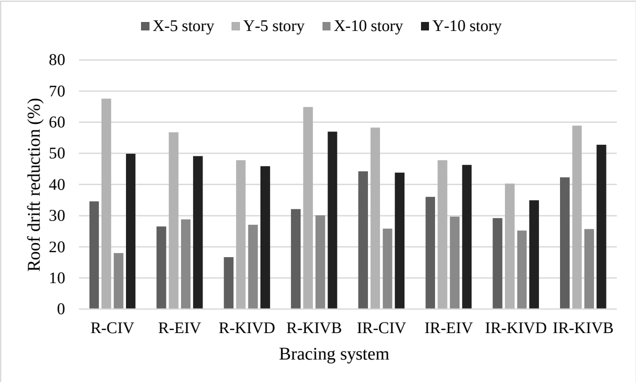

Fig 9. Roof drift reduction for different types of braced frames.

D. Displacement ductility factor

Ductility plays a major role in reducing the absorbed energy from the ground motion. Since it reduces the exerted lateral forces that may act on the structure. However, the too ductile structure is exposed to a high amount of sway, which leads to the discomfort of residence and reduces the serviceability of the structure. The displacement ductility factor (μ) is the ratio of the maximum roof displacement (Δu_{max}) to the yield displacement (Δy). The results of the nonlinear static pushover analysis show that MRF structures have the least μ compared to the braced frames. Their sways upon the application of lateral forces are relatively high and their yield displacements are high as well. On the other hand, all braced frames have very low yielding displacement, which results in high (μ). This is valid for all cases except the KIVD where its yield displacement is relatively high compared with the other bracing systems. Since the KIVD has the least amount of the lateral stiffness among the other bracing types. The results of the displacement ductility factors of all models are summarized in the bar chart shown in Fig. 10.

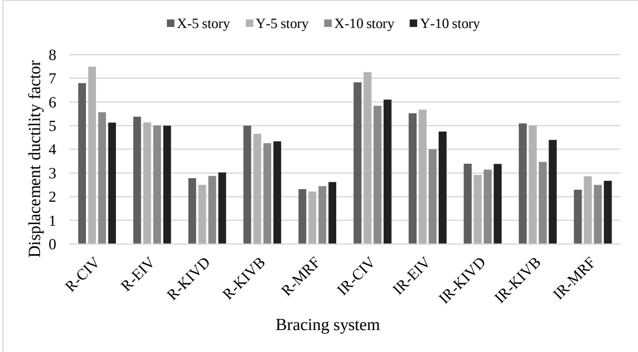

Fig 10. Displacement ductility factor (μ) for different types of lateral load-resisting systems.

A. Plastic Hinge Formation

When the stress in a structural member exceeds the yielding stress, the plastic hinges are formed. Initially immediate occupancy (labeled in green) hinges are formed as long as the rotation of the hinge is relatively small however upon the incremented loading the rotation angle will increase causing the plastic hinge to change its status to life safety (labeled in blue) or collapse prevention (labeled in red) hinges. It worth to mention that initial hinges are formed in the interstory then the formation propagates to both base and top stories. This can be linked to the high interstory drift ratio, which can be clearly observed in Figs. 11 to 14.

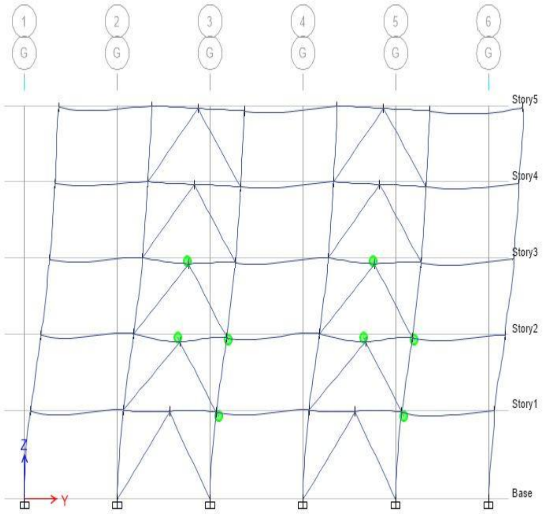

Fig11. First step plastic hinges forming in the y-direction for R-CIV 5-story building.

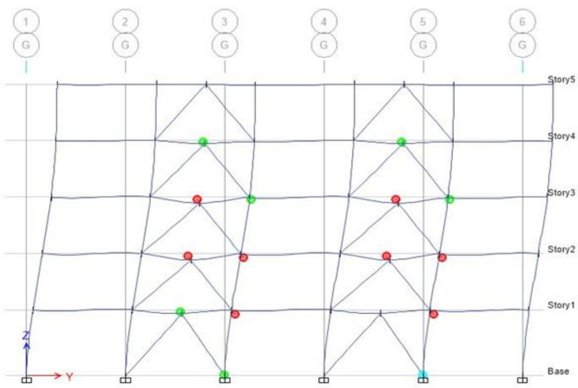

Fig12. Final step plastic hinges forming in the y-direction for R-CIV 5-story building.

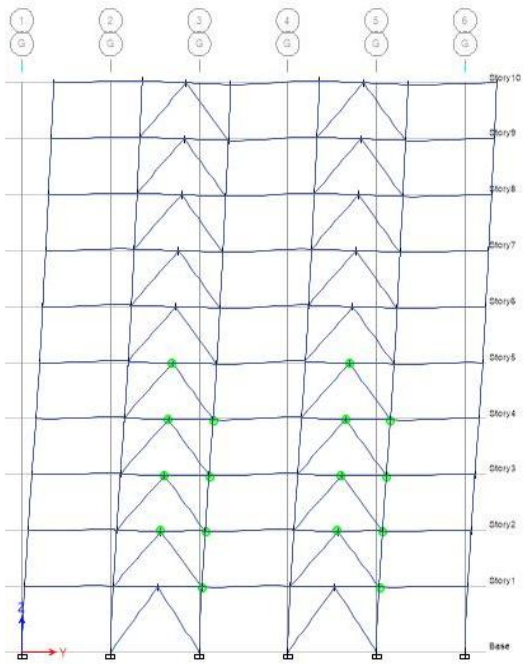

Fig. 13. First step plastic hinges forming in the y-direction for R-CIV 10-story building.

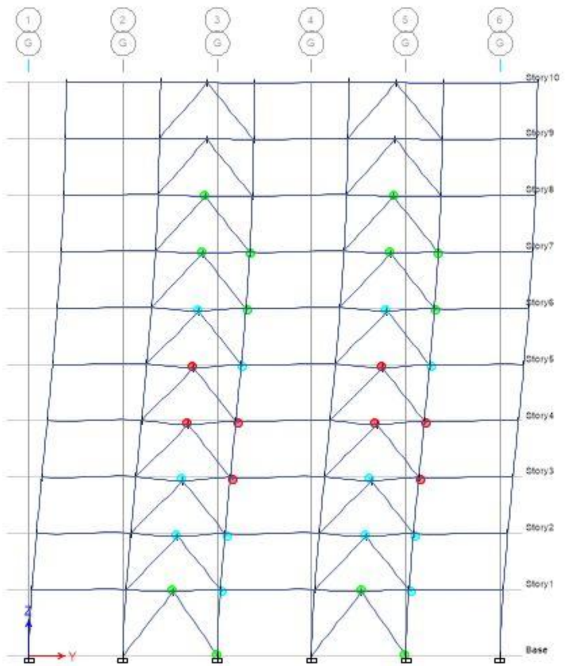

Fig. 14. Final step plastic hinges forming in the y-direction for R-CIV 10-story building.

B. Roof Acceleration

Peak floor acceleration is used to estimate the damages of the non-structural components such as electrical wiring and pipeline system. The results of the nonlinear time-history analysis show that roof acceleration is the highest for the CIV bracing system. On the other hand, the least roof acceleration is governed by the MRF system since it has high ductility, which dissipates a huge amount of the transmitted acceleration. The results of the roof acceleration of all models are summarized in the bar chart shown in Fig. 15.

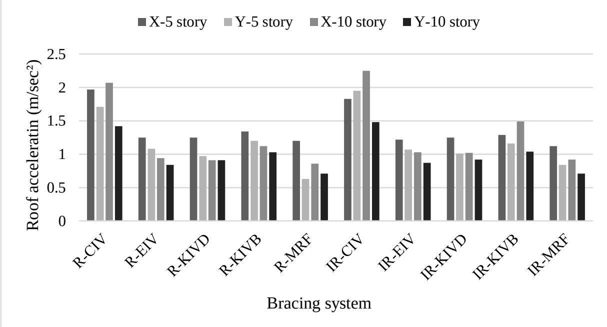

Fig 15. Roof acceleration for different lateral load-resisting systems.

VII. CONCLUSIONS

The seismic performance evaluation of steel structures equipped with various types of inverted-V bracing systems located in Famagusta city is presented. Both regular and irregular buildings with various story numbers are considered. For this purpose, 20 structural models are analyzed using ETABS2016 software. Both linear and nonlinear behaviors of the steel structural buildings are investigated in terms of many important parameters such as the total mass of the structure, the initial lateral stiffness and its degradation, the roof drift, the ductility of the structural system, plastic hinges formations, acceleration at the roof level and the total energy absorbed by the structure. The obtained results are summarized as follows:

1. All suggested bracing systems are cost-efficient since their masses are about 5% lower than the MRF mass in all of the studied cases.
2. CIV bracing system resulted in a tremendous enhancement of the initial stiffness compared with the other types of inverted-V bracing systems. However, its stiffness is suddenly reduced upon the development of the initial plastic hinges. On the other hand, KIVB bracing system significantly improved the initial lateral stiffness (more than 60%) and its stiffness did not show degradation as much as the CIV bracing system.
3. Moment-resisting framed structure resulted in the highest displacement. Ultimately, CIV and KIVB systems showed the minimum displacement for 5-story and 10-story buildings respectively.
4. The displacement ductility factor is the highest for CIV bracing system since it has low yielding displacement compared with the other bracing systems.
5. Maximum story acceleration for all the models in horizontal and vertical directions is observed in the case of CIV braced structures and minimum story acceleration in all the directions are observed in the case of MRF buildings.
6. The highest energy is observed for EIV and CIV bracing systems for 5- and 10-story buildings, respectively.
7. The practical equations submitted based on the regression analysis can be employed in similar cases as a guideline.

The advantage of the submitted equations is simplicity in finding the stiffness factor of the structures just by applying one parameter while the other influenced parameters are implemented implicitly in the equations.

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