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Seismic Propensity of Knee Braced Frame (KBF) As Weighed Against Concentric Braced Frame (CBF) Utilizing ETABS and OPENSEES

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Abstract – ***Steel braced frame is one of the structural systems used to resist earthquake loads in structures. Many existing reinforced concrete structures need retrofitting to overcome deficiencies and to resist seismic loads. The use of steel bracing systems for strengthening or retrofitting seismically in adequate reinforced concrete frames is a viable solution for enhancing earthquake resistance. Steel bracing is economical, easy to erect, occupies less space and has flexibility to design for meeting the required strength and stiffness. In the present study, seismic propensity of knee braced frames as weigh against concentric braced frames was investigated. These investigations were based on stiffness and ductility. Single - bay reinforced concrete frames in two levels which are a 1- story and a 10- story with three modes which are reinforced concrete frame without brace and reinforced concrete frame with concentric brace system and reinforced concrete frame with knee brace system were considered. Displacement analysis were performed using the Extended 3D Analysis of Building Systems (ETABS) software for investigating stiffness of these system and pushover analysis were performed through Open System for Earthquake Engineering Simulation (OPENSEES) software for investigating ductility of these system. Finally, analysis of cyclic loading was done by using again the OPENSEES software for the completion of the investigations. The results of these outputs indicated that concentric bracing can provide a stiffer bracing system but reduces the ductility of the reinforced concrete frame. Knee bracing can be employed to provide the desired ductility level for reinforced concrete frame. It is concluded that both concentric bracing and knee bracing systems may be used to design or to retrofit for a damage-level earthquake. However, when designing or retrofitting for a collapse-level earthquake, knee bracing is a more effective system.***

Index Term – concentric braced frame, ductility, knee braced frame, stiffness

I. INTRODUCTION

Advancement in technology is a tool to predict the reactions of structures against earthquakes. The seismic propensity of knee braced frames (KBF) as weighed against concentric braced frames (CBF) utilizing ETABS software and OPENSEES software has been investigated because of this technology. In conducting these investigations, the frames' stiffness and ductility was studied. Single-bay reinforced concrete frames in two levels 1-story and 10-story with three modes which are: a reinforced concrete frame without brace; reinforced concrete frame with concentric brace system; and a reinforced concrete frame with knee brace system were considered. Displacement analysis was performed through ETABS software for investigating the stiffness of these systems and pushover analysis was performed also through OPENSEES software for investigating ductility of these systems. Finally, analysis of cyclic loading was done by OPENSEES software for the completion of the investigations.

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II. METHODOLOGY

For nearly 30 years, ETABS has been recognized as the industry standard for building analysis and design software. Today, continuing in the same tradition, ETABS has evolved into a completely integrated building analysis and design environment. The system built around a physical object based on graphical user interface, powered by targeted new special purpose algorithms for analysis and design, with interfaces for drafting and manufacturing, is redefining standards of integration, productivity and technical innovation.

ETABS offers the widest assortment of analysis and design tools available for the structural engineer working on building structures. The following list represents just a portion of the types of systems and analyses that ETABS can handle easily:

- Multi-story commercial, government and health care facilities
- Parking garages with circular and linear ramps
- Staggered truss buildings
- Buildings with steel, concrete, composite or joist floor framing
- Buildings based on multiple rectangular and/or cylindrical grid systems
- Flat and waffle slab concrete buildings
- Buildings subjected to any number of vertical and lateral load cases and combinations, including automated wind and seismic loads
- Multiple response spectrum load cases, with built-in input curves
- Automated transfer of vertical loads on floors to beams and walls
- P-Delta analysis with static or dynamic analysis
- Explicit panel-zone deformations
- Construction sequence loading analysis

- Multiple linear and nonlinear time history load cases in any direction
- Foundation/support settlement
- Large displacement analyses
- Non buildings with base isolators and dampers
- Floor modelling with rigid or semi-rigid diaphragms
- Automated vertical live load reductions linear static pushover.

The program can automatically generate lateral wind and seismic load patterns to meet the requirements of various building codes. Three dimensional mode shapes and frequencies, modal participation factors, direction factors and participating mass percentages are evaluated using eigenvector or ritz-vector analysis. P-Delta effects may be included with static or dynamic analysis.

A model developed using this program is different from models produced in many other structural analysis programs for two main reasons:

This program is optimized for modelling building systems. Thus, the modelling procedures and design capabilities are all tailored to buildings.

This program's model is object-based. It consists of point, line and area objects. One make assignments to those objects to define structural members such as beams, columns, braces, floors, walls, ramps and springs. One can also make assignments to those same objects to define loads.

For the program's model of frames, assumptions of the study were the following:

Single-bay reinforced concrete frames in two levels 1-story and 10-story with three models which are: a reinforced concrete frame without brace; a reinforced concrete frame with concentric brace system; and a reinforced concrete frame with knee brace system were considered. One of the most powerful features that ETABS offers is the recognition of story levels, allowing for the input of building data in a logical and convenient manner. Users may define their models on a floor-by-floor, story-by-story basis, analogous to the way a designer works when laying out building drawings. Story levels help identify, locate and view specific areas and objects of the model; column and beam objects are easily located using their plan location and story level labels. The dimensions of stories were 3m in height, 4m in width. The models of the concrete frame are shown in figure1.

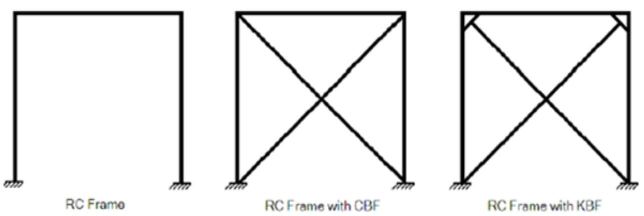

Figure1 Concrete Frames in 3 Different Modes

Knee Braced Frame

The best form of knee brace is when the knee element and the diagonal brace are parallel to the frame diameter in a way that according to the Figure 2, h/H= b/B. In this way the structure has its maximum seismic resistance.

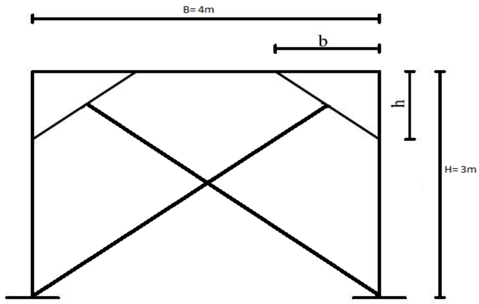

Figure 2 Situation of the Knee Element in Knee Bracing

Therefore the situations of the knee element and diagonal brace of frames have been verified here. In this research spaces h and b are supposed as follows: if we consider h/H= 0.2 , then we will have:

h/H= 0.2 => h= 0.6m

b/B= 0.2 => b= 0.8m

Frames sections and properties of materials are shown in below.

Table 1 Frame sections of 1-storey

Members	**Sections**
Column	**30cm x 30cm**
Beam	**30cm x 30cm**
Diagonal members	**UNP 120**
Knee members in KBF	**Box 120 x 10**

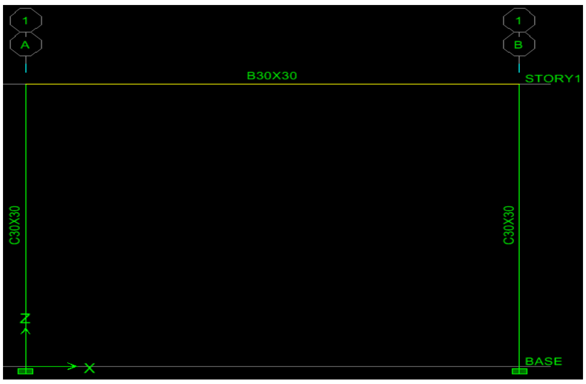

Figure 3 Frame sections of 1-storey

Table 2 Frame sections of 10-storey

Members	Storey1	Storey2	Storey3	Storey4	Storey5	Storey6	Storey7	Storey8	Storey9	Storey10
Column	50x50cm	50x50cm	45x45cm	45x45cm	40x40cm	40x40cm	35x35cm	35x35cm	30x30cm	**30x30cm**
Beam	50x50cm	50x50cm	45x45cm	45x45cm	40x40cm	40x40cm	35x35cm	35x35cm	30x30cm	**30x30cm**
Diagonal members	UNP 120	UNP 120	UNP 120	UNP 120	UNP 120	UNP 120	UNP 120	UNP 120	UNP 120	**UNP 120**
Knee members in KBF	Box 120x10	Box 120x10	Box 120x10	Box 120x10	Box 120x10	Box 120x10	Box 120x10	Box 120x10	Box 120x10	**Box 120x10**

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Figure 4 Frame sections of 10-storey

I. PROPERTIES OF MATERIALS

A. CONCRETE PROPERTIES ACCORDING TO IRANIAN 2800 STANDARD:

Fy= 40000 ton/m^2
Fys= 30000 ton/m^2
F'c =2100 ton/m^2
E= 15100$\sqrt{F'}$C

Concrete Cover = 0.05 m

B. STEEL PROPERTIES ACCORDING TO IRANIAN 2800 STANDARD:

Fy= 24000 ton/m^2
Fu=37000 ton/m^2
E= 2.03 x 10^6

where:

Fy= Yield strength
Fys= Shear Yield Stress
F'c= Compressive Strength of Concrete
E= Modulus of Elasticity
Fu= Tensile Strength

Properties are “assigned” to each object to define the structural behaviour of that object in the model. Some properties, such as materials and section properties are named entities that must be specified before assigning them to objects. Static loads represent actions upon the structure, such as force, pressure, support displacement, thermal effects, and others. Define as many named static load cases as needed. Typically, separate load case definitions would be used for dead load, live load, static earthquake load, wind load, snow load, thermal load, and so on. Loads that need to vary independently, for design purposes or because of how they are applied to the building, should be defined as separate load cases. After defining a static load case name, one must assign specific load values to the objects as part of the load case, or define an automated lateral load if the case is for quake or wind. The load values assigned to an object specify the type of load (e.g., force, displacement, and temperature), its magnitude, and direction (if applicable). Different loads can be assigned to different objects as part of a single load case, along with the automated lateral load, if so desired. Each object can be subjected to multiple load cases. The lateral loads can be in the form of wind or seismic loads. The loads are automatically calculated from the dimensions and properties of the frames. The seismic loads are calculated from the story mass distribution over the structure using code-dependent coefficients and fundamental periods of vibration.The proponent assumed that the frames were designed for gravity loads including live load and dead load.

I. LOADING of FRAMES:

A. DEAD LOAD AND LIVE LOAD ACCORDING TO IRANIAN 2800 STANDARD:

DEAD LOAD = 700 KG/M
LIVE LOAD = 200 KG/M
W = DL+ 0.2 LL (1)

B. SEISMIC LOADS ACCOEDING TO IRANIAN 2800 STANDARD:

$$V= C.\,W \quad (2)$$

$$C = \frac{A.B.I}{R} \quad (3)$$

$$T= \%5\, H^{\frac{3}{4}} \quad (4)$$

$$B= 1+S\left(\frac{T}{T_0}\right) \qquad 0 \le T \le T_0 \quad (5)$$

$$B= S+1 \qquad T_0 \le T \le T_s \quad (6)$$

$$F = \frac{W.Hi}{\sum_{j-1}^{i} W.Hj}.1 \quad (7)$$

Where:

V = Base shear
C = Seismic coefficient
A = Design base acceleration ratio (for very high seismic zone= 0.3).
B = Response factor of building (is depending on the basic period T).
I = The importance factor of building (is depending on the building performance considered 1.0).
W = The equivalent weight of the structure
R = Response modification factor (considered 7.0).
T = Period of vibration
F = Seismic force at level of storey
H = Height of storey from base
S = Soil factor (considered 1.75).

T_0 and T_s = Spectrum characteristic periods (considered T_0= 0.15 , T_s= 1.0).

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Table 3 Parameters used in calculation of seismic coefficient

A	I	R	S	T_0	T_s
0.3	1.0	7.0	1.75	0.15	1.0

Table 4 seismic coefficients (C) of frames

frames	T	B	C
1-Story frames	0.11	2.28	0.098
10-Story frames	0.64	2.75	0.1

Because of the minor difference between seismic coefficients of 1- story frames and 10- story frames, C= 0.098 was considered for both levels, 1- story frames and 10-story frames.

In its simplest form, developing a model requires three basic steps:

Draw a series of point, line and area objects that represent the building using the various drawing tools available within the graphical interface.

Assign structural properties (sections and materials) and loads to objects using the Assign menu options. Note that the assignment of structural properties may be completed concurrently with the drawing of the object using the Properties of Object box, which appears when Draw commands are used.

Assign meshing parameters to area objects if they are not horizontal membrane slabs or deck/plank sections that the program will automatically mesh into the elements needed for the analysis model.

When the model is complete, the analysis may be run. At that time, the program automatically converts the object-based model into an element based model–this is known as the analysis model–that is used for the analysis. The analysis model consists of joints, frame elements, link element and shell (membrane and plate) elements in contrast to the point, line and area objects in the user defined object-based model. The conversion to the analysis model is internal to the program and is essentially transparent to the user.

Utilizing the said software written above, the stiffness of the models was gathered. Comparison of their stiffness was done. ETABS software also performed a displacement procedure for linear analysis. Finally, the outputs of these analyses indicated the displacement of frames and the results of these analyses were shown in graphs based on the outputs of analyses. With reference to equation 8 (the displacement analysis), the stiffness of frames was computed as the ratio of overall lateral force to the overall displacement.

$$K= \frac{F}{\Delta_{max}} \qquad F = V \quad \Rightarrow \quad K= \frac{V}{\Delta_{max}} \tag{8}$$

Where:

K = Stiffness of frame
F = Overall lateral force
Δ_{max} = Maximum displacement
V = Base shear

OPENSEES (Open System for Earthquake Engineering Simulation) is a community-developed software framework for earthquake engineering applications in structural and geotechnical engineering. OPENSEES is intended to facilitate improvements in state-of-the-art computational simulation within the earthquake engineering community, and this powerful software framework has seen great improvements in its capabilities over the last few years. Because OPENSEES is an open-source software development effort, researchers and practitioners of earthquake engineering can readily add new features to this powerful software tool. OPENSEES includes a wide variety of linear and nonlinear elements for both frame and continuum analysis, and material models appropriate for earthquake engineering applications.

For the comparison of ductility in these frames, Open System for Earthquake Engineering Simulation (OPENSEES) software was performed. Specifically, the pushover analysis was executed for nonlinear analysis. For these analyses, modeling of frames was performed based on details and sections of the frames and also the properties of the materials to be used which were all indicated earlier. Then, pushover analyses were defined so that in these analyses a monotonically increasing pattern of lateral forces was being applied in frames until roof displacement reaches a certain level of deformation or the frames become unstable. Eventually, pushover analyses were run to the frames. The outputs of these analyses contained displacements and base shears of frames. The results of these analyses were shown based on the outputs of the study as indicated in Appendix A. The parameters and the equations to be used in solving the ductility were shown below.

$$\mu = \frac{\Delta_{max}}{\Delta_y} \tag{9}$$

Where:

μ = Ductility of frame
Δ_{max}= Pushover displacement capacity
Δ_y = Displacement pertaining to the yield point on the idealised elastic–perfectly plastic response curve
V_y = Yield strength level

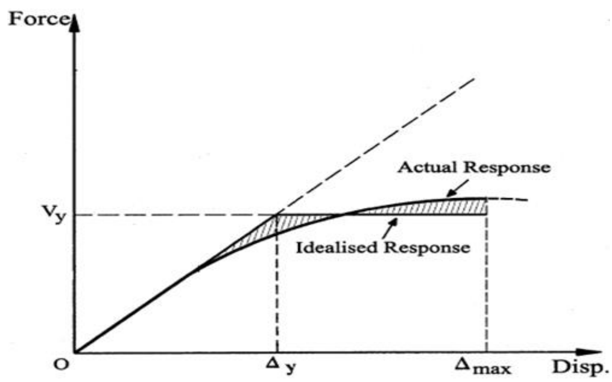

Figure 5 Parameters used in calculation of ductility

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Using again the OPENSEES program, analyses of cyclic loading were also performed in these frames. This is to complete the investigation written in the scope of this study. Applying the same schematic procedure to the program (defined the model and applied the properties of the materials) and including the range for displacement, the cyclic loading process was run for the frames. Afterwards, the frames in this range were displaced under cyclic loading and base shear was recorded in each phase as outputs of the analyses. The results of these analyses were shown based on the outputs of the study as indicated in Appendix B. The Energy absorption capability of frames is an important output of the process. Through this property, the frames will be affected by cyclic loading indicating the seismic performance of the frames. Thus, hysteresis loops that were obtained from the analyses of cyclic loading represent the amount of absorbed energy due to plastic deformation. The parameters and the equations to be used in solving the energy absorption are shown below.

$$E = F_{max} \cdot \Delta_{max} \quad F_{max} = V_{max} \quad \Rightarrow \quad E = V_{max} \cdot \Delta_{max} \tag{10}$$

Where:

E = Energy absorption of frame

F_{max} = Maximum lateral force

Δ_{max} = Maximum displacement

V_{max} = Maximum base shear

STATISTICAL METHOD

Statistics are mathematical computations used to analyze data. Tools of statistical analysis can describe, summarize and compare data. There are various tools that can analyze statistical data. These range from relatively simple computations to advanced analysis.

For this study, the t-test was used to compare the significance of the difference between the means of two independent frames. This statistic tool is simple, straight forward and easy to use. This can be performed through the use of Microsoft Excel. The following were the formulas used for the t-test.

The variance (or the standard deviation) is a measure of the dispersion or scatter of the values of the random variable about the mean μ. If the values tend to be concentrated at the mean, the variance is small; while if the values tend to be distributed far the mean, the variance is large.

S = standard deviation

$$S = \sqrt{\frac{\sum (x - \bar{x})^2}{n - 1}} \tag{11}$$

x = single observation

$\bar{x}$ = arithmetic mean of the set of observation

$$X_{mean} = \frac{\sum x}{n} \tag{12}$$

n = number of sample

The viability and difference of their displacement will be tested at 0.05 level of significance, and subjected for comparison using t-test, two-tailed right, for independent small sampled inferences concerning differences of the means with the formula presented as:

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \bullet \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{13}$$

Where:

$\bar{x}_1$ and $\bar{x}_2$ are the respective means of the samples

$\bar{s}_1$ and $\bar{s}_2$ are the respective standard deviation of the samples

$\bar{n}_1$ and $\bar{n}_2$ are the respective number of sample

RESULTS AND DISCUSSION

Displacement analysis was performed using the ETABS software. The weight (W), base shear (V), and the maximum displacement (Δ_{max}) for a 1-storey frame were obtained from the output as shown in Table 5. For each parameter, the maximum values were recorded.

Table 5 Weight (W), base shear (V), maximum displacement (Δ_{max}) of 1-story frames

1-Story Frames	$W_{(kg)}$	$V_{(kg)}$	Δ_{max} (mm)
Without braced frame	4467.5	437.8	0.4799
Concentric braced frame	4534.3	444.3	0.0472
Knee braced frame	4587.8	449.6	0.0802

Employing the data acquired from the diplacement analysis, the stiffness can now be computed using Equation 8. A summary of the result for the stiffness of a 1-storey frame with the specified type of bracing is presented in Table 6. The difference percentage between the maximum displacement of Concentric Braced Frame (CBF) and Without Braced Frame (WBF) is 90.54%. It signified that there is a distinct difference between the two types of frames. The displacement is inversely proportional to stiffness and relating it to the frames, CBF has greater stiffness compared to WBF by 90.31%. Comparing CBF and Knee Braced Frame (KBF), the percentage difference of their displacement is 41.15%. The stiffness of CBF is 40.45% higher compared to the stiffness of KBF.

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And comparing the percentage difference in displacement between the WBF and KBF, the computed value is 83.29%. With regards to their stiffness, KBF stiffness is higher by 83.73% compared to WBF. Correlating the difference percentages of their stiffness as computed above, there is a significant disparity in the stiffness between WBF and CBF and also between WBF and KBF. Considering the comparison made between CBF and KBF, it was shown that CBF is stiffer than KBF.

Table 6 Stiffness of 1-story frames

1-Story Frames	K (kg/mm)
Without Braced frame	912.31
Concentric braced frame	9414.61
Knee braced frame	5606.10

A summary of the seismic force for each storey is presented in Table 7. Specifically, this table is for the frame without brace. It is also the output of the displacement analysis. It will be used for the computation of the base shear (V). While for Table 8, this is for the concentric braced frame and Table 9 is for the knee braced frame.

Table 7 Seismic force at level of stories (F) with (without braced frame)

Storey	Storey1	Storey2	Storey3	Storey4	Storey5	Storey6	Storey7	Storey8	Storey9	Storey10
$F_{(kg)}$	177.56	340.91	466.67	596.78	678.53	780.56	826.35	905.48	923.65	891.56

Table 8 Seismic force at level of stories (F) with (concentric braced frame)

Storey	Storey1	Storey2	Storey3	Storey4	Storey5	Storey6	Storey7	Storey8	Storey9	Storey10
$F_{(kg)}$	179.99	345.79	474.05	606.65	690.95	795.51	843.91	925.61	946.41	903.71

Table 9 Seismic force at level of stories (F) with (knee braced frame)

Storey	Storey1	Storey2	Storey3	Storey4	Storey5	Storey6	Storey7	Storey8	Storey9	Storey10
$F_{(kg)}$	180.95	347.71	476.97	610.57	695.92	801.50	850.98	933.72	955.62	913.52

In view of the Table 7, Table 8, and Table 9 as presented above, the seismic force at storey 1 to storey 10 for each type of frame was increasing. Relating this to stiffness property, it can be observed that it is in a decreasing manner.

The same software was used for the displacement analysis for a 10-storey frame. As presented in Table 10, maximum values were obtained for each parameter. There were three types of frames considered as stated in the methodology.

Table 10 Weight (W), base shear (V), maximum displacement (Δ_{max}) of 10-story frames

10-Story Frames	$W_{(kg)}$	$V_{(kg)}$	Δ_{max} (mm)
Without Braced frame	67225.0	6588.05	36.5983
Concentric braced frame	68495.76	6712.58	12.5242
Knee braced frame	69055.91	6767.48	14.4251

Utilizing the values presented in the output, the stiffness for each type of frame can now be computed. Using Equation 8, a summary of the output is presented in Table 11. The difference percentage between the maximum displacement of Concentric Braced Frame (CBF) and Without Braced Frame (WBF) is 65.78%. It explained that there is a distinct difference between the two types of frames. CBF has greater stiffness compared to WBF by 66.42%. Comparing CBF and Knee Braced Frame (KBF), the percentage difference of their displacement is 13.18%. The stiffness of CBF is 12.47% higher compared to the stiffness of KBF. And comparing the percentage difference in displacement between the WBF and KBF, the computed value is 60.59%. With regards to their stiffness, KBF stiffness is higher by 61.63% compared to WBF. Correlating the difference percentages of their stiffness as computed above, there is a significant disparity in the stiffness between WBF and CBF and also between WBF and KBF. Considering the comparison made between CBF and KBF, it was shown that CBF is stiffer than KBF.

Associating the result for the stiffness between a 1-storey and 10-storey frame, there is distinct disparity in the comparison of the percentage difference between two types of frames. It is decreasing as the level storey of the frame increases with no regard to what type of frame is being considered.

Table 11 Stiffness of 10-story frames

10-Story Frames	K (kg/mm)
Without Braced frame	180
Concentric braced frame	535.96
Knee braced frame	469.14

The stiffness of frames was measured in accordance with the outputs that were obtained from the displacement analysis of each of the frames as given in Table 6 and Table 11. The results of stiffness in single-bay reinforced concrete frames in two levels 1-story and 10-story with three modes which are reinforced concrete frame without brace,

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reinforced concrete frame with concentric brace system and reinforced concrete frame with knee brace system show that in both levels 1-story frames and 10-story frames, concentric brace frames were at the highest stiffness value and also knee braced frames were stiffer than without braced frames. Pushover analysis was performed using OPENSEES software. As presented in Table 12, the output for the yield strength (V_y), pushover displacement capacity (Δ_{max}), and the displacement pertaining to the yield point was obtained particularly for the 1– storey frame.

With reference to the graphs found in Appendix A (the static pushover analysis), ductility of frames was computed as the ratio of the pushover displacement capacity to the displacement pertaining to the yield point on the idealised elastic–perfectly plastic response curve.

Table 12 Pushover displacement capacity (Δ_{max}) Displacement pertaining to the yield point (Δ_y) Yield strength level (V_y)

1-Storey Frames	V_y (N)	Δ_y (Cm)	Δ_{max} (Cm)
Without braced frame	50000	2	30.50
Concentric braced frame	1290000	2	8
Knee braced frame	1090000	2	16.50

Applying Equation 9, the ductility of the frame for each type was computed. The difference percentage between the maximum displacement of Concentric Braced Frame (CBF) and Without Braced Frame(WBF) is 73.77%. This explains that there is a distinct difference between the two types of frames. WBF has greater ductility compared to CBF by 73.77%. Comparing CBF and Knee Braced Frame (KBF), the percentage difference of their displacement is 51.51%. The ductility of KBF is 51.51% higher compared to the ductility of CBF. And comparing the percentage difference in displacement between the WBF and KBF, the computed value is 45.90%. In relation to their ductility, WBF has higher ductility by 45.90% compared to KBF. Correlating the difference percentages of their ductility as computed above, there is a significant disparity in the said property among the the three types of frames. WBF has the highest ductility and CBF has the least ductility.

Table 13 Ductility of 1-storey frames

1-Storey Frames	μ
Without braced frame	15.25
Concentric braced frame	4
Knee braced frame	8.25

Applying the same analysis, an output for the a 10–storey frame was acquired as presented in Table 14. Maximum values were presented for each parameter.

Table 14 Pushover displacement capacity (Δ_{max}) Displacement pertaining to the yield point (Δ_y) Yield strength level (V_y)

10-storey frames	V_y (N)	Δ_y (Cm)	Δ_{max} (Cm)
Without braced frame	95000	25	125
Concentric braced frame	245000	20	51
Knee braced frame	230000	20	63

Equation 9 was used to obtain the ductility for the 10–storey frame. The difference percentage between the maximum displacement of Concentric Braced Frame (CBF) and Without Braced Frame (WBF) is 59.20%. It explains that there is a distinct difference between the two types of frames. WBF has greater ductility compared to CBF by 49.00%. Comparing CBF and Knee Braced Frame (KBF), the percentage difference of their displacement is 19.05%. The ductility of KBF is 19.05% higher compared to the ductility of CBF. And comparing the percentage difference in displacement between the WBF and KBF, the computed value is 49.60%. In relation to their ductility, WBF has higher ductility by 37.00% compared to KBF. Correlating the difference percentages of their ductility as computed above, there is a significant disparity in the said property among the the three types of frames. WBF has the highest ductility and CBF has the least ductility.

Table 15 Ductility of 10-storey frames

10-storey frames	μ
Without braced frame	5
Concentric braced frame	2.55
Knee braced frame	3.15

The ductility of single-bay reinforced concrete frames in two levels 1-story and 10-story with three modes which are: a reinforced concrete frame without brace; a reinforced concrete frame with concentric brace system; and a reinforced concrete frame with knee brace system were determined as given in Table 13 and Table 15. These tables indicate that when reinforced concrete frames were braced, in return for the increase in yield strength, the ductility of reinforced concrete frames was reduced. This was particularly true for the concentric-braced frames. The knee braced frames exhibited much larger ductility compared with the concentric braced frames. In these analyses, the ability of concentric braced frames to reduce the global displacement of reinforced concrete frames was well demonstrated but brittle failure occurred at the maximum displacement of these frames.

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In connection with the computed ductility for a 1–storey frame and a 10–storey frame, WBF has the ability to deform under loads since it obtained the maximum value, while CBF is capable of resisting more loads because it has the least value of ductility.
OPENSEES was applied for the cyclic loading analysis. As shown in Table 16, these are the parameters that were obtained from the output.

Table 16 Maximum base shear (V_{max}), Maximum displacement (Δ_{max})

1-Storey Frames	V_{max} (N)	Δ_{max} (Cm)
Without braced frame	55000	19
Concentric braced frame	1000000	1.60
Knee braced frame	900000	2.50

With reference to equation 10 (equations for energy absorption), the total energy absorption of frames was computed as the maximum base shear multiplied by maximum displacement. The result of the process showing the graphs that will be used in Equation 10 can be seen in Appendix B. The computed energy absorption for a 1–storey frame was presented in Table 17.
The difference percentage between the maximum displacement of CBF and WBF is 91.58%. It explains that there is a distinct difference between the two types of frames. CBF has greater energy absorption compared to WBF by 34.69%. Comparing CBF and KBF, the percentage difference of their displacement is 36.00%. The energy absorption of KBF is 28.89% higher compared to CBF. And comparing the percentage difference in displacement between the WBF and KBF, the computed value is 86.84%. In relation to their energy absorption, KBF has higher energy absorption by 53.56% compared to WBF. Correlating the difference percentages of their energy absorption as computed above, there is a significant disparity in the said property among the the three types of frames. KBF has the highest energy absorption and WBF has the least value.

Table 17 Energy absorption of 1-storey frames

1-Storey Frames	E (N.Cm)
Without braced frame	1045000
Concentric braced frame	1600000
Knee braced frame	2250000

Presented in Table 18 are the values obtained from the output of the cyclic loading analysis for a 10–storey frame.

Table 18 Maximum base shear (V_{max}), Maximum displacement (Δ_{max})

10-Storey Frames	V_{max} (N)	Δ_{max} (Cm)
Without braced frame	95000	42
Concentric braced frame	250000	35
Knee braced frame	230000	42

Applying Equation 10, the energy absorption for a 10–storey frame with different types of bracing is presented in Table 19. The difference percentage between the maximum displacement of CBF and WBF is 16.67%. There is a least significance between the two. CBF has greater energy absorption compared to WBF by 54.40%. Comparing CBF and KBF, the percentage difference is the same as of the previous one, only that the energy absorption of KBF is 9.42% higher compared to CBF. There is no difference in the displacement between the WBF and KBF. But in view of their maximum shear, there is a 58.69% percentage difference. In relation to their energy absorption, KBF has higher energy absorption by 58.70% compared to WBF. Correlating the difference percentages of their energy absorption as computed above, there is a significant disparity in the said property among the the three types of frames. KBF has the highest energy absorption and WBF has the least value.

Table 19 Energy absorption of 10-storey frames

10-Storey Frames	E (N.Cm)
Without braced frame	3990000
Concentric braced frame	8750000
Knee braced frame	9660000

Energy absorption of single-bay reinforced concrete frames in two levels 1- story and 10-story with three modes which are: a reinforced concrete frame without brace; a reinforced concrete frame with concentric brace system; and a reinforced concrete frame with knee brace system were determined as given in Table 17 and Table 19.
Cyclic loading analysis of knee braced frames have been presented stable hysteresis loops, indicating that it has the most suitable energy absorption compared with the cyclic loading analysis of concentric braced frames that have been presented through narrow hysteresis loops and this time indicating small energy absorption. It is evident that hysteresis loops of without braced frames which obtained from the analysis of cyclic loading were at the least amount of lateral forces so that the absorbed energy of frames was very small.

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Using Equations 11 and 12, the mean and standard deviation of the displacement from 1-storey to 10-storey frames with different types of bracing were computed and are presented in Table 20.

Table 20 Mean and standard deviation of the displacement from 1-storey to 10-storey frame used for displacement analysis.

	CONCENTRIC BRACED FRAME	KNEE BRACED FRAME	WITHOUT BRACED FRAME
STOREY 1	0.577	0.7264	1.3564
STOREY 2	1.4643	1.8412	3.5957
STOREY 3	2.5741	3.2173	6.6362
STOREY 4	3.8337	4.7354	10.0259
STOREY 5	5.2319	6.4025	14.1928
STOREY 6	6.6986	8.1064	18.5286
STOREY 7	8.2081	9.8308	23.541
STOREY 8	9.7047	11.4856	28.3013
STOREY 9	11.1546	13.0338	33.0756
STOREY 10	12.5242	14.4251	36.5983
	61.9712	73.8045	175.8518
Mean Displacement	6.19712	7.38045	17.58518
standard deviation	4.147773179	4.775110243	12.47334436

Using Equation 13, the t_{actual} was computed and was compared to $t_{crtical.}$ A summary of the comparison is presented at Table 21 for the 1–storey frame and Table 22 for the 10– storey frame.

T-Test for the Significance of the difference between the means of two independent samples

Table 21 T–test for the displacement between concentric braced frame (CBF) and knee braced frame (KBF)

Comparison of the Displacement between Concentric Braced Frame (CBF) and Knee Braced Frame (KBF)	
critical t	2.10
actual t	0.44
α	0.05

Table 22 T – test for the Displacement between Concentric Braced Frame (CBF) and Without Braced Frame (WBF)

Comparison of the Displacement between Concentric Braced Frame (CBF) and Without Braced Frame (KBF)	
critical t	2.10
actual t	1.98
α	0.05

Table 23 T – test for the Displacement between Knee Braced Frame (KBF) and Without Braced Frame (WBF)

Comparison of the Displacement between Knee Braced Frame (KBF) and Without Braced Frame	
critical t	2.10
actual t	2.42
α	0.05

Based on Tables 21and 22, the result showed that there is no significant difference in the displacement between the Concentric Braced Frame and the Knee Braced Frame. Associating it with their stiffness, the same thing will be applied. While from Table 23, the results show that there is a significant difference in the displacement between Knee Braced Frame and Without Braced Frame. It means that there will be a significance difference also when it comes to their stiffness.

The presented result above for the stiffness property implies that the displacement for each type of frame is distinct and considerably different.

A bar graph is presented below to show the comparison of the stiffness, ductility and energy absorption of the 1–story level and 10–story level frames.

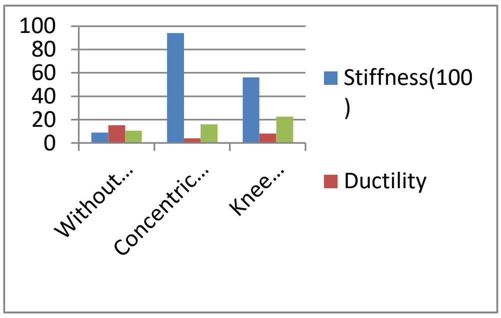

Figure 6 Comparison of the Computed Properties for a 1-storey Frame

From the bar graph presented in Figure 6 (for the 1–storey frame) and Figure 7 (for the10–storey frame), ductility is highest for a frame without brace. As stipulated in the computations above, the ductility of WBF is 49.00% higher compared to CBF and 37.00% higher compared to KBF. CBF has the least value for ductility.

While in Concentric Braced Frame and Knee Braced Frame, stiffness is highest among other properties. The comparison of their percentage differences is presented above. Stiffness is higher in Concentric Braced Frame compare to Knee Braced Frame. Ductility is higher in Knee Braced Frame compared to Concentric Braced Frame.

Correlating the result for the stiffness between a 1–storey and 10–storey frame, there is distinct disparity in the comparison of the percentage difference between two types of frames. It is decreasing as the level storey of the frame increases with no regard to what type of frame is being considered.

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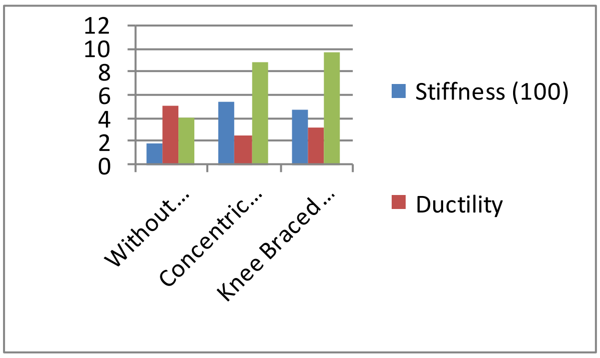

Figure 7 Comparison of the Computed Properties for a 10-storey Frame

II. CONCLUSION

This study was performed because of the very high importance of retrofitting concrete structures by means of bracing systems. It has attempted to investigate the seismic propensity of the knee braced frame as weighed against the concentric braced frame. These investigations were based on stiffness and ductility. Displacement analyses were performed for investigating the stiffness of each of these systems and pushover analysis was performed for investigating the ductility of these frames. Finally, analyses of cyclic loading were performed also for the completion of the investigations. Outcomes of these analyses show the effectiveness of bracing of concrete frames both as an effective shear resisting system at design level and as a retrofitting measure against horizontal earthquake loading. Furthermore, the results of this study lead the conclusions that:

The seismic performances of without braced frames are weak. Accordingly, they are required to be retrofitted with the capabilities provided by systems that have sufficient stiffness and ductility.

Correlating the result for the stiffness between a 1–storey and 10–storey frame, there is distinct disparity in the comparison of the percentage difference between two types of frames. It is decreasing as the level storey of the frame increases with no regards of what type of frame is being considered.

The strength capacity of reinforced concrete frames can be enhanced to a desired level using either concentric bracing or knee bracing. Therefore, the bracing systems can be conservatively designed for the required strength enhancement.

Based from the result obtained for a 1–storey frame and for a 10–storey frame, the ductility is highest for a frame without brace. While in the Concentric Braced Frame and Knee Braced Frame, stiffness is highest among other properties. Stiffness is higher in Concentric Braced Frame compare to the Knee Braced Frame. Ductility is higher in the Knee Braced Frame compared to the Concentric Braced Frame. Energy absorption is highest in the Knee Braced Frame.

Both concentric bracing and knee bracing systems can be employed to increase the yield capacity of a reinforced concrete frame. Substantial increases may be obtained using concentric bracing.

The global displacements of a reinforced concrete frame can be reduced to a desired level by providing either a concentric or a knee steel bracing system. Concentric bracing being the more effective of the two systems in increasing the stiffness of the reinforced concrete frame was also investigated.

Steel bracing reduces the ductility of the reinforced concrete frame. However, knee bracing can be employed to provide a desired ductility level for a reinforced concrete frame.

The knee braced frames as an energy dissipating system combine excellent ductility and stiffness.

Both concentric bracing and knee bracing systems may be utilised to design or retrofit for a damage-level earthquake. However, when designing or retrofitting for a collapse-level earthquake for which ductile behaviour is necessary, the knee bracing system is most suitable.

Concentric bracing is more suitable for a strength-based design. However, the relatively small post-yield capacity and the brittle failure mode of the concentric braced frame make this system unfavourable for a ductile design. Knee bracing, on the other hand, is suitable for both the strength-based and ductility-based designs. A knee-bracing system can therefore be successfully utilised to design for both the damage-level and collapse-level earthquakes for which the damage level may be considered as the yield capacity of the knee elements. This study proves that the overall seismic performance of knee braced frames, regarding stiffness and ductility appears to be more favourable than either the frames without brace or the concentric braced frames.

APPENDIXES

APPENDIX A

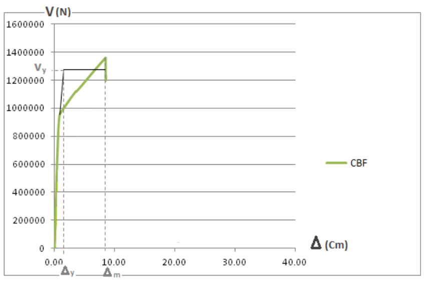

Figure 14 Pushover Curve Of Concentric Braced Frame (1-Story)

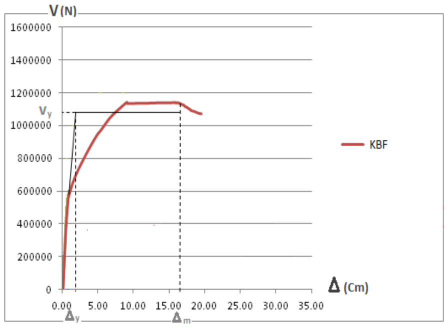

Figure 15 Pushover curve of knee braced frame (1-story)

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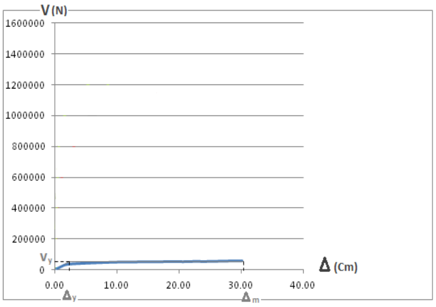

Figure 16 Pushover Curve Of Without Braced Frame (1-Story)

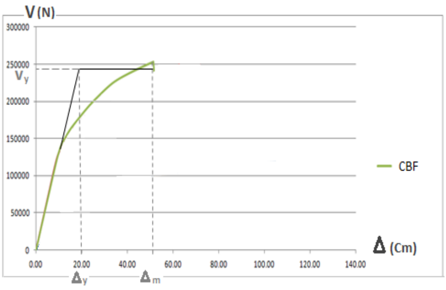

Figure 17 Pushover Curve Of Concentric Braced Frame (10-Story)

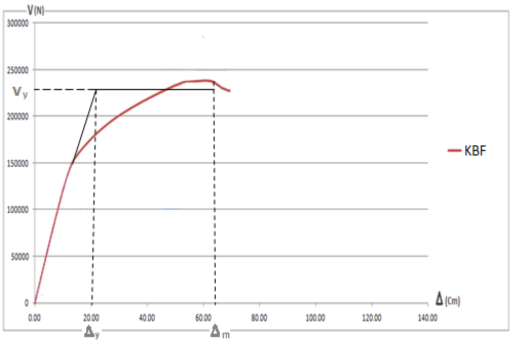

Figure 18 pushover curve of knee braced frame (10-story)

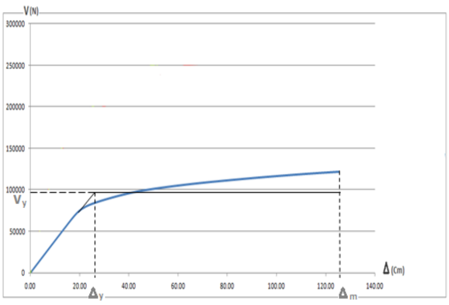

Figure 19 pushover curve of without braced frame (10-story)

APPENDIX B

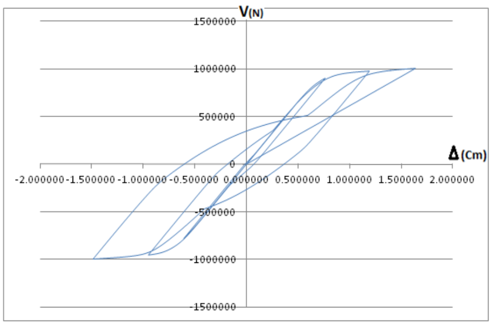

Figure 20 Hysteretic Behavior Of Concentric Braced Frame (1-Storey)

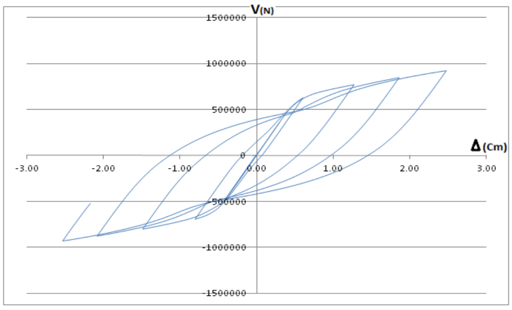

Figure 21 Hysteretic Behavior Of Knee Braced Frame (1-Storey)

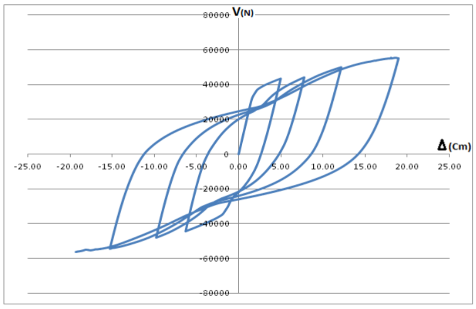

Figure 22 Hysteretic Behavior Of Without Braced Frame (1-Storey)

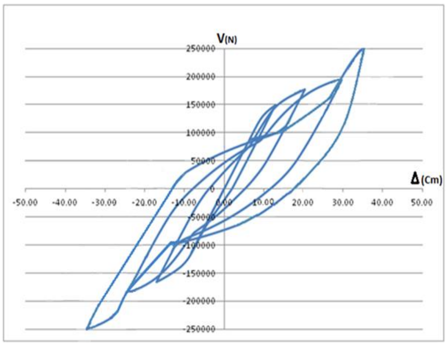

Figure 23 Hysteretic Behavior Of Concentric Braced Frame (10-Storey)

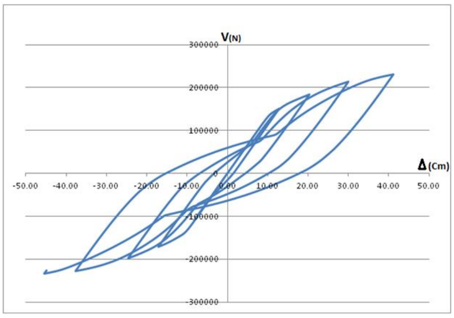

Figure 24 Hysteretic Behavior Of Knee Braced Frame (10-Storey)

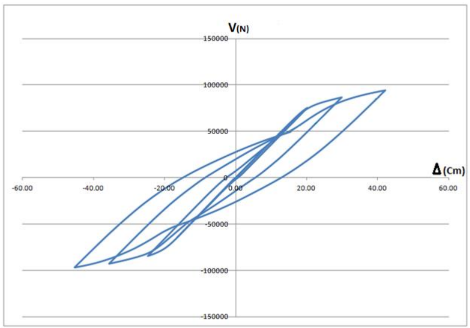

Figure 25 Hysteretic Behavior Of Without Braced Frame (10-Storey)

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