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TO STUDY LATERAL LOADING PERFORMANCE OF STEEL FRAME WITH NOVEL CROOKED BRACING SYSTEM

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Abstract - *This study investigated the Lateral loading performance of various curved braces, specifically the single curved V, single inverted curved V, D-type, double inverted curved X, and double curved X-type braces. A comprehensive nonlinear analysis, along with a dimensional parametric study, was conducted to evaluate the behavior of these curved braces under different conditions. A numerical finite element analysis was performed using ANSYS Workbench FE software. A comparative study between o grid and novel crooked bracings and effective model is identified and time history analysis with PGA data is performed. Conclusive statements on the overall performance comparison, highlighting the single and double curved braces we developed have greater ductility, load carrying capacity, energy absorption than o-grid and other conventional bracings. The result shows double inverted curved X-brace also demonstrated excellent load capacity and ductility, with a maximum load capacity of 139.65 kN and a ductility factor of 40.96, which 9.6 times than O-Grid bracing systems. By performing time history analysis, the result shows that the double inverted curved brace the top story displacement decreases by 16.69% & the acceleration drops by 28.39% compared to O-Grid and time period is reduces. So, the double inverted x-brace performs more effectively than O-Grid systems, showing a notable reduction in both acceleration and displacement.*

Key Words: **Novel Crooked bracing system, Innovative lateral loading system, Steel structures, Push over analysis, Time history analysis, PGA data**

1.INTRODUCTION

In the design of structures, it is necessary to consider lateral loads and Lateral Load Resisting Systems (LLRS). LLRS are indispensable in the design of buildings located in the seismic prone areas. In order to prevent structural collapse, it is important that during severe earthquakes, lateral load resisting systems should have appropriate ductility, stability and resistance.

The 1994 Northridge earthquake exposed unexpected brittle fracture in steel moment resisting frame (MRF) connections, challenging long-held assumptions about their seismic reliability (e.g. [1-2]). The paper reviews the damage sustained by steel buildings during 1995 Hyogo ken -Nanbu earthquake focusing on seismic design., building characteristics, and damage patterns.it highlights failures in welded beam to column connection and classifies the damage prior knowledge and challenging addressing it (e.g. [2-4]).

In high-rise buildings, seismic design often prioritizes stiffness over strength to enhance overall performance during earthquakes. Steel structures typically use moment-resisting frames and braced frames to counteract lateral forces. Moment-resisting frames provide high ductility by allowing controlled yielding in connections, but they often lack the stiffness needed for tall buildings. Concentric braced frames (CBFs), on the other hand, offer substantial stiffness but have limited capacity to deform without failure. Various configurations such as diagonal, X, V, and chevron bracing enhance seismic resistance by effectively tying braces into beam-column junctions.To combine the benefits of both stiffness and ductility, Eccentric Braced Frames (EBFs), developed by Roeder and Popov, incorporate shear links that deform inelastically to dissipate seismic energy. However, repairing these shear links after a major seismic event can be complex and costly. As an alternative, the Knee Braced Frame (KBF) was introduced by Ochoa, featuring a specially designed knee element that yields under stress, thereby absorbing energy more efficiently. This concept was further improved by Balendra and colleagues, who proposed modifying chevron braced systems by using relatively weaker braces paired with stronger beams. This adjustment enhances ductility and allows for a more distributed pattern of damage across the structure.

Following the 1995 Kobe earthquake, Buckling-Restrained Braced Frames (BRBFs) gained popularity in seismic-prone regions. These systems feature a steel core encased to prevent buckling, allowing it to yield in both tension and compression. This configuration offers reliable energy dissipation and stable hysteretic behavior. However, because the yielding core is relatively slender, BRBFs tend to be more flexible and may concentrate damage in specific stories. Moreover, they often experience significant residual deformations after seismic events due to their low post-yield stiffness. (e.g. [5-81]).

1.1 O-grid Bracing System

Many ways studied to improve steel bracing systems, and one effective idea is using circular-shaped elements. Murty [82] tested a circular part in a toggle bracing system and found that it absorbed energy well during loading. Similarly, Bazzaz et al. [83–87] and Andalib et al. [88, 89] studied bracing systems with circular components and found that they offered good ductility and energy dissipation. Inspired by these results, this study takes a new approach by using circular or elliptical shapes in a bracing system known as the O-Grid. Earlier computer simulations showed that O-Grid systems could carry heavy loads, deform without breaking (ductility), and absorb energy effectively during seismic events. The study is ongoing with two types named as OH and OI. And concluded OI enhanced better performance in terms of stiffness and ductility in the study by Maryam Boostani. [82-107]

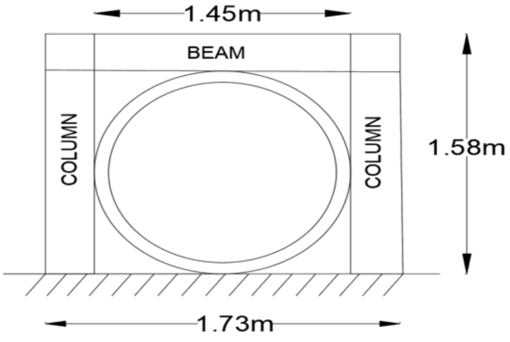


Fig -1: Schematic view of OI specimen

2. Novel-Crooked Bracing systems

The Novel Crooked Bracing system is a newly developed concept aimed at improving the seismic performance of structures through the use of curved bracing elements. The term "novel" reflects its innovative design approach, while "crooked" refers to the intentional curvature of the braces. This system draws inspiration from the O-Grid bracing model, where braces form an O-shaped curve that initially resists forces through bending. As lateral displacement increases, the brace transitions to a combined bending and tension behaviour, which helps delay out-of-plane buckling. This transition enhances energy dissipation and structural ductility during seismic events. In conventional bracing systems, while external forces are effectively resisted, braces are prone to sudden buckling when subjected to large displacements. This sudden failure reduces their energy absorption capacity and can result in concentrated force transfer to other structural members, increasing the risk of collapse. The O-Grid bracing configuration, by contrast, improves performance by being anchored at four critical points: the top of the beam, the base of the column, and both sides of the column. This configuration distributes forces more evenly and prevents localized buckling, making the frame more resilient under seismic loading. The curved shape of the O-Grid brace adds flexibility to the system, allowing it to yield more gradually under increasing lateral loads. Unlike straight braces, which are more rigid and prone to sudden instability, the curved design allows for a more progressive load transfer to the building structure. This results in improved performance in terms of strength, ductility, and energy absorption. These benefits have prompted the development of alternative curved bracing geometries that seek to expand the advantages of the O-Grid concept. This study introduces the Novel Crooked Bracing system as a refined continuation of the curved bracing approach. Five distinct shapes have been designed to explore the effects of curvature on seismic performance. These include the Single Curved V-type, which functions similarly to traditional chevron bracing, and the Single Curved Inverted V-type, analogous to the inverted V configuration. The third type, Single Curved D-type, takes inspiration from K-bracing systems. In addition, two double-curved types have been developed: the X-type and Inverted X-type, which mirror conventional X and inverted X bracing systems but feature curvature for enhanced performance. Each of these five bracing types was created with the intention of maintaining the general form and structural purpose of conventional systems while replacing the straight members with curved ones. The primary objective of this research is to investigate how this curvature affects the structural response under seismic loading. By analysing the behaviour of these curved configurations, the study aims to determine whether the incorporation of curvature can offer improvements in terms of energy dissipation, ductility, and stability compared to conventional bracing methods.

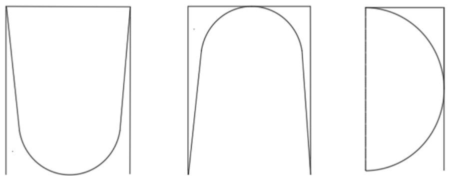


Fig -2(a): U-type, Inverted U-type, D-type Single curved bracing systems

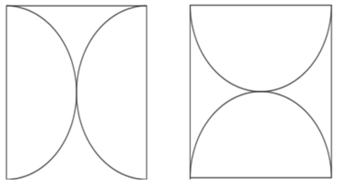


Fig-2(b): Curved inverted X-type, Curved X-type Double curved bracing systems

3. STUDY THE LATERAL LOADING PERFORMANCE OF NOVEL CROOKED BRACING SYSTEMS

Several structural models were created using ANSYS Design Modeler to investigate the effects of geometric variations on performance. A non-linear static analysis was carried out for each model to examine their response under applied loads. The study focused on altering two key parameters: the thickness of the web flange and the depth of the brace. By systematically varying these dimensions, the research aimed to understand how they influence the structure's stiffness and deformation behaviour.

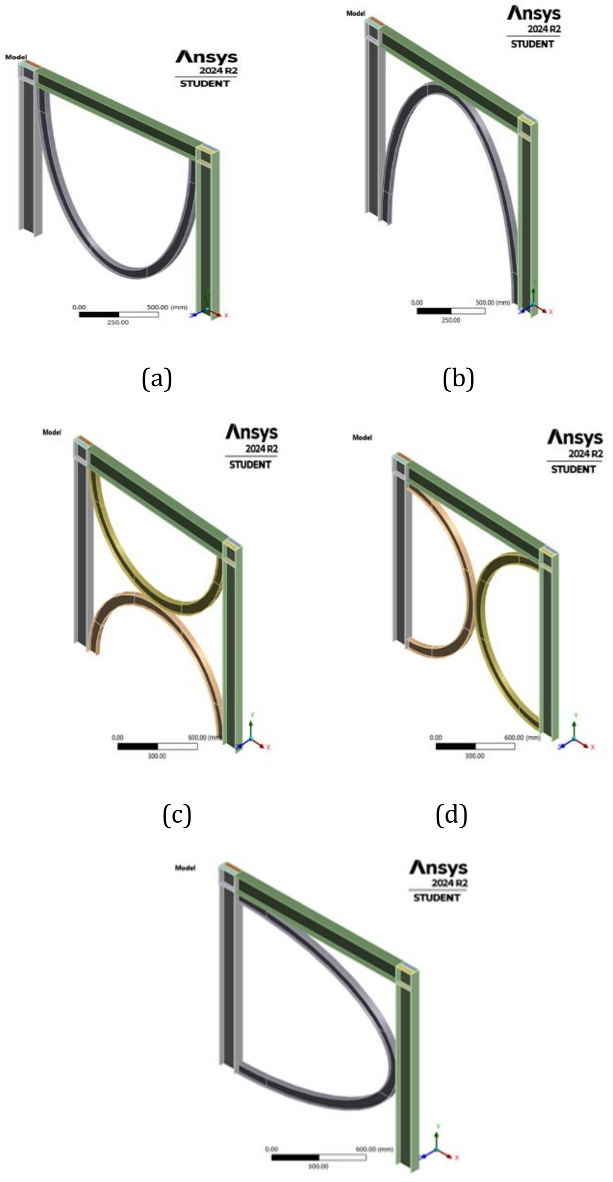
In total, fifteen models were analysed with web flange thicknesses set at 2 mm, 3 mm, and 4 mm, and brace depths at 41 mm, 79 mm, and 155 mm. The resulting load-deflection curves from each configuration were compared to evaluate how different thickness-depth combinations impact structural performance. This comparative approach provided valuable insights into the relationship between design geometry and structural stability, helping to identify more efficient and resilient design options.

3.1 Finite Element Modelling

To analyse the nonlinear behaviour of the structural specimens, finite element models were developed using ANSYS software. The frame dimensions used in the simulation were 1.73 meters in width and 1.58 meters in height. The steel components were modelled using 20-node hexahedral Solid186 elements, which are suitable for capturing complex stress distributions in three-dimensional analyses. A mesh size of 40 mm was chosen to ensure a balance between computational efficiency and accuracy. The material behaviour of steel was defined using a multilinear stress-strain model to represent its inelastic properties accurately. The structural steel used in the model corresponded to Fe345 grade, with its mechanical properties specified as follows: a yield strength of 0.24 kN/mm^2, an ultimate tensile strength of 0.345 kN/mm^2, a Young's modulus of 210 kN/mm^2, a mass density of 7850 kg/m^3, and a Poisson's ratio of 0.3. These values were input into the software to replicate the actual behaviour of the steel under loading conditions. All column bases were assigned fixed boundary conditions to simulate real-world support restraints. Displacement-controlled loading was applied to monitor the deformation patterns and load-response characteristics more precisely, especially under nonlinear regimes. To simplify the model and reduce computational complexity, the structural components and connection plates were merged and treated as rigidly connected. The simulation did not explicitly model welds, based on the assumption that they were sufficiently strong and would not fail during loading. This assumption allowed the analysis to focus on the primary structural elements and their interaction, rather than local connection behaviour.

Table -1: Steel Properties (Fe345)

Yield Strength(f_y)	240 MPa
Tensile Ultimate strength(fu)	345MPa
Modulus of Elasticity(E)	2.1×10^5 MPa
Poisson's ratio	0.3



(a) (b)

(c) (d)

(e)

Fig -3: Geometry-Novel Crooked Bracings

(a)Single curved U-type(b)Single inverted curved U-type(c)Double inverted curved X-type
(d) Double curved X-type(e) D-type

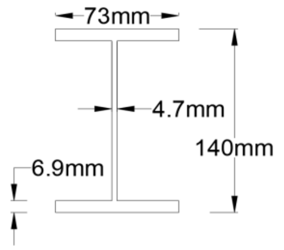


Fig -4: IPE140-Column & Beam section

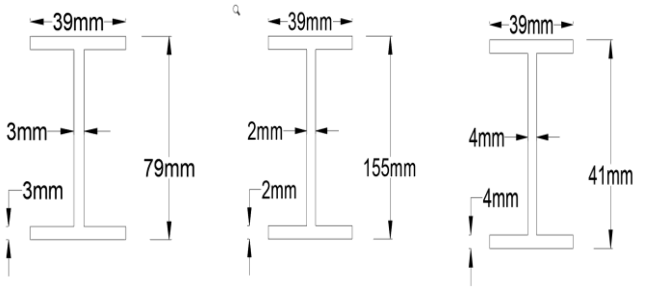


Fig -5: Dimensional Parameters of Novel Crooked bracings used in this study

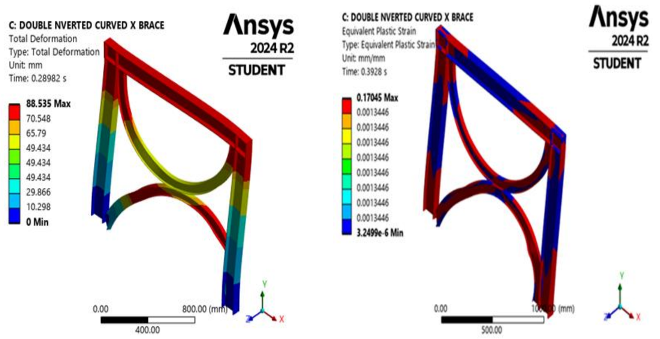


Fig -6: Total deformation & Equivalent plastic strain of double inverted X-brace

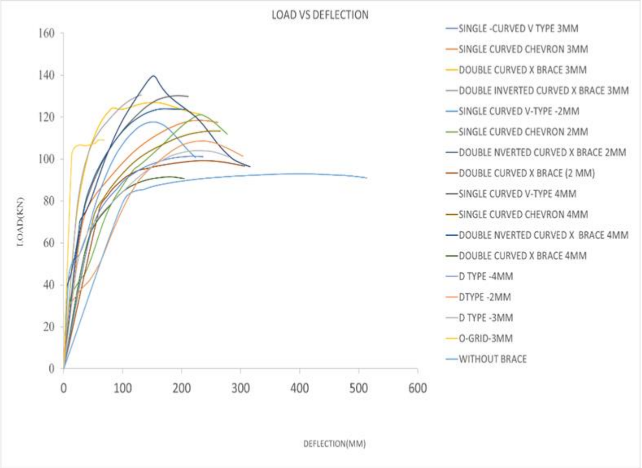


Chart - 1: Load-deflection curves

Among the dimensional parametric study carried out it is found that the double inverted x-brace exhibits highest load carrying capacity therefore higher strength. Fig 4The plastic hinges are formed firstly in the double inverted x-brace at 4 points, and by increasing the displacement, the beam was experienced plastic deformations, and finally, the columns were experienced plastic deformations.

3.2 Stiffness Characteristics

Stiffness refers to the resistance of a structure or structural element to deformation under an applied force or load. It is a measure of how much a material or structure resists bending, stretching, or compression when subjected to external forces. The stiffer a structure is, the less it will deform when a load is applied. The double curved x brace and double inverted x brace of parameter of thickness of web and flange 3mm& depth 79mm exhibits higher lateral stiffness compared to other curved braces. The displacement is higher for single curved U -type, D-type of thickness of web and flange 3mm& depth 79mm and hence lower lateral stiffness.

3.3 Ductility & Energy Absorption Characteristics

The ductility factor in structural engineering refers to the ability of a material or structural element to undergo significant plastic deformation before failure. It is a measure of how much deformation a material can sustain under load without fracturing, which is particularly important for structures subject to dynamic forces, such as earthquakes. A higher ductility factor indicates that the material or structure can undergo more deformation before failure, which is generally desired in earthquake-resistant design, as it allows the structure to absorb and dissipate energy. The ductility factor has been obtained as $\mu = \Delta u/\Delta y$. Where, Δu is maximum displacement of the frame & Δy is the first plastic yielding displacement of the frame. The higher ductility is for double inverted curved x type of thickness of web and flange 2mm & depth 155mm. And ductility is less for d-curved brace of thickness 4mm.

The higher the ductility of a material or structure, the more energy it can absorb without fracturing. The double inverted x brace of thickness of web and flange 2mm &depth 155mm have greatest energy absorption.

3.TO PERFORM THE TIME HISTORY ANALYSIS WITH PGA DATA OF EFFECTIVE CURVED BRACING MODEL IN MULTISTOREY FRAME

Double inverted curved x-brace have high lateral load carrying capacity and exhibits better performance. So Double inverted curved x-type is used to perform the time history analysis with PGA data in multi storeyed frame and compare the results with o-grid. In a multi-storey frame, modal analysis helps identify the natural frequencies and mode shapes of the structure. This analysis reveals how the frame, with the brace system, vibrates at different frequencies under dynamic loading conditions. It impacts the overall stiffness of the structure, influencing the modes of vibration. Time history analysis of the double inverted X brace evaluates the structure's response to time-varying loads, such as earthquakes or wind forces. The time history analysis for the multi-storey frame with a double inverted X brace helps assess the effectiveness of the brace in minimizing displacement, energy absorption, and maintaining stability during dynamic events. The multi storeyed frame is of dimension 30m x 9m having 10 stories. The defined steel Fe345 steel is used for modelling the FE stimulation. The boundary condition is fixed at column bases. the load is given as a Peak Ground Acceleration (PGA) data. A mesh size of 40mm been utilized in the finite element simulation with element type solid 186 and element shape is hexahedron. The geometry of double inverted x-brace & o-grid brace is shown in fig.7a&7b

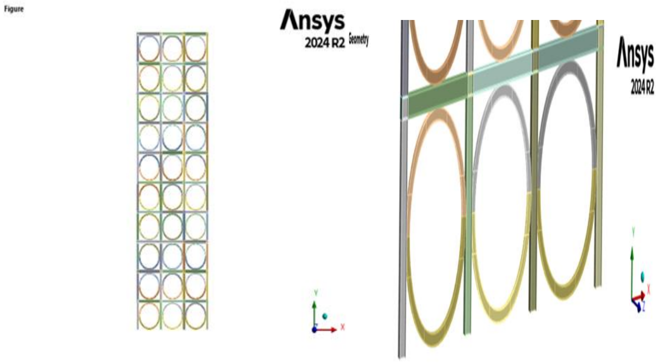


Fig -7(a): O-Grid in Multistoried frame

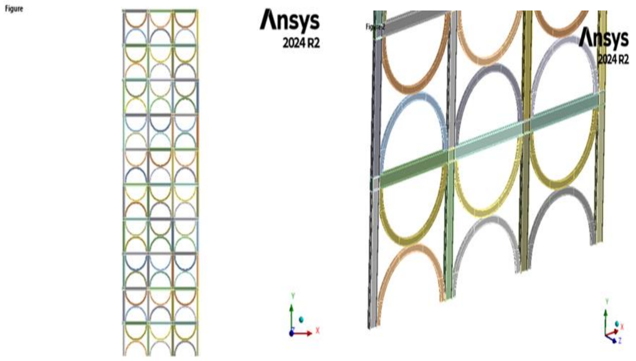
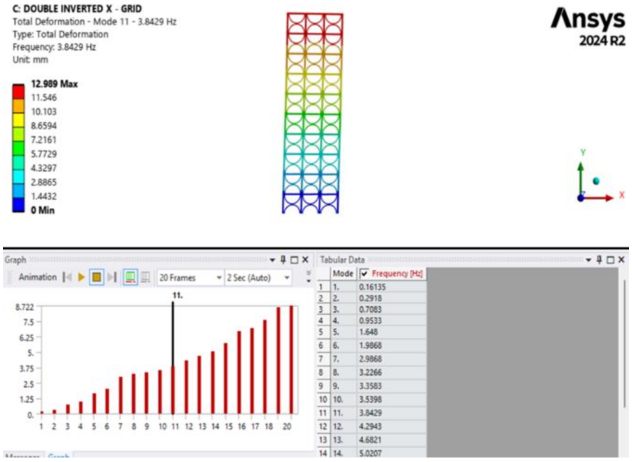
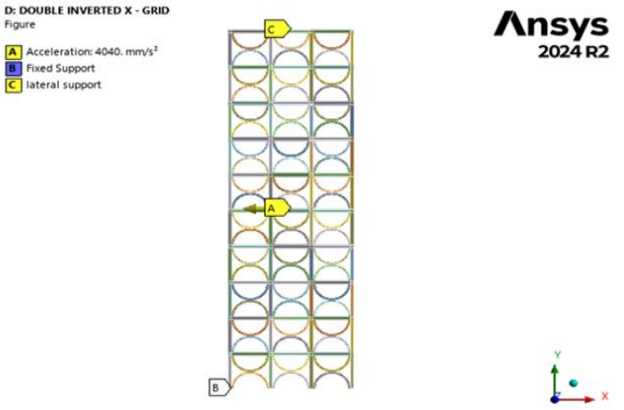


Fig -7(b): Double inverted x-brace in Multistoried frame


C: DOUBLE INVERTED X - GRID
Total Deformation - Mode 11 - 3.8429 Hz
Type: Total Deformation
Frequency: 3.8429 Hz
Unit: mm

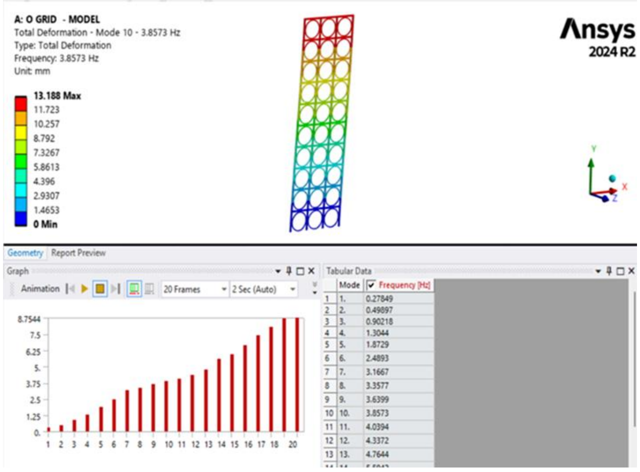
	Mode	☑ Frequency [Hz]
1	1.	0.16135
2	2.	0.2918
3	3.	0.7083
4	4.	0.9533
5	5.	1.648
6	6.	1.9868
7	7.	2.9868
8	8.	3.2266
9	9.	3.3583
10	10.	3.5398
11	11.	3.8429
12	12.	4.2943
13	13.	4.6821
14	14.	5.0207

(a)



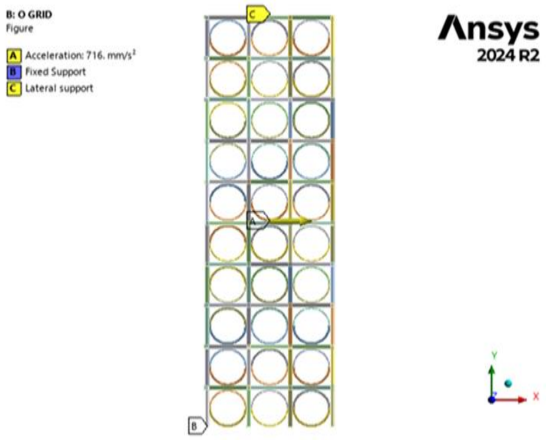
(b)

Fig -8(a): Double inverted X-brace(a) Modal Analysis
(b) Time history Analysis


A: O GRID - MODEL
Total Deformation - Mode 10 - 3.8573 Hz
Type: Total Deformation
Frequency: 3.8573 Hz
Unit: mm

	Mode	☑ Frequency [Hz]
1	1.	0.27849
2	2.	0.49897
3	3.	0.90218
4	4.	1.3044
5	5.	1.8729
6	6.	2.4893
7	7.	3.1667
8	8.	3.3577
9	9.	3.6399
10	10.	3.8573
11	11.	4.0394
12	12.	4.3372
13	13.	4.7644

(a)



(b)

Fig -8(b): O-Grid(a) Modal Analysis
(b) Time history Analysis

Zone 5 is considered the most vulnerable to severe seismic activity, similar to the level of shaking observed during the El Centro earthquake. That is why they are often compared or used as reference data for structural design and earthquake engineering in such regions.

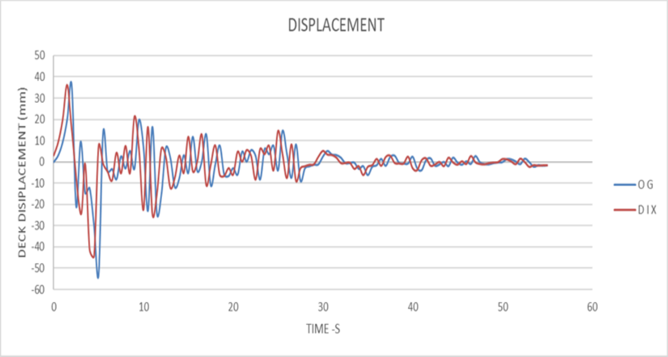


Chart-2: Displacement – Time

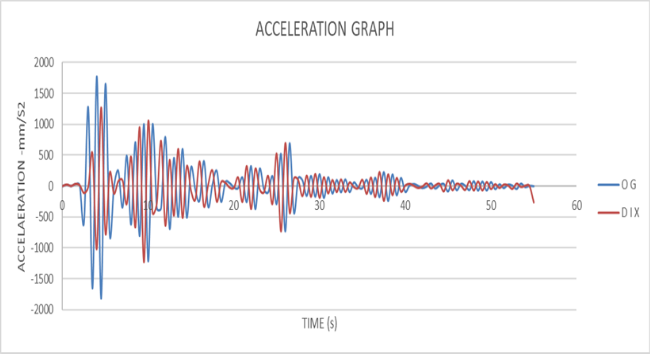


Chart-3: Acceleration – Time

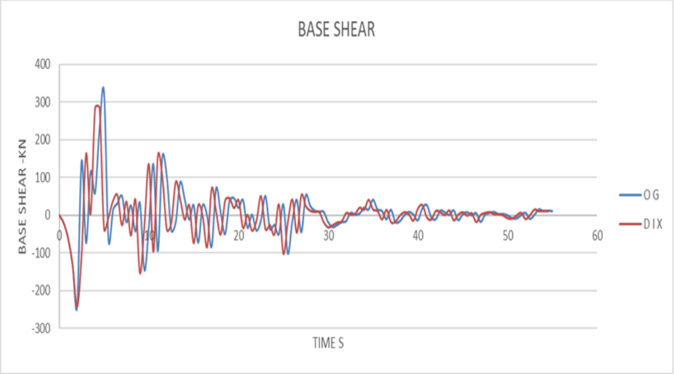


Chart -4: Base shear -Time

Table -2: Time History Analysis result

UNITS	mm	mm/S^2	kN	HZ	S
CASES	DISPLACEMENT	ACCELERATION	BASE SHEAR	FREQUENCY	TIME-PERIOD
OGRID	53.21	1772	325.92	3.85	0.26
DOUBLE INVERTE D X	44.33	1269	283.84	3.84	0.26
%	16.69	28.39			

The Double Inverted Curved X-Brace outperforms the O-Grid in terms of structural performance. Specifically, the double inverted x-brace leads to a reduction in displacement (58.34 mm) compared to the O-Grid, which shows higher displacement. Additionally, the acceleration is 1772 mm/s^2, which is higher than the O-Grid's 1269 mm/s^2, indicating better structural response to dynamic forces. The time period of the double inverted x-brace is also reduced, which suggests a quicker response to seismic or dynamic loads, improving the overall stability of the structure. Furthermore, the top story displacement decreases by 16.69% and acceleration reduces by 28.39% in the double inverted x-brace system, indicating better control of forces and displacements.

4. CONCLUSIONS

This study investigated the seismic behaviour of various curved braces, specifically the single curved V, single inverted curved V, D-type, double inverted curved X, and double curved X-type braces. A comprehensive pushover analysis, along with a dimensional parametric study, was conducted to evaluate the behaviour of these curved braces. To ensure the accuracy and reliability of the results, a numerical finite element analysis was performed using ANSYS Workbench FE software. The study focused on assessing several critical structural aspects, including failure modes, plastic hinge formation, strength, stiffness, energy dissipation capacity, and ductility. The findings revealed that the different curved brace types we developed exhibited varying structural behaviours, with some designs showing better performance in terms of energy dissipation and ductility. Specifically, the failure modes and plastic hinge formations were influenced by the brace design, which directly impacted the overall strength and stability of the structure. The O-Grid brace exhibits higher stiffness compared to the other curved braces, but the curved braces still possess adequate stiffness for their intended purpose. Global buckling was not observed in any of the curved brace systems, and most of the dissipated energy was due to a combination of bending deformation and tension yielding in the bracing members. On the other hand, the double inverted curved X-brace with a 2mm thickness& depth 155mm showed the highest energy absorption and ductility, whereas the double curved X-brace with a 2mm thickness & depth155mm absorbed the least energy. This not indicate a specific bracing have high load carrying capacity, ductility, stiffness and energy absorption but all single and double curved bracings we developed exhibits better performance than the o-grid bracing system. The double inverted curved X-brace also demonstrated excellent load capacity and ductility, with a maximum load capacity of 139.65 kN and a ductility factor of 40.96, which 9.6 times than O-Grid bracing systems. Both of which were highly favourable ductility factors of the specimens indicated that the distance between yielding and ultimate deformation was acceptable, which was expected due to the high number of plastic hinges observed in the braces. Therefore, these curved bracing systems have been shown to meet the demands for stiffness, load-bearing capacity, and energy absorption effectively.

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