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Optimization Of Castellated Beam Configurations for Improved Structural Performance and Weight Reduction

Yashkumar Prakash Shasane[1], Prof. Trupti Narkhede[2]
[1,2]Department of Civil Engineering, Mahatma Gandhi Mission's College of Engineering and Technology, Kamothe, Navi Mumbai-410209

ABSTRACT

The increased use of castellated beams in contemporary steel construction is a result of a higher demand for lightweight, high-performance structural systems, affording greater depth-to-weight ratios and service integration. The current study examines the performance and improvement of castellated beams with regards to the web configurations, thicknesses and positions of stiffeners in an organized manner. A Finite Element Analysis (FEA) was performed with ETABS with results for various load scenarios; capacity, stress distribution, deflection and modes of failure. The simulation was verified by actual beam specimens being tested in the lab for real-world verification. There was also was consideration of the seismic performance analysis with a 22 story structural model with outrigger and belt truss systems integrated with castellated beams to evaluate displacement, drift and shear performance. Through the comparision a analysis of the geometries including web thickness, opening size and angle of cut it was possible to understand the impact on strength, stiffness and stability. It was concluded that modified designs of castellated beams will enhance the load-bearing capacity while using less material towards a more efficient structural capacity and economic benefit. The practice of sustainability in design was also provided by implementing less steel and improving seismic performance in order to find innovative economical construction solutions.

Keywords: Castellated beams, Finite Element Analysis, ETABS, Structural optimization, Stiffeners, Seismic performance

I. INTRODUCTION

In contemporary steel constructions, the move towards lightweight and high-performance structural components has resulted in the popularity of castellated beams [1]. Castellated beams are made by cutting and re-welding standard rolled I-sections in a zigzag or saw-tooth arrangement to create web openings (or, the standard I-section webs are removed, and openings are fabricated by adding channel sections for continuity). Castellated beams provide significant benefits compared to solid-web beams [2]. The most notable benefit of using castellated beams is greater structural depth for no extra weight, the moment of inertia, and section modulus values increase resulting in improved load-carrying capacity. However, the introduction of web openings causes a redistribution of internal stresses and possible stability problems, especially in the erection stage [3]. These challenges require that due consideration be given to the design and use of castellated beams to ensure safety, serviceability, and functional performance. Due to their increased depth and perforated geometry, castellated beams are suitable for multi-storey buildings, and industrial buildings, and for buildings in which services need to be more efficiently integrated, including HVAC, piping, or electrical conduits [4]. Castellated beams allow services to pass through the web of the beam and minimize floor-to-floor height and remove the need for expensive post-occupancy modifications. However, significant issues persist, such as stress concentrations in the vicinity of the openings, a reduction in shear capacity, web post buckling, and lateral-torsional instability. Therefore, optimization of beam configurations is critical to achieve a balance of structural strength and weight efficiency [5].

Traditional design methods are often insufficient in developing an understanding of the interactions and impacts of geometric parameters, material properties, and loading conditions in castellated beams [6]. Furthermore, existing literature usually presents design methods as discrete considerations, e.g., web opening shape or stiffener location, without a comprehensive method for optimization [7]. A cohesive design framework accounting for the implications of opening size, opening spacing, web thickness, and web fabrication angle on strength and stability continues to be absent. This paper aspires to address the aforementioned gaps in the literature by performing a systematic study of castellated beam configurations both experimentally and numerically [8]. The study employs finite element analysis (FEA) using ETABS software, to investigate failure modes, structure behavior, and weight efficiency under different loading conditions. The aim is to develop optimized designs of castellated beams that improve structural performance by minimizing material demand and construction costs [9]. The resulting identification of optimal geometric configurations will lead to advancements in the development of more sustainable and cost-effective structural systems.

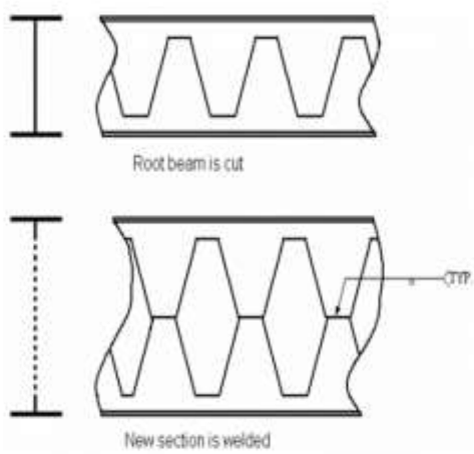

Fig 1. Fabrication Process of a Castellated beam

1.1 Problem Statement

Castellated beams have discrete web openings which makes them an economical structural solution when a reduced weight is required, without losing the load-carrying capacity. The discrete web openings create a one-of-a-kind configuration of geometry that develops complex failure mechanisms, such as web buckling, flexural distortion and local stress concentrations surrounding the voids. To date, research has focused on the unique contribution of an individual characteristic of a Castellated beam configuration, such as the geometry of the web openings, which leads to an incomplete total understanding of the configuration and its full contribution to structural performance. additionally, there exists no consensus on the optimal geometrical configuration, which will enhance mechanical performance and structural weight savings. Without a common design basis, even the use of Castellated beams in practice is limited. However, the impact associated with increased web thickness on the implications for failure reduction and structural performance under variable loading conditions is poorly understood. This research is designed to address the issue of the mechanical performance of Castellated beam configurations by analyzing geometrical properties in order to optimize mechanical performance while minimizing risk of failure and weight economy [10].

1.2 Objectives

1. To Study Structural Behaviour of Castellated Beam under Various Loading.
2. To study the behaviour of castellated beam under the influence of flexure load.
3. To check influence of duct/voids on the structural response of castellated beam.
4. To check effectiveness of increment in thickness of web to improve the performance of castellated beam.
5. To validate results of ETAB with analytical results of castellated beam.
6. To compare normal stress, equivalent stress, shear stress for various size of web thickness.

II. LITERATURE REVIEW

Phattaraphong Ponsorn (2020) examined the efficiency criteria for castellated and cellular beams, noting that the wider design limits and flexibility to make beams of different lengths causes castellated beams tend to have higher efficiency. They concluded that cellular beams need lengths of between thirty to fifty times their radius of gyration to be more efficient than original beams, whereas castellated beams can also be designed efficiently for longer and shorter bay lengths. The authors stressed the influence of the web post width to resist buckling and Vierendeel moments on overall efficiency, while the opening cut angle has little effect on overall efficiency. The authors were able to discuss design recommendations based on AISC and the research provides design recommendations to optimize structural performance and minimize weight in steel beams [11].

Ajim S. Shaikh (2015) assessed the structural behavior of castellated beams that had perforated webs, with the goal of increasing the depth of the section and moment of inertia, without any added weight. The research identified the issue of Vierendeel bending around openings, and the author stated that failure could be avoided by providing plates below the concentrated loads. The research emphasized that castellated beams are structurally efficient and economic; this allows for their use in modern structural applications [12].

A. Kaveh (2018) conducted a study on optimization of semi-rigid jointed composite castellated beams using meta-heuristic algorithms: particle swarm optimization, colliding bodies optimization and enhanced colliding bodies implementation. As optimization factors, the study examined characteristics such as profile section, the cutting depth, cutting angle, spacing between holes, filled end holes and overall connection stiffness. Constraints were implemented in order to ensure practical application, which included structure, moment, shear, deflection and vibration. The efficacy of combining castellated beams with semi-rigid connections for cost and performance optimization was demonstrated the study, by assessing the efficiency of different methods to each other through numerical examples [13].

Mr. Chetan Thakur (2019) directed toward optimizing the stiffeners in castellated beams and address common structural failure issues experienced in the past, with the intention of possibly improving future design. The study pointed out that castellated beams continue to be used more often due to their cost effectiveness, increased strength, and low amount of steel needed. He points out that although we do have past design codes that are based off of empirical formulae, the studies that demonstrate the behavior of castellated beams with stiffeners are not fully understood. He analyzes the performance of the stiffeners and considers their location on the beam, their size, and their thickness; while attemptingto optimize and enhance stability and performance-metric of castellated beams to provide a better approach to design [14].

Noorulhuda K. Hussein (2025) looked into how hexagonal castellated beams behave structurally and how to make them work best with and without vertical stiffener plates using common building materials. The study used theory modelling, finite element analysis, and actual tests to look at how much weight something could hold, how it would bend, and how stress would be distributed under different types of pressure. Additionally, multiple common stiffener plate configurations were evaluated based on their dimensions, spacing, and placement to drive improved performance. The findings demonstrated that vertical stiffener plates substantially improved load capacity and decreased deflection, with experimental to numerical ratios of ultimate loads scaling between 60% to 65%. The research provided beneficial design considerations for architects and engineers, which supported the drive for better structural efficiency and sustainability [15].

Ayat Naji (2025) evaluated the structural performance of castellated steel beams with enlarged webs; specifically, the research considered design parameters (e.g. the number of openings, angle of cut) against load capacity, stiffness, and deflection. The experiment included seven beam specimens; of this, six were castellated beams, and were tested under one-point loading. They saw that cutting down on the number of holes made the beams stronger and better able to hold weight. It also made the beams less likely to bend. The Service Limit Deflection went up by up to 68.9% for castellated beams over RB-S. There were three cutting angles that were looked at: 58°, 52°, and 45°. The 52° angle had the best mix of strength and stiffness. The study showed how important it is to make castellated beams better designed so that they work better in large-span cases [16].

METHODOLOGY

Fig 2. Methodology Flowchart

This research employs a comprehensive and systematic methodology to optimize castellated beam configurations for improved structural performance and weight efficiency. The approach begins with an in-depth **literature review** to identify critical factors influencing the performance of castellated beams, including web thickness, perforation geometry (sinusoidal, hexagonal, circular), fillet radius, and spacing-to-diameter ratio. It is important to understand how things fail, like Vierendeel bending, web post bowing, and lateral-torsional instability.

1. **Finite Element Modelling (FEM)** using ETABS software is employed to simulate castellated beams under various loading conditions—flexural, shear, and combined loads. Multiple beam configurations (ISMB 100, 125, 150) with sinusoidal openings of varying fillet radii (¼, ⅙, ⅛ of opening diameter) are modeled to evaluate stress distribution, deformation, and collapse mechanisms. Parametric analysis is conducted to assess the impact of web thickness, spacing of openings, and stiffener placements.
2. **Design validation** are carried out by using codal provisions which are given in IS 800:2007 for flexural, shear and deflection checks; supplementary checks are conducted using Eurocode and equations based on empirical research for web post buckling and Vierendeel bending check; load combinations are used according to IS 800:2007 and IS 875 for Dead Load (DL), Live Load (LL), Wind Load (WL), Earthquake Load (EL) and serviceability check.
3. **Experimental investigations** This means that nine physical beam specimens are tested under controlled loading conditions to confirm the results of the Finite Element Model (FEM). Deflection, crack initiation, and ultimate load capacities are observed and recorded. Reinforcement methods, such as stiffeners or concrete encasement, may also be used when required in order to aid in enhanced performance.

Finally, a comparison of the various configurations has been undertaken to determine the design that is most efficient in terms of structural integrity and resource economy. At the same time, we also explored an additional data-driven layer of design optimization based on predicting failure loads using Artificial Neural Networks (ANN) technology.

III. RESULTS AND DISCUSSION

A 22-story structure was evaluated for seismic capacity through ETABS analysis on the merits of displacement, drifts, and shear capacity assessment with castellated beams and outrigger-belt trusses. Summary findings show that the structure is stable, loads are efficiently transferred, and the structural response methods all comply with safety criteria. Greater rigidity, enhanced energy dissipation, and probability-based design reduce uncertainties in the seismic design process to a more robust level.

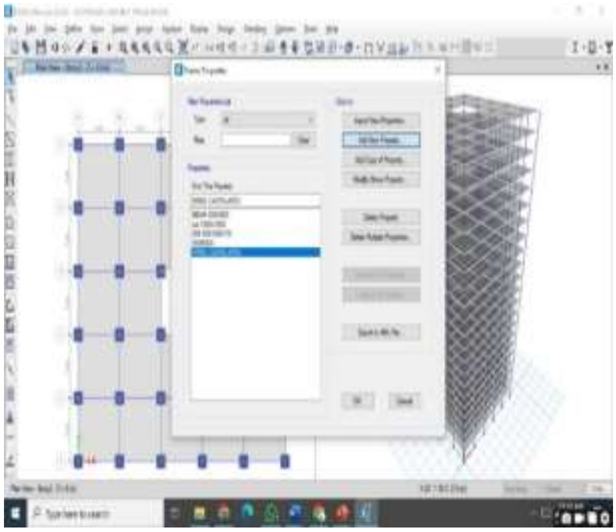

Fig 3. Frame Properties of a Structural Model in ETABS

The screen capture shows the ETABS interface where frame properties for the model are being defined. The properties shown are different steel beam section types, indicating dimensions and material properties as a property type called, STEEL CASTELATED, which is a section type consistent with the design process. The properties are part of defining material and section properties to utilize in the building frame model's analysis, which is important to a structural design context.

Fig 4. Frame Section Property Data and Property/Stiffness Modification Factors in ETABS

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In ETABS, this screenshot shows the dialog for the Frame Section Property Data section, where a user specifies the properties of a steel castellated section by defining the shape, material properties, and hole size. The Property/Stiffness Modification Factors portion allows for the modification of factors affecting the cross-sectional area, shear areas, and moments of inertia, which helps refine the structural analysis model and create better simulations that are more indicative of real-world situations.

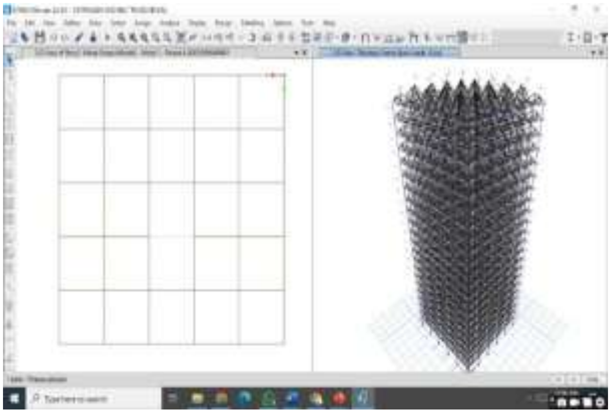

Fig 5. Outrigger and Belt Truss Model in ETABS – Mode Shape Analysis

This image depicts a 3D representation of a high-rise building utilizing an outrigger and belt truss system. The left side of the image shows the shape mode analysis that gives insight into the way this building structure will behave dynamically under its own vibrations. The color shows the range of displacement regardless of the magnitudes on the scale from blue to red. This helps us to understand how the structure is going to respond to potential seismic or wind loads.

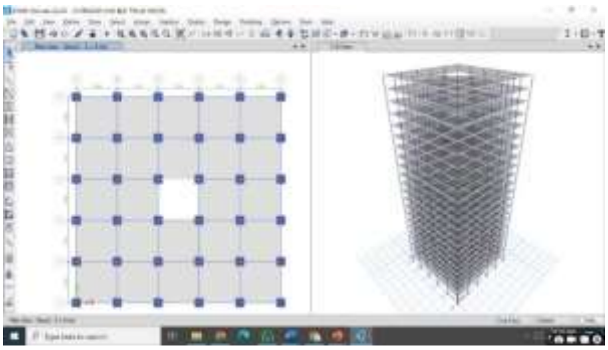

Fig 6. Plan and 3D View of Outrigger and Belt Truss Model in ETABS

The image represents the framework of a structure in ETABS, with a plan view on the left side that shows the floor system, grids and nodes, and a 3D view on the right of the structure. The plan view shows the grid and structural components of the floor systems, such as beams and columns, and the 3D view shows the entire structure of the building, including the floor systems and outriggers and belt trusses for stability and load distribution.

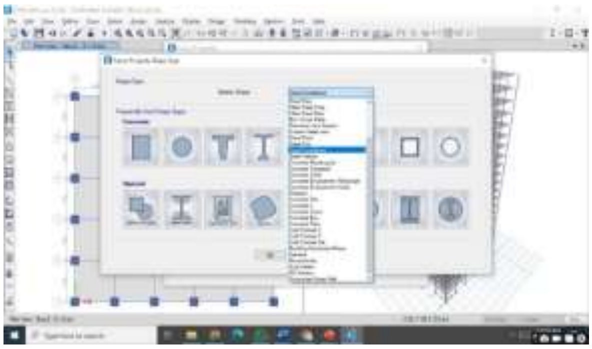

Fig 7. ETABS Frame Property Shape Type Selection

This illustration presents the ETABS interface used to select frame property shape types. This function allows users to specify from multiple section shapes for the frame elements, such as concrete, steel, and specialty shapes as shown. The displayed options allow for assigning varying section shapes, which could be I-beams, pipes, rectangular sections, etc., for use in the structural analysis model. The interface improves the overall flexibility of material and geometry selection when modeling a structure in ETABS.

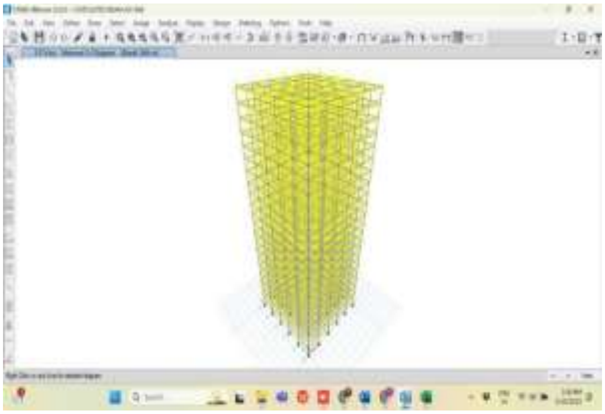

Figure 8. 3D Moment Distribution Diagram (Dead Load)

This diagram illustrates the distribution of moments in a structural model being considered in a three-dimensional view under dead load conditions. The yellow lines signify the moment values, and the thickness of the lines varies with the calculated moment in the beams. This is a common analysis to understand the response of the structure to dead load forces, to help engineers efficiently design the reinforcement or assess the stability of the structure.

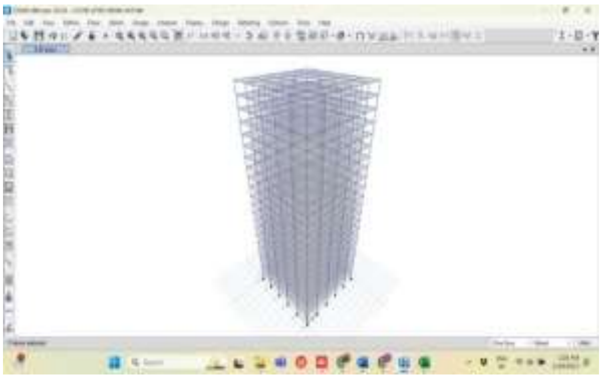

Fig 9. 3D Model of a Structural Frame in ETABS.

This figure depicts the 3D model of a structural frame modeled and analyzed using ETABS software. The grid system shown within the mesh of the building frame indicates the structural members (i.e., beams and columns). This model will help visualize the building construction, geometry, footprint, and framing system for the subsequent analysis of load transfer and overall structural performance. A thoughtful and integrated frame design permits the building, to behave in service to the loads and forces that would be applied in the field.

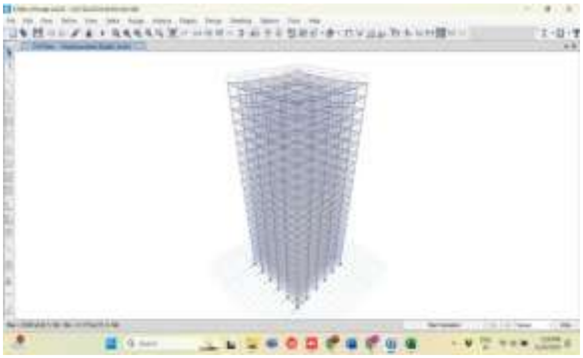

Fig 10. 3D View of Displacements (Dead Load) in ETABS Model

The picture exhibits a three-dimensional view of a structural model in ETABS, replicating the dead load displacements. The model reflects a high rise building, with displacements in millimeters. Also, the model indicates high and low displacement, the values themselves convey the level of deformation of the structure. The color spectrum represents the level of displacement of the structure and signifies where is the areas of maximum deflection and maximum stress concentration.

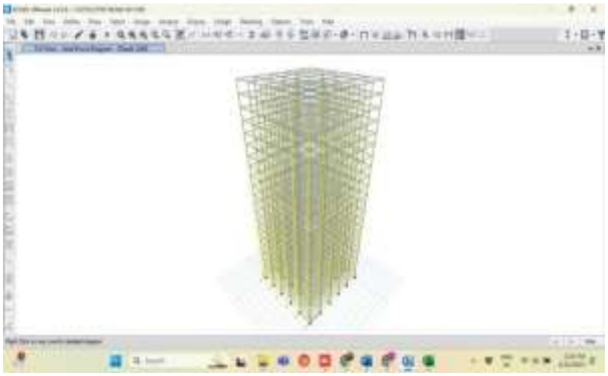

Fig 11. 3D Axial Force Diagram (Dead Load) in ETABS

This three-dimensional view illustrates the axial force distribution throughout the structural frame under dead load conditions. This diagram indicates the internal axial forces present in the structural members, which are important for assessing the overall structural stability and load capacity. The color-coded representation shows areas with relatively high axial forces, which are important for evaluation of potential stress concentrations and design issues.

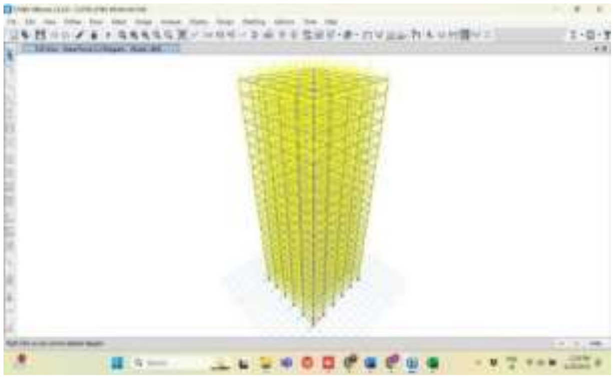

Fig 12. 3D View of Shear Force Diagram (Dead Load)

This image displays, from a 3D view, the shear force distribution in a structural frame under dead load condition. The shear force values that occur at individual locations on the structure are indicated by the yellow grid. It is assumed that dead load is not variable and induces shear forces that are significant in order to determine the capacity and stability of a frame under static loading. The figure may also assist in determining potential locations of maximum shear stress, for the designer should consider the design of the reinforcement layout.

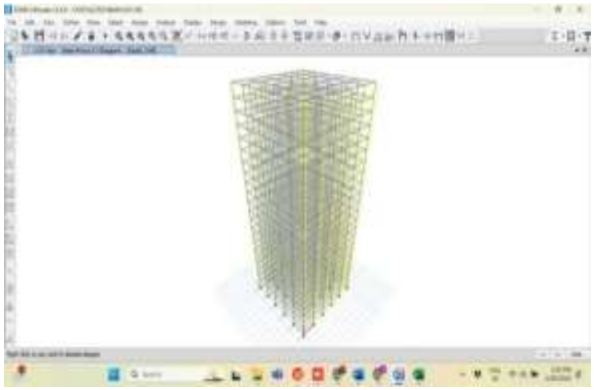

Fig 13. Shear Force Diagram for 3D Structural Model (Dead Load)

This illustration shows the shearing force distribution in the frame of a building due to dead load conditions (if utilizing the beams). This illustration shows the shear force acting on the frame, with the reactions given in kilonewtons (kN). The model helps visualize the forces and transfer of forces and how they are distributed within the structure; this is an important aspect in understanding internal forces and making sure the building is safe and stable, under dead load conditions.

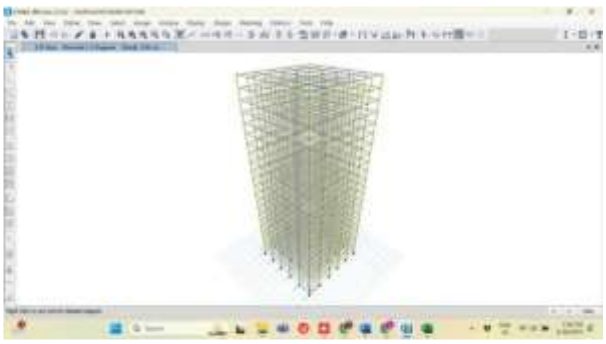

Fig 14. 3D View of Structural Model in ETABS with Moment Distribution in X and Y Direction

The figure observable is in the ETABS 3D structural model and depicts the moment distribution associated with the building frame under dead load. The elements indicated represent the overall structural frame, with yellow lines denoting the connections present in the frame. The moment distribution diagram is important for verification of internal forces in a frame, and to ensure that the structure can resist bending and deformations. The moment distribution across the structure will also assist in evaluating design strength, as well as in determining stability under different loading conditions.

Table 1: Story Response Displacement Data

TABLE: Story Response			
Story	**Elevation**	**X-Dir**	**Y-Dir**
	m	mm	mm
Story22	66	42.196	0.002
Story21	63	40.687	0.002
Story20	60	39.112	0.002
Story19	57	37.442	0.002
Story18	54	35.661	0.002
Story17	51	33.759	0.002
Story16	48	31.737	0.002
Story15	45	29.599	0.002
Story14	42	27.355	0.002
Story13	39	25.02	0.002
Story12	36	22.612	0.002
Story11	33	20.152	0.002
Story10	30	17.666	0.001
Story9	27	15.182	0.001
Story8	24	12.731	0.001
Story7	21	10.35	0.001
Story6	18	8.08	0.001
Story5	15	5.968	0.001
Story4	12	4.066	0.001
Story3	9	2.439	0.001
Story2	6	1.158	0.00046
Story1	3	0.311	0.00016
Base	0	0	0

Fig 15. Max Story Displacement

The table shows the story response for a multi-story building under seismic or lateral loads, with displacements computed in the X-direction and Y-direction. Each story elevation is presented in meters, with corresponding displacements measured in millimeters. As we travel up the building height, story displacement increases, with the maximum story displacement occurring on Story 22 (66 meters), measuring 42.196 mm in the X-direction. In fact, as we go down the stories, the displacements decrease in both directions, reaching extremely low values just above the base. For example, the displacement of Story 1 is recorded as 0.311 mm in the X-direction and 0.00016 mm in the Y-direction, which signifies minimal movement on the lowest floor of the building. Overall, the data show that upper floors have greater displacement as compared to the lower stories, which is typical for lateral loading scenarios. The information for displacements is important for evaluating the structural integrity and safety of the building, as it pertains to evaluating the seismic design.

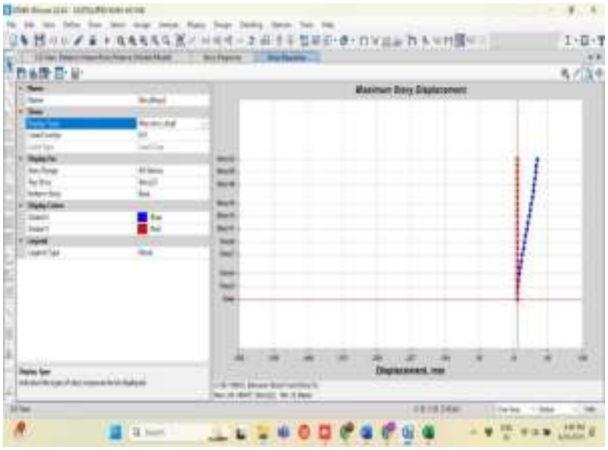

Fig 16. Maximum Story Displacement

The plot shows the greatest story displacement of a building structure, under a given load case (EX1). The plot shows displacements measured in millimeters for stories from Story 22 down to the base of the structure. The blue shows displacements in the global X-direction and the red shows displacements in the global Y-direction. The plot shows that the magnitude of the displacements is rapidly increasing upwards from the base. This suggests that the story is moving in bigger and bigger ways as you go up through the load, with the biggest movements happening at Story 22.

Table 2: STORY SHEARS

TABLE: Story Response			
Story	**Elevation**	**X-Dir**	**Y-Dir**
	m	kN	kN
Story22	66	-45.137	0
		-45.137	0
Story21	63	-101.26	0
		-101.26	0
Story20	60	-152.17	0
		-152.17	0
Story19	57	-198.11	0
		-198.11	0
Story18	54	-239.34	0
		-239.34	0
Story17	51	-276.12	0
		-276.12	0
Story16	48	-308.7	0
		-308.7	0
Story15	45	-337.33	0
		-337.33	0
Story14	42	-362.28	0
		-362.28	0
Story13	39	-383.79	0
		-383.79	0
Story12	36	-402.11	0
		-402.11	0
Story11	33	-417.51	0
		-417.51	0
Story10	30	-430.24	0

TABLE: Story Response

Story	Elevation	X-Dir	Y-Dir
	m	kN	kN
		-430.24	0
Story9	27	-440.55	0
		-440.55	0
Story8	24	-448.69	0
		-448.69	0
Story7	21	-454.93	0
		-454.93	0
Story6	18	-459.51	0
		-459.51	0
Story5	15	-462.69	0
		-462.69	0
Story4	12	-464.73	0
		-464.73	0
Story3	9	-465.87	0
		-465.87	0
Story2	6	-466.38	0
		-466.38	0
Story1	3	-466.51	0
		-466.51	0
Base	0	0	0
		0	0

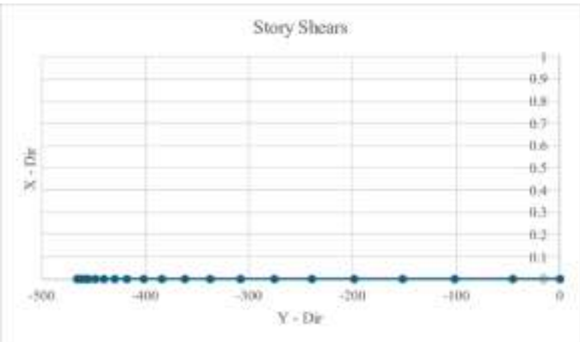

Fig 17. Story Shears

The table presents the story response data for a multi-story building under lateral or seismic loading conditions, with forces recorded in kilonewtons (kN) for both the X-direction and Y-direction. The X-direction shows negative forces at each story, indicating that the building experiences a compressive load along the X-axis. As we move from the top of the building (Story 22) to the bottom (Story 1), the force increases in magnitude, starting from -45.137 kN at Story 22 to -466.51 kN at Story 1, which suggests that the lower stories experience larger compressive forces compared to the upper stories. The Y-direction forces are consistently zero, indicating no significant lateral forces acting along the Y-axis. This distribution of forces is typical in buildings subjected to horizontal seismic or wind loads, where the top stories experience lower forces, and the bottom stories bear the brunt of the compressive loads. This data is essential for structural design and safety assessments.

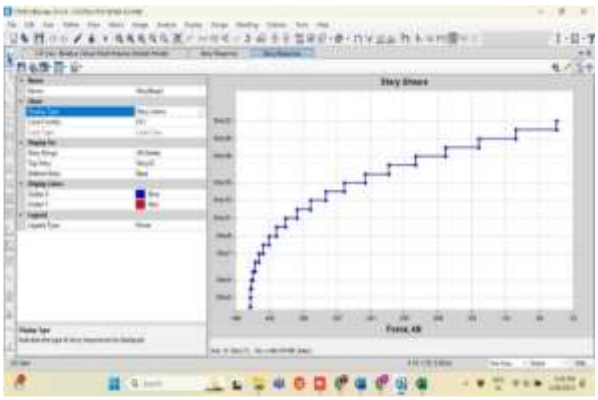

Fig 18. Story Shear Distribution Plot

The plot shows the distribution of story shear forces (in kN) along the height of the building structure, from Story 2 to Story 22. The shear forces increase with the height, peaking at the top stories. This suggests that higher stories experience greater lateral forces, which is typical in structural response under loading conditions. The plot helps in identifying the shear force magnitudes at various levels, which are crucial for designing shear walls and other structural elements to ensure stability.

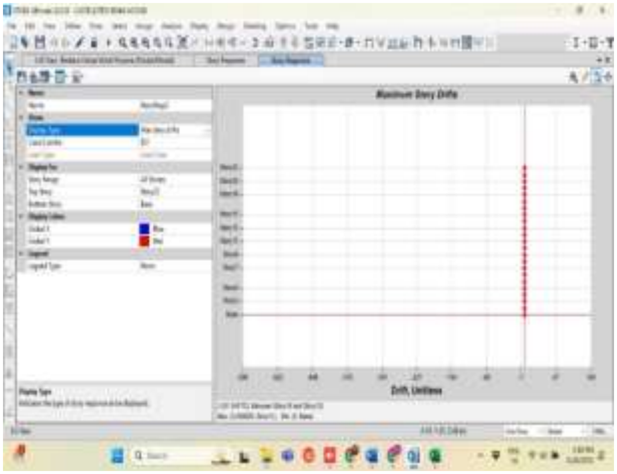

Fig 19. Maximum Story Drifts

The image displays the maximum story drift response of a multi-story building analyzed using ETABS software. Story drift is the relative displacement between adjacent floors of the building under seismic or lateral loading conditions. The graph shows the displacement values across different stories (from Story 1 to Story 22) along with the base. The highest drift occurs at Story 12, marked by a red dot, indicating significant displacement at that floor relative to others. This suggests potential structural vulnerability at this story under seismic loading. The drift is measured in units, and the graph highlights that the structure experiences minimal drift at the lower stories, with the displacement increasing significantly as we move upward, especially towards the top floors. It is essential to evaluate this drift for structural safety; as excessive story drift can lead to failure or damage in buildings subjected to strong lateral forces.

Table 3: MAX STORY DRIFT

TABLE: Story Response			
Story	**Elevation**	**X-Dir**	**Y-Dir**
	m		
Story22	66	0.0005	1.7E-07
Story21	63	0.00053	1.3E-08
Story20	60	0.00056	3E-08
Story19	57	0.00059	1.8E-08
Story18	54	0.00063	9.9E-09
Story17	51	0.00067	8.3E-09
Story16	48	0.00071	8.3E-09
Story15	45	0.00075	8.5E-09
Story14	42	0.00078	8.7E-09
Story13	39	0.0008	9.3E-09
Story12	36	0.00082	1E-08
Story11	33	0.00083	1.2E-08
Story10	30	0.00083	1.5E-08
Story9	27	0.00082	1.9E-08
Story8	24	0.00079	2.4E-08
Story7	21	0.00076	3.2E-08
Story6	18	0.0007	4.7E-08
Story5	15	0.00063	7.6E-08
Story4	12	0.00054	9.8E-08
Story30	9	0.00043	1E-07

TABLE: Story Response

Story	Elevation	X-Dir	Y-Dir
Story2	6	0.00028	9.9E-08
Story1	3	0.0001	5.4E-08
Base	0	0	0

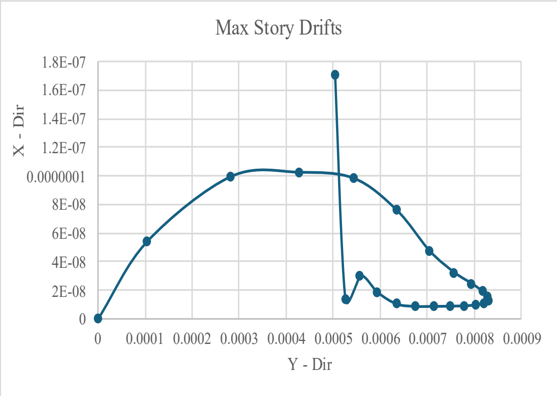

Fig 20. Max Story Drifts

The table shows the story reaction displacement data for a building with multiple floors when it is subjected to earthquake or horizontal loads. For each story, the displacement values are shown in both the X and Y directions. For the Y-direction, the motion values are given in scientific notation, which means that the movements are very small, especially at higher floors. As the stories go from top (Story 22) to bottom (Story 1) in the X-direction, displacements slowly go down. For example, Story 22 at a height of 66 meters has a displacement of 0.0005 meters in the X direction. This displacement slowly drops as the stories go down, with Story 1 at a height of 3 meters having a displacement of 0.0001 meters. The shift values in the Y direction are always much smaller, with the biggest values at the top stories. They stay in the micro- to nano-meter range, though. The base should have the least amount of movement (0 shift), since it is the reference point. This information is very important for figuring out how well the building's structure works and how stable it is when side forces are applied.

IV. CONCLUSION

In conclusion, this study demonstrates that the integration of castellated steel beams with outrigger and belt truss systems offers a highly effective and efficient structural solution for high-rise buildings subjected to seismic and static loads. Using ETABS in the analysis of the 22-story structure confirmed the structural performance to evaluate displacement, story drift, and shear force distribution. The use of castellated beams has advantages due to their increased strength-to-weight ratio, cost efficiency, and lightness of the structure, but careful analysis is still needed to evaluate their effect on stress distribution. As expected, the top and bottom stories exhibited the highest displacement and shear values. The difference between maximum drift at mid-height (Story 12) and the soft-story failures at the bottom two stories indicates that some further design attention may be warranted. The use of outrigger and belt trusses increased lateral stiffness of the overall structure significantly and decreased the total displacement experienced, improving the overall lateral load-resisting system stiffness and performance. In addition, the 3D visualizations of internal forces assisted the detailed structural assessment and helped the develop the optimal solution. The results provide an assurance that these structural systems can comply with acceptable performance under the code standards, optimize resource materials, and improve performance and resilience during a seismic event. Research highlights the need for advanced modeling and modern structural systems to achieve sustainable, safe, and cost-effective high-rise buildings within seismically active regions.

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