Parametric and Structural Analysis of Barrel Vault Trusses: A Review of Single- and Double-Layer barrel vault truss

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***Abstract*—one of the earliest architectural designs is the double-layered braced barrel vault. It is made comprised of a bracing element that connects the upper and bottom layers. Using this kind of barrel vault increases the vault's structural rigidity and offers highly promising structural systems with spans exceeding 100 meters. These kinds of structures are challenging to evaluate because to their high static indeterminacy. This research enhances structural analysis by introducing a new load type and variable parameter, comparing results to previous studies on membrane geometries. It examines the impact of bracing types, boundary conditions, and factors like pattern, depth-to-spacing ratio, and bracing configuration on force distribution, material usage, and cost under Indian loading conditions. The study also evaluates structural parameters such as span, deflection, self-weight, and cost, providing insights into optimal design solutions and buckling behavior in space trusses**

***Index Terms*—Steel barrel vault, Modelling, buckling Behavior, Optimization, Axial Forces, Deflection, Staad-Pro**.

1. INTRODUCTION

One of the earliest space structures is the double layer braced barrel vault. It is made up of a top layer and a bottom layer joined by bracing members. Barrel vault truss is more cost-effective than flat DLG truss when large span is taken into account. It is used to cover huge unobstructed spaces like stadiums, markets, exhibition halls, aviation hangars, workshop warehouses, and concert halls since it is lightweight, affordable, and quick to erect. [1] The braced barrel vaults of the past were single-layer constructions. Engineers now favour double-layer systems to cover wide areas. The component members of double-layer barrel vaults are almost entirely subject to axial forces, and the removal of bending moment's results in the full utilization of all the elements' strength, whereas single-layer barrel vaults are primarily subject to flexural moments and thus bending moments. Due to their statically indeterminate nature, the double layer barrel vault constructions are extremely rigid. By using barrel vaults of this kind, the vault structure becomes more rigid and offers highly promising structural systems with spans exceeding 100 meters. However, because of their great static indeterminacy, their investigations result in incredibly time-consuming calculation if carried out by hand. His limited use has been attributed to the complexity of complex analysis as such. However, it is possible to analyses and construct extremely complicated space structures more accurately and quickly by using computer algorithms. Therefore, computer software must be used. [2] Because it provides the best potential solution by minimizing the cost of the structure or maximizing its efficiency, structural optimization has emerged as one of the most fascinating areas of structural engineering in recent decades. Therefore, it will be advantageous to have the best possible design for two layer barrel vault buildings, which will result in lightweight and affordable structures, given their growing popularity.

Double layer gird

As seen in figure 1.1, the braced double layer barrel vault is made up of member elements placed on a cylindrical surface. A circular segment is the most common type of curve, however parabolas, ellipses, and funicular lines can all be employed. Braced two layer barrel vaults consist of the following parts:

a) Members

b) Member Connectors

c) Support members.

Two planar networks of members that form top and bottom layers parallel to one another and are connected by vertical and inclined web members make up double-layer grids, also known as flat surface space frames. All members of double-layer grids can only withstand tension or compression since they have pinned joints that lack moment or torsional resistance. These fundamental components can be used to create a variety of double-layer grid designs. [3] They are created by altering the top and bottom layers' relative directions as well as the top layer nodal points' placement in relation to the bottom layer nodal points. Additional variations can be introduced by changing the top-layer grid's dimensions relative to the bottom-layer grid. Thus, interior apertures can be made by omitting every second element in a conventional design. Based on the fundamental constituent forms, double-layer grids can be divided into two categories: latticed grids and space grids. The grid patterns of the top and bottom levels may differ or be identical

Figure 1.1: Double layer steel braced barrel vault structure

Figure courtesy: alcox steel India

2 LITERATURE REVIEW

Vuk Milosevic, Dragan Kostic, (Issue: 15 September 2023) "Deflections of barrel vault shaped membrane model under external loads." These constructions generate distinctive buildings by fusing structural performance with architectural attributes. They are renowned for their significant deflections under external stresses, though. Comparing this to the deflections of steel or concrete buildings under the same load makes it particularly apparent. Tensile membrane deflections have been the subject of numerous studies lately. This study adds to the corpus of knowledge already available in the sector. The use of a new load type and a new variable parameter is what makes the study novel. The research's objective is to gather data so that it may be compared to earlier findings on various membrane geometries. A numerical model of the membrane with a changeable height in the shape of a barrel vault is tested. The membrane's tension and the material's characteristics vary. Maximum deflections under wind, snow, and focused loads are noted and discussed. [1]

Jedrzej Chrust, Marcin Chybiński1, Piotr Garasz (Issue: 01September 2022) The influence of various types of bracing on force distribution in braced barrel vaults

In this paper the authors' analyzed four single-layered braced barrel vaults with different types of bracing. Each braced barrel vault was constructed from steel hollow sections and measured 20 m by 28 m. The Autodesk Robot Structural Analysis tool was used to perform static-strength assessments of the constructions, accounting for wind, snow, glass cover, and self-weight. According to the EN 1991-1 4 standard, wind pressure perpendicular to the longitudinal wall was calculated in the wind load scenario. But for braced barrel vaults, the regulation doesn't say how to figure out wind pressure perpendicular to a gable wall. Because of this, two variations proposed by the authors of this article were examined for this wind direction. The impact of bracing type on material consumption and force distribution in a braced barrel vault was examined. It was also assessed how the braced barrel vault's force distribution was affected by the boundary conditions of the gable wall. The force distribution in the examined braced barrel vault was influenced by the boundary circumstances as well as the type of bracing. [2]

Smit m. Kevadiya, Zalak Bhavsar (Issue: 06 June 2020) "Parametric study of braced barrel vault structure to cover large span".

When designing huge span bridges, the designer must focus on elements such as simplicity of construction and simple fabrication in addition to the structural and architectural components of the building. The optimization of the structural material has become more and more important in recent trends. These days, maximizing material utilization while using the least amount of energy is a major area of focus. This explains why designing structures with the least amount of weight per square inch is so popular. Simultaneously, efforts are undertaken to streamline the fabrication process while saving various types of energy throughout building. The most successful solutions of this type are definitely braced barrel vaults. The barrel vault shape is what defines their primary roof shape. Naturally, their basic form can be modified in a variety of ways to meet the needs and objectives of the particular construction. Studying how different design parameters affect the structure's cost and performance is crucial for cost-effective engineering design of these structures. The goal of this study is to determine how the pattern, bracing pattern, supporting arrangement, and relative depth to spacing ratio affect the cost and performance of a structure under Indian loading conditions. [3]

Shah Rajkumar, Prof. Satyen Ramani (Issue: 03 | March-2019) "Parametric study on space truss for covering a large area".

Space trusses are frequently used to span wide spaces, including stadiums and airplane hangars. It has also been determined that the geometric dimensions of a structural design's modular components are the primary factors that affect its efficacy. This study examines the parametric effects of geometry conditions on space truss performance. The local buckling member is obtained by analyzing many characteristics. The structure is analyzed and designed using STAAD PRO software. The outcome is to recommend the best space truss. Obtain the buckling load with various factors in this analysis, and find the key parameters influencing behavior. [4]

Sarika B. Shinde, Pandit.M.Shimpale, (Issue: 9 Jan 2016) "Study of barrel vault".

The research of Double Layer Barrel Vaults (DLBV) of 3D Truss and Slab types is the goal of this work. A straightforward structural configuration consisting of a network of longitudinal, transverse, and braced members with only one direction of curvature is the truss type double layer barrel vault. Slab barrel vaults are made of a concrete shell with a single direction of curve that is supported by a longitudinal beam. Aspect Ratio (Rise/Span) is considered in the analysis and design of both types of barrel vaults, taking into account loads such as live, dead, wind, and combination loads. The barrel vault of the truss type is developed in accordance with IS: 800-2007. And IS: 456-2009 is used to design the slab type. The comparison of span, maximum deflection, self-weight, and cost criteria is the result of this effort. [5]

Maksym Grzywiński (Issue: Jan-2016) "Optimization of double-layer braced barrel vaults".

The discrete optimization problem in structural space design for civil engineering is discussed in this study. Mass minimization should meet serviceability and restrict state capacity requirements. Truss bar cross-sectional areas are used as design variables. Optimization constraints include computational and technological needs, stresses, displacements, and stability. [6]

Mulesh K. Pathak (Issue: 02 | Feb-2014) "Performance of single layer steel barrel vault under buckling".

Buckling is a critical stress and deformation state when a small perturbation results in a significant increase in deformation or perhaps the part's complete structural failure. Normal static arguments do not show structural behavior of the part beyond 'buckling'. Buckling failures are a result of component size and modulus of elasticity rather than material strength. Consequently, high-strength materials will buckle just as easily as low-strength ones. When compressive loads are applied to a structure, a buckling analysis might be required. The study described in this paper aims to assist steel braced barrel vault designers by highlighting the key distinctions in identifying the configuration or configurations that would work well under various application scenarios. The analysis is parametric in nature and includes a number of other significant elements, such as the rise to span ratio and various boundary conditions, such as whether a barrel vault functions as a beam, an arch, or a shell. This study presents the buckling strength of three distinct double layer braced barrel vault configurations with four different types of boundary conditions and rise/span ratios ranging from 0.2 to 0.7. The study provides an evaluation of the impact of the vault configuration on the total buckling strength by taking these factors into account. [7]

3 SUMMARIES OF LITERATURE AND GAP

From literature survey it is found that lot of work has been done on optimization of double layer barrel vault trusses of large span considering various bracing pattern, load type different support arrangement and specific size, shape, weight etc. This represents area for further study of research, The work on optimum analysis and design of large scale double layer barrel vault truss problems considering various parameters such as deflection, Steel Consumption and buckling factor with respect to different height to span ratios and using different geometries

4 RESULTS AND DISCUSSION

The relationship between the snow value and the maximum deflections caused by wind loads is examined. Only when the elastic and shear moduli have the lowest analyses values does the maximum deflection under wind load increase. The snow load deflections become greater than the wind load deflections as these values rise. The wind load deflections are greater for lower models and smaller for higher models. While deflections from snow are greater in all other situations, wind load has a larger maximal deflection under the highest examined prestress intensity. (Vuk Milosevic, Dragan Kostic., 2023). According to the study, the bracing type has an impact on the braced barrel vaults' overall performance as well as the distribution of axial force. Pratt type 2 bracing is not advised since it is prone to buckling and has the most compressed bars. As a substitute, Pratt type 1 bracing is more effective. Axial loads are the main forces, and the bars at the ends of the vaults are the most severely laden. The critical buckling length along the y-axis was used to assess the bars' buckling resistance. Because Pratt type 2 bracing had more bars in compression, it used the most steel. Although the Foppl type bracing produced a taller vault, it was not the lightest choice because it required more steel. Support circumstances revealed that whilst correcting all displacements (variant a) resulted in a distinct axial force distribution, permitting displacement at the gable wall supports (variant b) increased axial compression forces. By permitting mobility, variant b accounts for thermal expansion, which is crucial to avoiding structural failure brought on by temperature fluctuations. (Jedrzej Chrust, Marcin Chybiński1 2022) The findings the buckling factor, vertical deflection (mm), and steel consumption (kg/m2). Steel usage is found to be highest when the maximum number of divisions with support condition type-2 are used h/s=0.125, TYPE-1 bracing configurations the outcomes for the other two cases, 1 and 3, are nearly identical. However, once more, the maximum values for these two support requirements also apply when there are a maximum of ten divisions. Steel consumption is shown to be highest when the maximum number of divisions with support condition type-2 are used, with h/s=0.20 and TYPE-1 bracing arrangements. The support-3 type cases with four divisions have the lowest value for the other two conditions, 1 and 3. Additionally, it has been noted that the steel consumption value rises with the number of divisions under all support conditions (Smit m. Kevadiya, Zalak Bhavsar, 2020). The study investigates the buckling behavior of a space grid structure under varying support conditions, depths, and spans, with welded connections considered in the analysis. The total buckling performance is determined through linear buckling analysis of 24-meter models. The structure with four sides has the largest load-carrying capacity, followed by three sides, two sides, and lastly four corners, which has the lowest capacity, according to an analysis of the support conditions. The analysis shows that as the span increases, the load-carrying capacity decreases, with the bottom span supporting the most weight. A depth of 2 meters offers a higher load capacity than 1 meter, showing that capacity increases with depth (Shah Rajkumar, Satyen Ramani, 2019) the member's deflection cannot be so great as to compromise the structure's strength or effectiveness or cause finishing damage. The Code of Practice for General Construction in Steel IS: 8007 states that the maximum vertical deflection cannot be greater than L/325 of the span. L/400 is the maximum vertical deflection allowed. Few DLBV compression members have been found to cause failure for the L/325 criterion due to slenderness, but not for the L/400 threshold, for a constant length. (Sarika B. Shinde, Pandit.M.Shimpale, 2016) Factors like loads, grid size, depth, and rise have a big impact on barrel vault optimization. Another important factor is the number of groups in each layer, which in our example is limited to no more than four. The displacement in the best solution is 4.4 cm (with a limit of 19.2 cm), suggesting that the structure is rather robust and that much better solutions might be possible. The bottom layer close to the boundary line experiences the highest normal forces, 298 KN. There were five supports on one side, and the solution would probably be better with more supports. Increasing the height (rise) would reduce the forces within the structure; however, it would also result in a longer and heavier overall structure. (Maksym Grzywiński 2016). Each vault geometry joint's loads are computed using the fundamental loads and load combinations. Software is used to do static analysis since the structure is modelled as a space truss. The expert program STAAD-Pro is used to perform the preliminary analysis and design. The design takes into account the necessary IS: 800-1984 checks. The STAAD-Pro's facilities are also utilized to obtain the best sections. Finding the lowest multiplication factor for the load that will cause a structure to buckle is done through a buckling analysis from an analytical perspective. Several buckling load factors (BLF) are the outcome of such an analysis. The factor of interest is always the first BLF, or the lowest factor. Buckling will happen if it is less than unity because the load is applied to the building. The buckled structure's shape is also determined by the analysis. Here, STAAD-Pro 2007 is used to do buckling analysis. (Mulesh K. Pathak 2014)

5 CONCLUSIONS

Compared to other loads, the concentrated load has different effects, especially in displacement patterns that are strongly concentrated around the load point. However, compared to wind and snow loads, the greatest displacements under concentrated loads are smaller. Similar deflection patterns are produced by wind and snow loads, with the greatest deflections, which are determined by curvature and distance from supports, occurring between the center of the membrane and the middle of its straight edge. Wind and snow load deflections are comparable in magnitude. With the exception of concentrated loads, where increasing height can occasionally increase deflections, increasing the membrane's elastic modulus, structure height, and prestress generally reduces deflections. (Vuk Milosevic, Dragan Kostic., 2023). In summary, the type of bracing and the boundary conditions significantly influenced the axial forces in the braced barrel vault structure. Pratt type 2 bracing led to the highest steel consumption due to the compression in the diagonal bars, which were prone to buckling. The extremities of the structure experienced the highest load, and the axial forces were also affected by the support conditions at the gable wall. Higher axial compression occurred in structures with unstabilized longitudinal displacements at the gable wall, with the highest forces at the center, while structures with fixed supports had lower axial compression forces, with the maximum occurring at the edges. (Jedrzej Chrust, Marcin Chybiński1 2022) Support condition type-3 is most economical solution for both h/s ratio whatsoever the bracing pattern. Also, support condition type-2 proved to be costlier one. As h/s ratio increase there is general trend that Max. Vertical deflection tends to decrease and buckling factor increase. The buckling factor is maximum in case of support-2 type structure, hence support condition-2 is batter for strength criteria. Deflection is found to be maximum in all case for support-2, even though the larger c/s is provided. The optimum solution in terms of steel consumption is depend upon the different number of divisions, support condition and bracing pattern. (Smit m. Kevadiya, Zalak Bhavsar, 2020). This essential buckling load can be carried by the member. The member will buckle if the load exceeds the critical buckling load. The highest load bearing capacity for various support conditions is for four-sided support conditions, followed by two-sided, three-sided, and four-corner support situations. II. The load carrying capacity is obtained for three different spans; as the span increases, the load carrying capacity decreases. III. The weight carrying capacity is obtained at two different depths; as depth increases, so does the load bearing capacity. (Shah Rajkumar, Satyen Ramani 2019) This paper examines, analyses, and designs the Slab Type and Double Layer Barrel Vaults in Staad. In Pro.2007, this ranged from 0.2 to 0.4 Aspect ratios (Rise/Span) for spans of 10 to 30 meters. The study comes to the conclusion that the deflection of a double layer barrel vault increases or reduces with varying member sizes for an aspect ratio (Rise/Span) of 0.2 to 0.4, while the deflection of a slab type barrel vault grows with varying aspect ratios. The Code of Practice for General Construction in Steel IS: 800 states that the maximum vertical deflection cannot be greater than L/325 of the span. Additionally, the choice of barrel vault is crucial from an architectural and economic standpoint; we propose that a 3D truss type barrel vault will meet both requirements. (Sarika B. Shinde, Pandit.M.Shimpale, 2016) The optimization of barrel vaults is significantly impacted by loads, grid size, depth, and rise, as well as the number of groups in each layer (for instance, no more than four). The best solution's displacement of 4.4 cm (with a limit of 19.2 cm) indicates that the structure is extremely rigid and may look for even better alternatives. Near the boundary line, the bottom layer had the highest normal forces (298 KN). One side had five supporters; if that number rises, there will undoubtedly be better options. Although an increase in height (rise) may lessen the stresses acting on the building, it will sadly cause an overall increase in length and weight. (Maksym Grzywiński 2016). The four configurations exhibit varying buckling load capabilities depending on boundary conditions. Configuration-2 (SOS) offers the highest buckling strength, nearly four times greater than others. Configuration-3 (SOD) performs better under beam and corner-supported conditions, while Configuration-1 (DOS) does better under arch and edge-supported conditions. Configuration-2 (SOS) experiences the least buckling strength loss with increasing Rise/Span ratio, while Configuration-1 (DOS) sees more loss than Configuration-3 (SOD). The absence of internal members in Configuration-4 (DOD) significantly impacts buckling behavior, especially in beam, shell, or arch modes. The arch mode shows the most increase in buckling strength with Rise/Span ratio, while the beam mode shows the least. (Mulesh K. Pathak 2014).

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