Hosseini, A., Briseghella, B., Giaccu G.F., Fenu, L. (2025). Optimizing Gridshell Dome Shapes Based on Seismic Response: The Impact of Dynamic Analysis and Supplementary Damping Devices . In: Marmo, F., Cuomo, B., Cutolo, A. (eds) Computational Mechanics and Applied Mathematics: Perspectives from Young Scholars (GIMC SIMAI Younh 2024) Lecture Notes in Mechanical Engineering. Publisher: Springer Cham.

The editorial copy is available at https://doi.org/10.1007/978-3-031-76591-9

# Optimizing Gridshell Dome Shapes Based on Seismic Response: The Impact of Dynamic Analysis and Supplementary Damping Devices

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**Abstract.** This study investigates the optimization of gridshell dome shapes using seismic design demand parameters as the primary objective function. The innovative methodology integrates shape optimization with seismic analysis, deviating from traditional approaches that separate geometric design and seismic performance enhancement. By integrating computational methods, utilizing parametric modeling through Grasshopper, and structural analysis with OpenSees, the framework employs a genetic algorithm for optimization. Nonlinear time-history analysis, incorporating material and geometric nonlinearities, reveals that the optimal shape of the dome is significantly influenced by its seismic response. The results show that the optimal dome shape can vary substantially based on seismic performance criteria, indicating a dynamic interplay between structural form and seismic forces. Moreover, the optimal shape can be further influenced by implementing a supplementary damping system. In this case, both the gridshell shape and seismic dampers arrangement require adjustments to achieve optimal seismic performance. These findings highlight the critical role of integrated seismic analysis in shaping optimization, emphasizing that the ideal dome geometry is not static but evolves in response to seismic demands and damping configurations.

**Keywords:** parametric design; shape optimization; gridshell; viscoelastic damper; seismic performance.

## 1 Introduction

Gridshell structures are highly regarded for their inherent geometrical rigidity and optimal material efficiency. These curvilinear, shell-like forms, made from interlocking beams, are both lightweight and capable of spanning large areas without internal support [1]. However, their slender steel members can lead to low stiffness and damping, causing potential instability under dynamic forces, especially in earthquake-prone regions [2]. To address this, researchers recommended adding a complete or partial layer to the lattice structure [3, 4]. Various vibration control mechanisms, developed since the 1970s and 1980s, have also been employed to enhance seismic performance [5].

Studies have shown that optimizing viscoelastic (VE) dampers can be a cost-effective solution to improve structural resilience [6]. For instance, Yang's research replaced selected bars in a double-layer reticulated shell with VE dampers, optimizing their placement for better performance [7].

In gridshell structures, the focus has been on identifying optimal damper configurations. For example, Zhou et al. optimized semi-active damper placement using algorithms, finding the lower three rings to be the most effective [8]. Yang and Ma confirmed that replacing diagonal bar members with dampers in these rings is optimal [9].

Despite these advancements, simultaneous optimization of gridshell shape and damper configuration has not been explored. This study aims to enhance structural performance by optimizing both the shape and damper configuration simultaneously, rather than sequentially.

The gridshell model is developed using Grasshopper for geometric definition and OpenSees for structural analysis [10]. An Evolutionary optimization algorithm, specifically a Genetic Algorithm, refines VE damper configurations in the lowest ring and the dome’s shape. The performance criterion of the optimization algorithm is calculated using nonlinear time-history analyses, which assess the seismic response of the structure. This study explores how variations in rise-to-span ratio and base tangent inclination influence damper utilization and shape optimization, aiming to improve seismic performance in gridshells.

## 2 Proposed Methodology

This study presents a parametric design framework for the simultaneous optimization of dome structures' shape and VE damper configuration under vertical static and seismic loads. The dome shape is defined using a cubic Bezier curve, and node coordinates and connections are parametrically modeled. The analysis is performed in OpenSees, integrating dome geometry and VE damper placement. The framework accounts for material and geometric nonlinearity, employing gravity and time-history analyses. A genetic algorithm optimizes both dome shape and damper arrangement, aiming to minimize displacement while considering constraints such as member strength, maximum allowable deformation, and buckling resistance. The study procedure is outlined in Fig. 1.

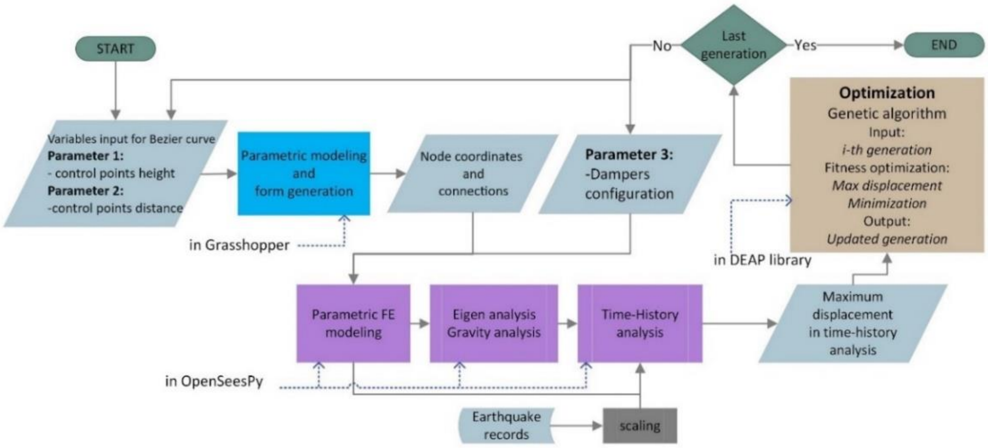

**Fig. 1.** Study procedure

### 2.1 Parametric Modeling and Analysis

This study uses Grasshopper, a visual programming language in Rhino 3D, for parametric modeling of single-layer steel gridshells. The process begins with a 2D cubic Bezier curve (defined in Eq. 1) to establish the dome's basic shape. Bezier curves are generated using 'control points' [11]. As shown in Fig. 2, two main parameters define the gridshell dome's geometry: the height of the middle control points and their distance, which correlate directly with the curve's apex height (H) and slope of tangent (α). The Bezier curve offers great flexibility, allowing for diverse shapes including catenary, spherical, and ellipsoidal forms by adjusting the slope of the tangent at the curve's ends.

$$B(t)= P_0(1-t)^3 + 3P_1t(1-t)^2 + 3P_2t^2(1-t) + P_3t^3 \qquad \text{for } 0<t<1 \qquad (1)$$

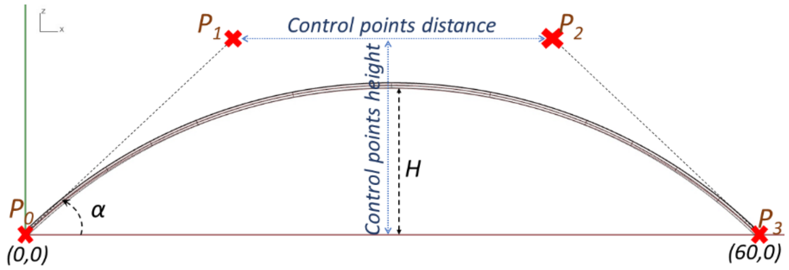

**Fig. 2.** Initial 2D Bezier curve introduction

The gridshell elements include radial, latitudinal, and diagonal types (Fig. 3a). A 60m span Kiewitt-8 gridshell dome was chosen for its simple parametric modeling. Besides the parameters defining $H$ and $\alpha$, additional parameter lists possible replacements of first-ring diagonal members with VE dampers.

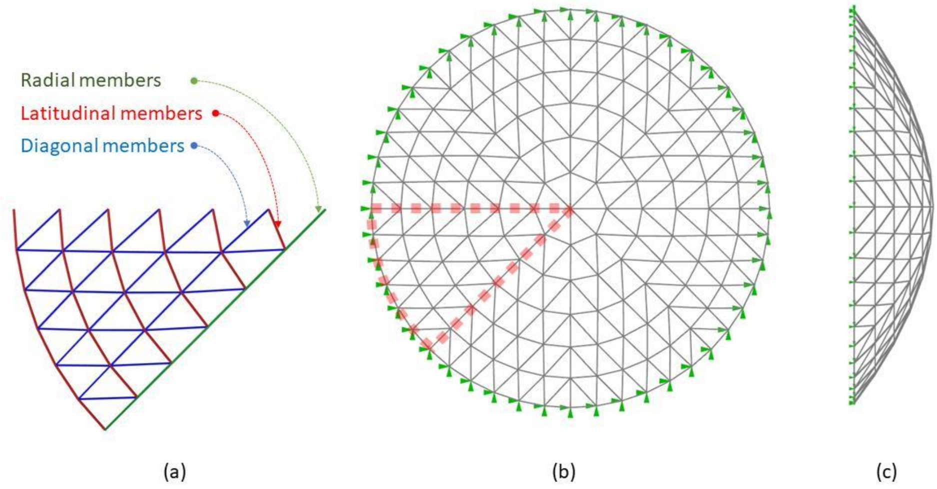

**Fig. 3.** (a) One-eighth of the Kiewitt-8 dome. (b) Top view of the dome. (c) Side view of the dome

The finite element model is built in OpenSees using node coordinates and connections generated in Grasshopper. OpenSeesPy integration enables parametric modeling and optimization of various design scenarios (Fig. 1).

The Kiewitt-8 gridshell dome (Fig. 3) consists of 8 radial members (meridians) and 6 equally spaced latitudinal rings, with symmetrically distributed diagonal members. Steel circular hollow sections ($E$ = 206 GPa, $f_y$ = 235 MPa) are used for structural elements. The material behavior is modeled using OpenSees' 'steel01' definition, accounting for uniaxial bilinear response and kinematic hardening. The gridshell employs two distinct member sizes: diagonal members utilize sections of Φ159 x 6.3 mm, while Φ152 x 5.0 mm sections are specified for both radial and latitudinal members

The structure features rigid connections, except for hinged connections where dampers replace members. It's fixed by 48 nodes with three-way hinges. Elements are modeled as inelastic displacement-based frame elements using OpenSees' 'dispBeamColumn' command, with five integration points and eight fibers across the cross-section. A 2 kN/m2 roofing load is evenly distributed among nodes. 2% Rayleigh damping is applied and periodically recalibrated using the first two predominant natural frequencies [12].

The VE dampers that were utilized to substitute the diagonal structural members in the first ring were assumed to behave linearly. The VE damper characteristic consists of two key parameters, damping coefficient $C_d$ = 700 kNs/m and stiffness $K_d$ = 700 kNs/m acting in accordance with the Kelvin-Voigt model,

The study employs modal, static, and dynamic time-history analyses, considering both geometric and material nonlinearities. Maximum resultant displacement is tracked to evaluate seismic performance.

Genetic algorithms (GA), a type of evolutionary algorithm, are well-known tools for identifying optimal solutions in structural engineering. The study evaluates seismic performance by monitoring maximum resultant displacement, a challenging task due to shell structures' nonlinear behavior across various parameters.

Structural optimization in this study focuses on maximizing seismic performance through three main aspects:

- Optimizing dome shape parameters $H$ and $\alpha$.
- Configuring dampers using a binary list for 10 diagonal members in one-eighth of the Kiewitt-8 gridshell dome (in case of locally symmetric damper placement, the list gets mirrored, and the variables become 5).
- Applying constraints such as maximum displacement, allowable stress, and overall stability, including span/300 for displacement and implicit criteria for material nonlinear behavior and buckling resistance.

Using OpenSeesPy and the DEAP library [13], optimization is conducted via genetic algorithms across two scenarios:

- Dome shape optimization: Adjusting parameters 1 and 2 to optimize the dome's tangent height and slope.
- Joint optimization of dome shape and damper configuration: Integrating parameters 1, 2, and 3 to streamline the optimization process, reducing variables to 7 for improved symmetry and efficiency.

## 2.2 Seismic Actions

A set of seven earthquake records is used for nonlinear dynamic time-history analysis. The earthquakes analyzed in the study include Corinth (1981), Landers (1992), New Zealand-02 (1987), Manjil (1990), Hector (1999), Imperial Valley-02 (1940), and Northridge (1994). The ground motion accelerations are scaled to fit the design spectrum using the Spectral matching approach, as shown in Fig. 7. This study considers the main horizontal component of the records. Thus, the seismic analysis of the structure is performed subjected to one-direction excitation.

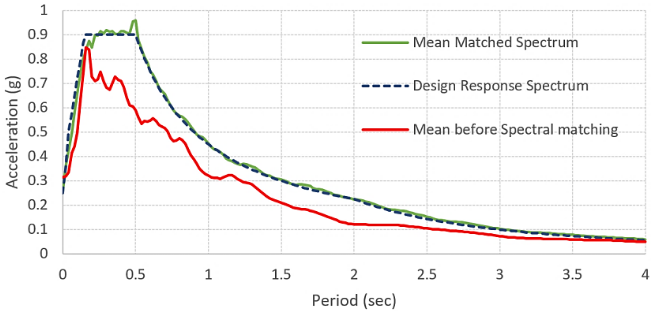

**Fig. 4.** Mean spectrum of the records before and after spectral matching.

## 3 Effects of Variation of Height and Base Tangent

Examining the Kiewitt-8 lattice dome's response under seven seismic excitations, focusing on two geometric parameters: the control points' reciprocal distance and elevation, which are transformed into dome height and base angle for intuitive analysis.

**Table 1.** Shape optimization information

| Variable input parameters | Range of variation | Fitness optimization |
|---|---|---|
| Height (Control points' elevation) | 9.75 – 20.25 m (13 – 27 m) | Maximum resultant displacement |
| Base tangent inclination (Control points' distance) | 35 –70 ° (11.5 – 21.5 m) | |

To independently evaluate base tangent inclination, the "base angle deviation from arc" parameter is introduced. This parameter measures the angle difference between the dome's base angle and a spherical dome's base angle of the same height, differentiating dome geometries.

Reducing the dome height linearly lowers the maximum displacement by about 15%. Higher tangent values yield a more rounded ellipse-like curve, while lower values result in a catenary-like curve, both showing reduced displacements under seismic actions. Excessive reduction of base tangent inclination can lead to instability and increased displacement under asymmetric loads, with optimal angle ranges for uncontrolled Kiewitt-8 gridshell domes found to be about 5 degrees less than the corresponding arc angle.

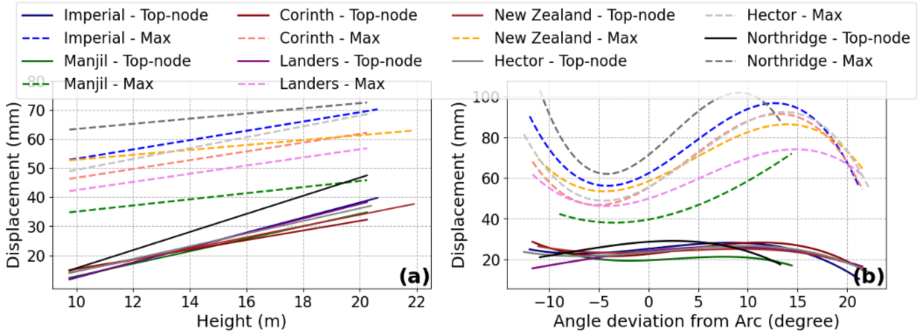

**Fig. 5.** (a) Trendline of height vs displacement for the uncontrolled model; (b) Trendline of base angle deviation from Arc vs displacement for uncontrolled model

## 4 Optimization of Damper's Replacement, Height, and Base Tangent

To assess the impact of VE dampers on the optimal shape of the Kiewitt-8 gridshell dome, variables such as height, base tangent inclination, and damper configurations are analyzed to minimize maximum displacement. The analysis focuses on locally symmetric topologies to streamline the range of possible configurations, enabling straightforward demonstration and reasoning of the dampers' effects on the dome's seismic performance and structural optimization, as detailed in Table 2.

**Table 2.** Overall optimization information

| Variable input parameters | Range of variation | Fitness optimization |
|---|---|---|
| Height (Control points' elevation) | 9.75 – 20.25 m (13 – 27 m) | Maximum resultant displacement |
| Base tangent inclination (Control points' distance) | 35 –70 ° (11.5 – 21.5 m) | |
| Dampers' Configuration (locally symmetric topologies) | 0 – 31 | |

Managing numerous genes within a genome for genetic optimization is a complex procedure. Specifically, in this case, the configuration of the dampers cannot be directly quantified by a singular value; instead, it is represented by a unique numerical identifier for each damper configuration. Fig. 6 displays 32 symmetric damper configurations, each labeled with a sequential number. For the GA, changing the configuration of dampers is effectively achieved by altering these numerical identifiers.

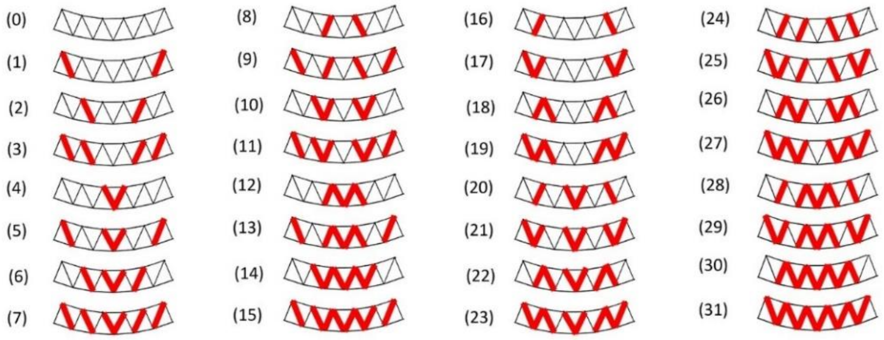

**Fig. 6.** Locally symmetric topologies of diagonal members of the first ring with VE dampers (red shows dampers)

Fig. 7a specifically highlights the impact of height on the maximum and top displacement of the gridshell dome. While the overall influence of height on displacement is modest. Contrary to expectations that lower heights always result in reduced maximum displacement, a median height range of 11 to 15 meters is identified as producing the lowest maximum displacement when dampers are installed. Note that the trend of the maximum displacement with height is less regular, being affected not only by the overall response of the gridshell but also by local effects.

Conversely, Fig. 7b indicates the optimal base angle for the gridshell when equipped with VE dampers, revealing a preference for angles closely aligned with an arc yet exhibiting a slight positive deviation, indicating a more ellipsoidal shape. This finding, when compared with Fig. 5, clearly illustrates how the incorporation of VE dampers changes the optimal dome shape from having a base angle lower than the reference arc to curves having a base angle higher than it, thereby tending towards an ellipsoidal form.

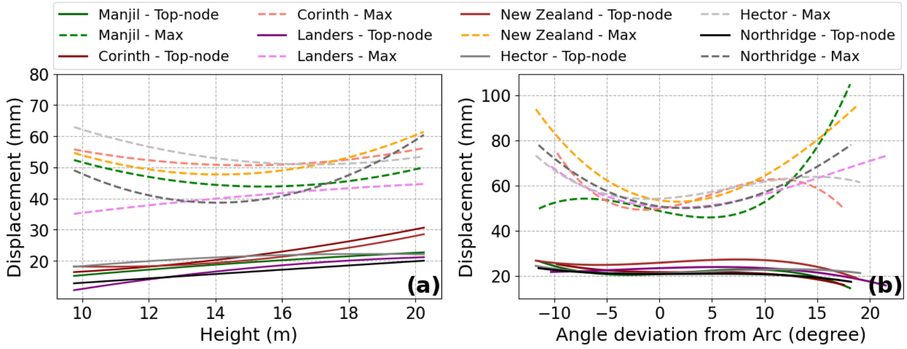

**Fig. 7.** (a) Trendline of displacement vs height for the controlled model; (b) Trendline of displacement vs base angle deviation from Arc for the controlled model

The use of VE dampers in Kiewitt-8 gridshell domes offers significant benefits in reducing maximum deformations, particularly influenced by the second mode of the structure. VE dampers shift this mode to align with the structure's predominant period, effectively dampening vibrations and minimizing deformations. However, their impact varies with dome geometry: in shallow domes (low height-to-span ratio), where the first mode predominates, dampers have minimal effect and may even increase deformation by reducing dome stiffness. Conversely, in domes with higher rise/span ratios, dampers are highly effective in reducing top node displacement by addressing the dominant second mode, particularly for intermediate height-to-span ratios.

Additionally, VE dampers enhance earthquake resistance by reducing sensitivity to different accelerograms. Comparing figures depicting maximum displacement variation with base tangent inclination underscores the noticeable effect of damper implementation. Optimization efforts reveal that no single combination of height, base tangent inclination, or damper configuration consistently optimizes maximum displacement; instead, multiple viable solutions exist, emphasizing the need for thorough evaluation. Fig. 8 consolidates results across various earthquakes, indicating several configurations (notably numbers 7, 11, 15, and 23) achieve consistently low maximum displacements with minimal variation, affirming their robust performance.

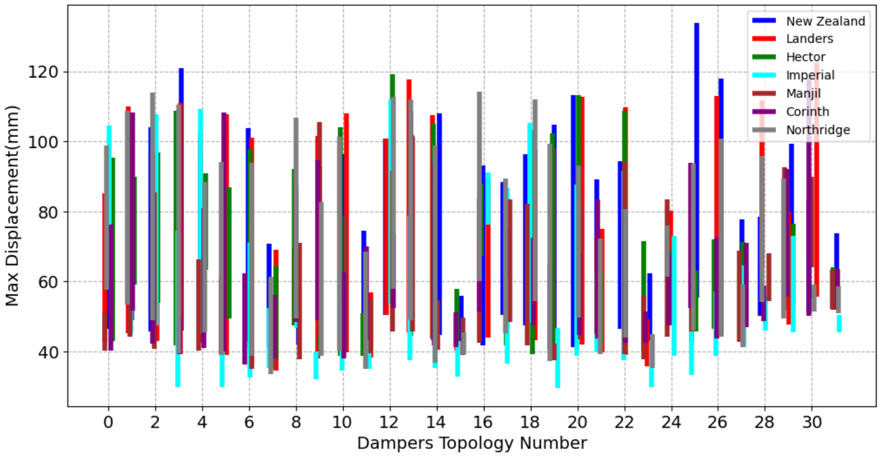

**Fig. 8.** Range of variation of Maximum displacement per dampers' topology

## 5 Conclusion

This study introduces a novel design methodology that simultaneously optimizes the structure's shape and the placement of viscoelastic (VE) dampers to enhance earthquake response. The approach employs parametric design and genetic optimization algorithms, incorporating nonlinear time-history and buckling analyses to address material and geometric nonlinearities.

Applied to steel grid-shell domes, the methodology revealed that integrating VE dampers during the shaping process leads to an optimal ellipsoidal form, reducing displacements. Without dampers, a shape resembling a parabola proved more effective for seismic response.

The optimal configuration of VE dampers significantly reduced maximum displacements, with effectiveness increasing in high-displacement scenarios. Reductions of over 50% were observed in some cases.

This research demonstrates the potential of combining parametric modeling, structural analysis, and optimization techniques to improve the seismic performance of grid-shell structures. The findings have practical applications in designing safer, more resilient structures in seismic regions.

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