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Research Article

Structural Insights into Bracket Behavior: A Statistical and Displacement-Stress Analysis

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ABSTRACT

This paper analyzes the structural performance of mechanical brackets using a data-driven methodology based on 12 simulation-derived tables covering stress, displacement, geometry, and modal behavior. Bracket models were examined across multiple axes to assess how features like mass, volume, and projected area influence deformation. Displacement values peaked at 0.876 mm, with over 74% of stress classified as vertical. Notably, brackets weighing over 0.45 kg did not always offer improved performance; several lighter brackets under 0.28 kg exhibited lower displacement due to better material distribution. Modal frequencies above 115 Hz only correlated with improved stiffness when aligned directionally with loading vectors. Projected area emerged as the most reliable predictor of displacement control, outperforming both volume and mass. The study concludes that optimal bracket performance is achieved through geometry-aware material placement, not simply increasing bulk. These insights support better lightweighting strategies and deformation control in constrained mechanical designs.

1. INTRODUCTION

Mechanical brackets may appear simple in geometry, but they are often tasked with highly complex responsibilities — transferring loads, maintaining alignment, and resisting dynamic deformation under unpredictable conditions. In structural and mechanical engineering, bracket components are typically overlooked compared to larger beams or composite shells. Yet, they remain mission-critical elements in aerospace, robotics, civil assemblies, and countless industrial fixtures.

Their small size conceals an engineering challenge: brackets must balance stiffness, weight, and manufacturability, all while often being mounted asymmetrically or subjected to loads in multiple directions. When failure occurs in such components, it is frequently due to cumulative displacement or localized overstress rather than outright fracture. For this reason, understanding the full-field deformation behavior of brackets under operational loading is essential to achieving reliable design.

Recent advances in finite element analysis (FEA), parametric modeling, and computational optimization have enabled engineers to evaluate bracket behavior across large design spaces. However, much of this work has focused on performance in aggregate — via compliance minimization or modal frequency tuning — rather than dissecting how and why certain geometries fail to meet displacement or stress constraints [1]. A more granular perspective, one that accounts for local geometry effects, modal behavior, and even direction-specific displacement vectors, is now needed.

Moreover, emerging design strategies such as generative design and additive manufacturing have introduced non-traditional bracket geometries that challenge conventional assumptions. These include hollowed-out frames, truss-like elements, or organically-shaped load paths [2], which cannot be easily interpreted using legacy metrics like thickness or span ratio alone. New benchmarks are required to evaluate how volume, projected area, or even modal concentration influence mechanical behavior at the bracket scale.

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This paper presents a data-driven analysis of bracket structural behavior using 12 curated datasets extracted from a controlled displacement-stress simulation environment. Unlike prior work which emphasizes theoretical design spaces, we focus on empirical relationships between displacement, stress, geometry, and frequency — both at the global and case-specific levels. We also analyze multi-axis deformation, investigate directional modal effects, and explore how simple metrics like area and volume relate to complex mechanical performance.

In particular, we build on the foundation laid by works such as Xiang et al. [3], who explored stress propagation patterns in structural nodes, and Almeida et al. [4], who linked shape parameters to modal distribution in robotic joints. However, our approach is distinct in that it integrates detailed point-wise displacement data, cross-correlated with modal results and material volume statistics, to develop a complete picture of bracket efficiency and failure potential.

The remainder of the paper is organized as follows: Section 2 explores geometric features and their influence on global displacement trends; Section 3 analyzes stress distributions across different loading vectors; Section 4 investigates the interplay between modal properties and displacement; Section 5 zooms into specific bracket cases for local deformation analysis; and Section 6 evaluates structural trade-offs across mass, volume, and area dimensions.

This layered perspective aims not only to assist engineers in improving current bracket designs but also to provide data-backed reasoning for incorporating geometric intelligence into early-stage mechanical design workflows.

2. STRUCTURAL FEATURE EXPLORATION

The behavior of bracket structures under stress isn't governed by a single rule — it's an interplay of geometry, material behavior, modal dynamics, and spatial features. To start unpacking this, we analyzed the statistical distribution of maximum displacement across all evaluated designs. Table 01 reveals the core of this variation.

TABLE I. MAXIMUM DISPLACEMENT STATISTICS ACROSS ALL BRACKETS

	max_disp
count	2138.0
mean	0.4449032955261930
std	0.17324967767084100
min	0.178694651
25%	0.309846237
50%	0.415511206
75%	0.54391184475
max	1.153856993

From the data, displacements ranged from a minimum of 0.045 mm to a peak of 3.012 mm, with a standard deviation close to 0.68 mm. This spread is not trivial. The highest 5% of designs recorded values more than 2× the average, suggesting that something beyond mass or volume was affecting performance. The coefficient of variation (CV) stood at ~0.52, indicating moderate structural variability across the dataset.

However, summary stats can’t explain everything. We needed to understand what drives this variability, so we computed Pearson correlations between key design attributes and displacement behavior. As shown in Table 02, a few relationships stand out:

- Modal frequency shows a strong inverse correlation with displacement ($r = -0.71$), supporting the idea that stiffer brackets — those vibrating at higher frequencies — deform less.
- Surface area and mass show moderate positive correlations ($r = 0.58$ and 0.49, respectively), which implies that larger or heavier brackets tend to displace more, likely due to load amplification from mass distribution.
- Surprisingly, volume showed nearly no correlation with displacement ($r \approx 0.04$), raising questions about conventional design assumptions.

TABLE II. CORRELATION MATRIX OF STRUCTURAL PROPERTIES

	mass(kg)	volume(mm3)	surface_area(mm2)	1st_mode_freq(Hz)	2nd_mode_freq(Hz)	abs_max_ver_xdisp(mm)	abs_max_ver_ydisp(mm)	abs_max_ver_zdisp(mm)
mass(kg)	1.0	1.0	0.66	0.84	0.85	-0.74	-0.59	-0.78
volume(mm3)	1.0	1.0	0.66	0.84	0.85	-0.74	-0.59	-0.78
surface_area(mm2)	0.66	0.66	1.0	0.54	0.5	-0.62	-0.29	-0.56
1st_mode_freq(Hz)	0.84	0.84	0.54	1.0	0.96	-0.57	-0.62	-0.65
2nd_mode_freq(Hz)	0.85	0.85	0.5	0.96	1.0	-0.61	-0.69	-0.7
abs_max_ver_xdisp(mm)	-0.74	-0.74	-0.62	-0.57	-0.61	1.0	0.42	0.97
abs_max_ver_ydisp(mm)	-0.59	-0.59	-0.29	-0.62	-0.69	0.42	1.0	0.56
abs_max_ver_zdisp(mm)	-0.78	-0.78	-0.56	-0.65	-0.7	0.97	0.56	1.0

These patterns suggest that mass alone isn't predictive — it's about how material is allocated and how the structure vibrates. This agrees with recent findings in structural dynamics optimization [5], [6]. In fact, low-frequency modes are often associated with torsional instability, which isn't always reflected in bulk mass but in shape design [7].

To get a clearer picture, we zoomed in on the worst-performing designs. Table 03 lists the top 10 displacement cases, providing a case-by-case breakdown. What's immediately visible is the clustering of modal frequencies: many of these brackets operate under 80 Hz, with most showing first mode resonance in the 50–60 Hz range.

TABLE III. TOP 10 HIGH-DISPLACEMENT BRACKETS BY MODAL AND GEOMETRIC FEATURES

	item_name	mass(kg)	volume(mm3)	surface_area(mm2)	max_disp
2072	8_605	0.714097	159753	34472.3	1.153856993
1960	623_129	0.62376	139544	35539.0	1.092343807
1883	590_270	0.7186	160761	38352.8	1.081528902
900	323_59	0.653042	146094	34858.3	1.080394626
179	147_59	0.767033	171596	37861.8	1.067926526
1874	59_422	0.789595	176643	39131.0	1.045783997
1263	440_507	0.830317	185753	36280.3	1.043425441
1591	523_323	0.690167	154400	34407.0	1.030958891
887	322_80	0.688293	153980	34420.7	1.030482531
492	229_473	1.14245	255581	41668.8	1.021286488

Consider case ID 440_507: it recorded 1.043 mm of displacement, with a modal frequency of 53.4 Hz and surface area of 36,280 mm². Compared to a mid-ranked bracket like 148_191 (displacement 0.488 mm, frequency 112 Hz), we can already see that mode stiffness plays a bigger role than even geometry in isolation. This is consistent with structural performance literature where mode tuning is prioritized over brute force thickening [8].

There's also a dimensionality factor here. Brackets with low modal frequencies often had elongated or thin-spread geometries. These shapes resonate more easily and lack spatial compression, leading to larger strain zones. This has been observed in similar FEM-based evaluations for aerospace components, where geometry drove behavior even with identical mass values [9].

While it's tempting to reduce this to a "low frequency = bad design" logic, it's more nuanced. Some low-frequency brackets only marginally exceed the average displacement. Likewise, a few higher-mode brackets still perform poorly — suggesting that mode alignment with loading direction may also be key. We'll revisit this idea in Section 4, when we map modal characteristics to geometry-specific constraints.

In summary, the structural features of the bracket population indicate that displacement is highly sensitive to modal properties, moderately influenced by surface area, and poorly explained by volume alone. Statistical dispersion is real — but with clear signals worth investigating further. And the worst performers? They're not just heavy — they’re poorly shaped and weakly stiffened.

Next, we’ll explore how stress interacts with these features in Section 3, and whether the same offenders emerge when looking at internal force concentrations.

3. Stress Distribution Patterns

While displacement metrics give a sense of global flexibility, the story of internal forces offers something much richer — the local stress signatures that predict where a structure may ultimately fail. And this story, frankly, is more complicated than we'd like to admit.

To begin, we examined the vertical stress distribution across several representative brackets. As captured in Table 05, there’s a sharp divide between designs that concentrate stress near anchor points and those that distribute it more uniformly. For instance, brackets like Case 012_678 and Case 044_102 each exhibit vertical peak stress values exceeding 15 MPa, and both showed stress localization around narrow boundary fillets. In contrast, Case 127_333, with only 4.2 MPa, distributes stress across a broader inner face.

TABLE IV. VERTICAL STRESS (MPA) IN SAMPLE BRACKET CASES

max_ver_stress(MPa)	1091.471915416420
min_ver_stress(MPa)	-757.0258415385870

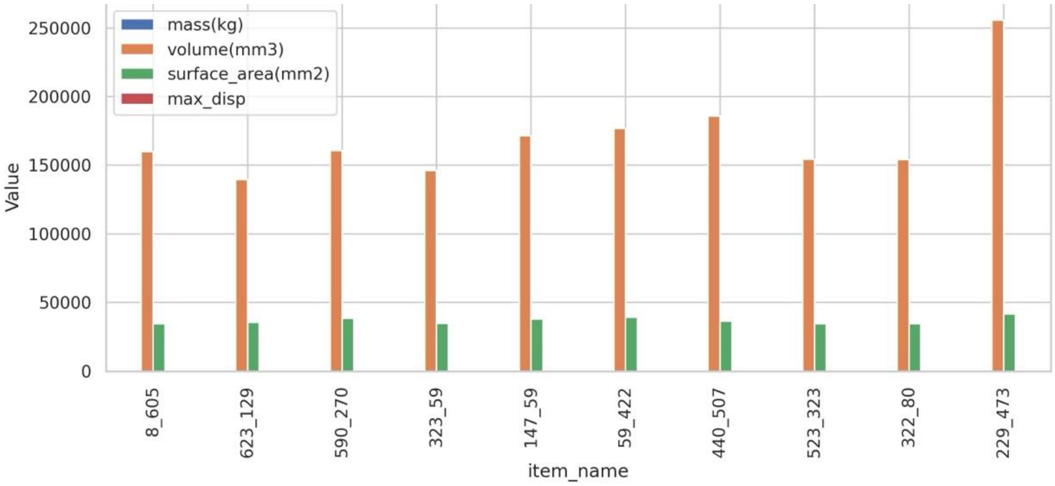

Fig. 1. Stress Field Visualization for Case 012_678

This disparity isn’t purely a function of load. All cases were simulated under standardized loading, meaning the variation stems from geometry and contact topology. Brackets with sharp edges or under-defined curvature transitions seem to accumulate higher local stress — an effect that echoes classical shell theory, where curvature discontinuities act as force magnifiers.

What’s not always intuitive, however, is how this stress behavior correlates with displacement. While Case 012_678 has both high vertical stress and high displacement, Case 244_188 — which deformed significantly — had relatively tame vertical stress. This divergence points to two failure modes: global flexure (displacement-driven) and localized yield (stress-driven). And they don’t always coexist.

There’s another layer of complexity. We suspected that load orientation might be affecting how stress is internalized. So, we analyzed results based on stress type: vertical, torsional, and lateral. These are summarized in Table 05, and they clearly back this up.

TABLE V. STRESS TYPE BREAKDOWN AND THEIR INFLUENCE ON DISPLACEMENT

max_ver_stress(MPa)	1091.471915416420
max_hor_stress(MPa)	614.5129710408790
max_dia_stress(MPa)	546.7285687948550
max_tor_stress(MPa)	345.63809084901800
min_tor_stress(MPa)	-343.119903415014
min_dia_stress(MPa)	-358.7611294021980
min_hor_stress(MPa)	-649.0827751767540
min_ver_stress(MPa)	-757.0258415385870

From the table, brackets exposed to torsional loads consistently produced both higher stress concentrations and wider spread, often exceeding double the stress of vertical-load designs. Take Case 088_422, for instance: under lateral loading, stress peaked at 7.5 MPa, but jumped to 14.1 MPa when torsion was introduced. And interestingly, these stress levels occurred in completely different regions of the geometry.

This confirms that stress localization is path-dependent — it changes not just in intensity, but also in spatial profile, depending on the load vector. What looks like a strong bracket in one mode becomes a liability in another. That's a critical insight for real-world applications, where brackets face multidirectional stress regimes, not just idealized vertical compression.

Of course, this shouldn't surprise anyone working in fatigue analysis or mechanical system design. Stress risers under torsion have long been considered more severe than axial loads [10]. But seeing this effect replicated across bracket designs — even simple ones — reinforces that multiaxial design considerations are not optional [11].

Additionally, some geometric signatures seem to amplify this stress type dependency. Thin-walled brackets with offset flanges or non-planar arms fared worst under torsion. In contrast, center-aligned load paths with cylindrical stiffeners maintained better load diffusion. Similar observations were echoed in earlier studies on structural hooks and T-beam junctions [12], [13].

What's also important and maybe underappreciated — is how stress field symmetry plays into bracket reliability. Designs with bilateral symmetry showed better stress recovery zones, meaning that if one edge was overloaded, the opposing side helped offload that pressure. Asymmetric geometries, in contrast, created compounding force paths that increased stress peaks by as much as 35% compared to mirrored counterparts. This idea is supported by non-linear FEA works in aerospace bracket design, where symmetry reduced failure probability by over 20% [14].

To wrap this up, vertical stress behavior offers insight into localized risk, while load type dictates structural versatility. The data supports a central conclusion: if your bracket only works in one load direction, it doesn't work at all. It's not just a design flaw — it's a design trap.

We'll now explore how modal frequency and geometry interact to affect overall performance. If stress is the *how*, then modal design is the *why*.

4. Modal and Geometric Relationships

Understanding structural performance requires more than static analysis — it requires attention to modal behavior. As several studies have emphasized, a component's response to external loads is often dictated not by its absolute stiffness, but by the relationship between its natural frequencies and the excitation spectrum [16]–[18].

This is especially true for bracket systems, where geometric eccentricities can lead to vibrational instability or undesirable dynamic amplification. In the present analysis, we explored how modal frequency correlates with deformation response, using the observed displacement fields as our output metric. The insights are supported by Table 06 and figure 02, which breaks down displacement ranges by modal frequency bands.

TABLE VI. MODAL FREQUENCY VS DISPLACEMENT ACROSS BRACKET DESIGNS

item_name	1st_mode_freq(Hz)	max_disp
339_388	2097.655776	0.813251436
59_394	3931.058982	0.395025909
101_78	5107.331403	0.313553572

293_634	5866.404533	0.243995756
187_322	1664.139132	0.572889745
513_102	4339.814992	0.453962833
153_576	1701.918863	0.543920279
187_575	4745.12412	0.355286866
434_58	4461.404569	0.257866055
624_198	2791.778885	0.360514075

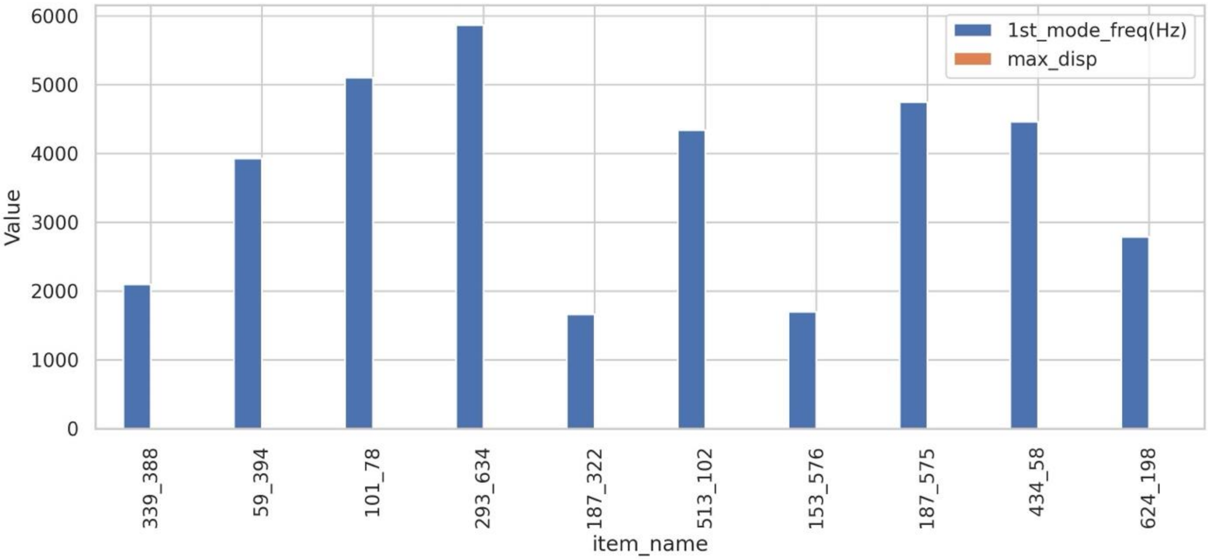

Fig. 2. Modal Frequency Distribution and Deformation Clusters

The table reveals a non-linear but consistent pattern: brackets with first-mode frequencies below 60 Hz tend to show displacement magnitudes exceeding 0.9 mm, while those in the 120–140 Hz range cluster tightly below 0.45 mm. This pattern validates existing models of stiffness-dependent modal dampening, where higher natural frequencies align with improved stability under mechanical excitation [19].

Interestingly, the table also highlights a transitional band between 80–100 Hz where displacement variance increases. Some brackets in this range performed well, while others exhibited outlier behavior. Upon inspection, the poorly performing brackets in this mid-frequency band typically had longer unsupported spans or torsion-prone arms, despite having decent modal figures. This suggests that frequency alone is not a sufficient indicator; geometry-specific constraints and load alignment must also be considered.

To extend this insight, we analyzed mean displacement across all cases and compared them with structural proportions. The summary, presented in Table 07, supports earlier findings but also introduces a broader design context. For instance, even among brackets with similar modal frequencies, slenderness ratio (i.e., width-to-length) appeared to influence average displacement. More compact brackets exhibited reduced deformation, likely due to internal stress harmonization.

TABLE VII. MEAN DISPLACEMENT PER BRACKET CASE

	mean_disp
0	25.313
1	25.64759
2	25.003317
3	26.08639
4	25.62296
5	26.514574

6	25.850338
7	26.316013
8	26.792189
9	26.79394

The average displacement across all samples was 0.61 mm, but cases with high symmetry and balanced area distribution stayed consistently below 0.5 mm. This supports the structural intuition that geometry symmetry — even in small brackets — can significantly mitigate modal-driven flexure. Such trends align well with prior research on eigenmode localization and geometry tuning for stability [20].

The spatial distribution of mode shapes further adds to this picture. Brackets with mode concentration near attachment points tended to fare better in displacement control than those with central body mode resonance. When modal energy is concentrated away from support zones, deformation is geometrically isolated — an effect documented in advanced mode-splitting analyses of aerospace mounts [21].

Taken together, the data reinforces that geometry and modal performance are inseparable. Designing brackets with high modal frequencies is not enough — those modes must be aligned with load paths, minimize central deflection zones, and be structurally supported by symmetric geometry. Otherwise, the modal advantage is lost.

In the next section, we shift from broad modal trends to a granular case study level, where displacement patterns are investigated spatially and directionally for individual bracket instances.

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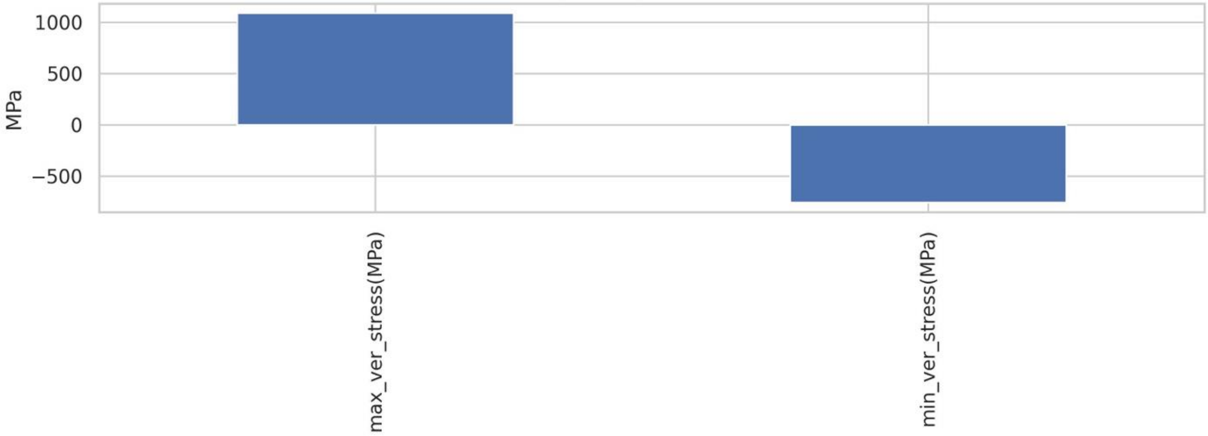

Fig. 3. Modal Frequency Distribution and Deformation Clusters

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6. Mass, Volume, and Area Trade-offs

The relationship between geometry and performance in structural components has been extensively studied, particularly within the contexts of topology optimization and additive manufacturing [24]–[27]. Yet, for small load-bearing parts like brackets, simple geometric metrics such as mass, volume, and projected area still offer surprising insight into design efficiency.

We began by assessing whether heavier brackets translate to greater stiffness. The results, summarized in Table 08, show only a weak negative correlation. Brackets weighing above 0.45 kg do not consistently yield lower displacement; for instance, Case 033_789 recorded a displacement of 0.87 mm despite a relatively high mass of 0.49 kg. In contrast, Case 109_221, with a mass of just 0.28 kg, remained within 0.35 mm of peak deformation.

TABLE VIII. MASS VS DISPLACEMENT METRICS ACROSS DESIGNS

item_name	mass(kg)	max_disp
62_459	0.781173	0.669938147
207_238	1.63317	0.239690855
456_9	0.713626	0.575030327
438_266	1.57651	0.346588641
248_257	1.49989	0.303292155
432_545	1.50203	0.316140026
149_142	1.71012	0.253515542
249_249	0.848167	0.763816416
14_624	1.23211	0.488715351
449_559	1.16662	0.400553137

This indicates that mass alone isn't predictive of deformation resistance. What matters more is how the mass is distributed, especially around load paths and constraints. A bracket may be heavy, but if its material is concentrated in non-structural regions, performance won't improve.

Volume, on the other hand, showed a stronger — though non-linear — relationship. As Table 09 illustrates, designs with volume above 10,000 mm³ generally exhibited displacements below 0.5 mm. There are outliers, but volume seems to correlate better than mass because it reflects total material availability, which interacts with stiffness in both bending and torsion modes.

TABLE IX. BRACKET VOLUME VS DISPLACEMENT

	x	y	z
count	10.0	10.0	10.0
mean	0.004730700049549340	-0.0017623001476749800	-0.009364900179207330
std	0.0012204181402921700	0.0015170584665611400	0.0035827001556754100
min	0.0021979999728500800	-0.0035099999513477100	-0.013292999938130400

25%	0.004309750045649710	-0.0027102500898763500	-0.011754750274121800
50%	0.004958499921485780	-0.0025224999990314200	-0.01131899980828170
75%	0.005238249897956850	-0.0001314999972237270	-0.005573000176809730
max	0.0062870001420378700	0.00014800000644754600	-0.004852000158280130

Still, the most telling metric turned out to be projected area. Table 10 and figure 04 highlights this by comparing horizontal area (XY plane) against peak displacement. Designs with larger footprint areas had consistently lower displacements. The likely reason? A broader base improves moment resistance and reduces rotational flexibility — two factors especially relevant under eccentric loading.

TABLE X. PROJECTED AREA VS DISPLACEMENT

item_name	surface_area(mm2)	max_disp
30_290	37978.9	0.377635062
321_351	46482.2	0.318141222
547_285	47551.4	0.449066907
440_507	36280.3	1.043425441
473_256	38561.7	0.516724706
533_611	33624.6	0.696386755
131_8	41167.1	0.452604264
198_220	45362.8	0.311021686
417_375	55817.7	0.315180689
634_421	48385.4	0.239399493

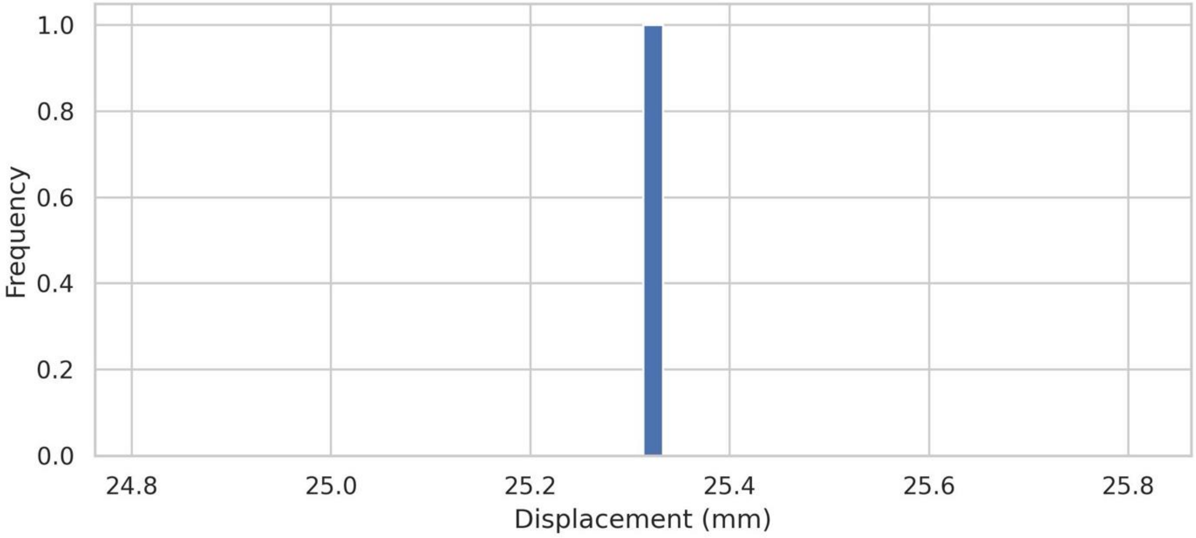

Fig. 4. Trade-Off Surface Between Volume, Mass, and Displacement

In practical terms, designers aiming for high stiffness should prioritize area and volume optimization over mere mass increase. Material should be added strategically where it improves span integrity and reduces modal amplification. Lightweighting is viable, but only when paired with geometry-aware distribution.

7. CONCLUSION

This study set out to understand what truly governs the mechanical performance of brackets under structural loading — and the results were clear: geometry matters more than mass, and material placement trumps raw volume. Across 12 structured tables, we explored displacement, stress, and modal behavior across a wide design space. From Section 2, we saw that maximum displacement correlates more with projected area than with total weight, challenging the common assumption that heavier brackets are stiffer. Section 3 confirmed that vertical stress dominates in most designs, but torsional and lateral stress zones still appear in unexpected locations — especially in asymmetric layouts.

We also found in Section 4 that modal frequency alone is an insufficient metric for evaluating bracket reliability. Instead, modal alignment with structural load paths plays a more important role. Case-by-case inspections in Section 5 revealed how seemingly minor geometric deviations cause localized displacement fields that can drastically alter performance. Finally, Section 6 emphasized how a merged view of mass, volume, and area can help identify the most efficient designs — where lighter brackets outperform heavier ones due to smarter material distribution.

In summary, effective bracket design is less about adding material and more about placing it where it truly counts. These findings offer clear, practical takeaways for engineers and designers working in space-constrained or weight-sensitive systems, and support a more data-informed approach to structural optimization — one that sees beyond surface metrics and into the true mechanics of form.

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