

Impact of Cantilevered Aesthetic Design on Structural Load-Bearing Efficiency: A Comparative Analysis

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Abstract- One of the key forms that architects use to achieve the 'visual lightness', is the cantilevered structure, which is becoming more and more popular in modern architecture. The issue is that each of these design decisions is associated with actual engineering issues concerning the structure's stability. This study examines the effect of the cantilevered design on load-bearing efficiency and compares this to that of a traditional, centrally supported beam. Using a quantitative experimental approach, small physical models were built and put under controlled stress tests based on the AS Level Physics principles of Moments ($\tau = F \times d$) and Equilibrium. The results showed a clear mechanical trade-off. The centrally supported beam could withstand 1.8 kg; the cantilevered one could only handle 0.45 kg, about 75% less. The cantilevered model also started to bend significantly at 20% of the load. These results validate the mathematical trade-offs of a minimalist design, and the need to either increase the material strength or decrease the functional loads on floating forms to compensate for the built-in mechanical weakness.

Index Terms- Bending Moment, Cantilever Beam, Structural Equilibrium, Load-Bearing Efficiency.

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I. Introduction

The balance between appearance and weight bearing capacity has always been a question for architecture and physics. For the past decade or two, modern architecture has been moving even further down the path of minimalism, visual lightness and forms that seemingly defy gravity. A hallmark of high-modernist design is the cantilevered shape: that is, an architectural element that extends horizontally beyond its base, having no structural member to support it from below. The cantilever is commercially popular, and widely admired, as demonstrated in buildings such as Frank Lloyd Wright's Fallingwater house, the CCTV Headquarters in Beijing, and numerous modern residential overhang structures.

The problem is that the attractiveness of a cantilever is based on the physics of beam balance. A beam is a structural element which is subjected to loads acting across its length causing it to bend [1]. If a beam is supported at the middle, the load is distributed among two or more points of contact and the structure finds a stable balance because the counter-moments of these points cancel out. A cantilever beam works very differently. One end is fixed and the other end is free, resulting in all of the force applied at the fixed end where the bending moment and internal stress is concentrated. This is the actual engineering cost of the floating look, and it's the buildup of stress at one point.

The research involves creating small-scale models of a centrally supported beam and a cantilevered beam, using the same materials, and incrementally adding loads to each model in a controlled manner, and calculating the percentage of load bearing efficiency lost when moving from a balanced support to a cantilevered support. It is all based on the ideas of moments, bending stress and equilibrium; and the goal is to deliver a simple, "rule of thumb," numerical explanation of the "beautiful" structural compromises embedded within the aesthetic choices of the cantilevered beam.

Only small uniform models are considered for static vertical load-bearing capacity. Considerations such as wind loading, material fatigue, thermal expansion and dynamic oscillation are very important in actual buildings but not in this specific analysis.

II. Literature Survey

The cantilever beam has been a focus of structural mechanics since Galileo Galilei first addressed the behaviour of a loaded horizontal beam supported at one end in the “Discorsi e Dimostrazioni Matematiche”, [2]. The mathematical model which is still employed to estimate the distance of the bend in a cantilever was developed later, by Daniel Bernoulli and Leonhard Euler, and known as beam theory, which relates bending moment, stiffness of material and curvature. Even today, in the era of computer based methods for analysing beams, the Bernoulli-Euler equation remains fundamental to structural engineering.

Subsequent studies further developed these concepts. Malatkar [4] demonstrated the sensitivity of steady vibration of a cantilever beam to the position of the load with respect to the fixed support and that the sensitivity increases as the load is moved away from the fixed support. This is directly related to the current study, which is loaded at the tip of the cantilever. Malatkar also highlighted the fact that the relationship between deflection and distance of load from the fixed joint is not linear, which further illustrated that sometimes geometry is more significant than the material itself when it comes to the performance of a beam.

Srivastava and Beg [5] performed an in-depth study on element analysis of cantilever beams with point load and compared the theoretical results with the simulation results obtained from SolidWorks FEA software. They indicated differences of less than 20% between the analytical and the simulated values. But more important was that their results validated their hypothesis that the primary factor limiting the load capacity of a cantilever is the stress concentration at the fixed joint.

Fixed-end connection is frequently indicated as the first failure point when dealing with cantilevered slabs and balconies in architectural engineering under both static and dynamic loads [6]. Experimental studies of tapered cantilever beams have revealed that some of this stress concentration can be relieved by increasing the amount of material near the fixed support, since the second moment of area I is increased where the bending moment M is highest, thereby reducing the bending stress $\sigma = MY/I$ at the critical section [7]. It is a technique widely used in the design of cantilevered elements of modern buildings [8].

The influences of curved and reshaped beams have also been investigated in detail. The experimental testing of beams with geometric cutouts, such as the light weight components of aircrafts and buildings, validates that the stress concentration rises the more that the cross sections of a beam are reduced towards the supports [9]. This applies particularly to cantilevered architectural details, which may be tapered or perforated to give the impression of being lighter.

This study provides a first-hand, experimental result of the loss in efficiency when a beam is switched from centrally supported to cantilevered, with the same materials, as opposed to relying on computer simulation alone. Furthermore, it embeds these results within the ongoing debate on architecture and provides a simple mechanical analysis of the structural expense of an aesthetic decision.

III. Problem Definition

The main issue addressed by this research is that there is no simple and experimentally verified number for the load-bearing efficiency difference between a beam supported centrally and a beam supported as a cantilever, with all other factors - material, beam cross-section, and length of the beam - being equal.

The theory of cantilever beams is understood, but the precise percentage loss in performance due solely to the shift of the support is not often explained in teaching or in architectural practice. Cantilevered shapes are often used by architects and designers

because of the visual effect they create, without a sense of a number that represents the structural cost they're willing to pay. Similarly, AS Level Physics students typically encounter moment calculations in a conceptual manner and are not presented with a practical example of how the location of a support can affect actual performance [10].

The question here is: how much extra load bearing capacity and deflection resistance does the cantilevered version lose, given two beams that are identical except for their supports? There are two reasons why answering that is valuable. It is useful for students in understanding the physics of moments and equilibrium and it is a benchmark efficiency factor for designers to consider when making aesthetic structural decisions.

IV. Methodology

I. Experimental Design

This research uses a quantitative experimental approach to compare the structural integrity of two small beam models. The design is based on a controlled comparison, in which all other variables are kept constant except for the support. The two models were constructed from the same materials and therefore the only variable was the support position, which accounts for any variations in performance.

Model A (Control) is a centrally supported beam having one pivot located at the exact centre of the length of the beam. This is a balanced, symmetrical arrangement, where loads applied at each end create equal and opposite moments about the central pivot and keep the beam in balance. Model B (Experimental) is a cantilevered beam, with the support firmly fixed at one end and the other end left free to bend. It is the only form that concentrates stress and acts as a single support in cantilevered architecture.

Both models were made from uniform card paper, strong adhesive (GMSA and UHU), and thin metal rods for reinforcement. One important control was to use the same materials in both. Holding these steady leaves the support position as the only independent variable.

II. Loading Protocol

Using calibrated 50-gram weights, masses were incrementally added to each model. For Model A, the weights were distributed evenly at each end to see how well the beam was balanced on the pivot in the center of the beam. In model B, the masses were only attached at the free end that provides the maximum possible perpendicular distance (d) from the load to the fixed support. The maximum bending moment $\tau = F \times d$ is considered the worst case for a cantilever, when d is the length of the whole beam.

This loading continued until either permanent and visible bending or a failure at the support joint occurred. The load at which each of these first appeared was noted as the threshold for that model. Every trial was done under static conditions on an identical surface, to rule out any other factors.

III. Mathematical Framework

The experiment's analysis relies on three related concepts from classical mechanics:

Moments (Torque): The turning effect of a force is measured by $\tau = F \times d$, where F is the force applied in newtons and d is the perpendicular distance between the line of action of the force and the pivot. In Model B, d is largest because the load is applied at the free tip, so that the fixed support must withstand the maximum clockwise moment, which is done only by the stress within the material.

Equilibrium: A structural member is in static equilibrium when the net force and the net turning effect acting on it are both zero ($\Sigma F = 0$, $\Sigma \tau = 0$). That balance is provided by counter-moments around the central pivot for Model A. In Model B, the fixed

support has to create an equal and opposite reaction moment on its own through the resistance of the material, which is seen to be much tougher, [1].

Bending Stress: The stress at a cross-section of a beam with a bending moment M is $\sigma = MY/I$, where Y is the perpendicular distance between the neutral axis and the outermost fibre of the cross-section, and I is the second moment of area [8]. In a homogenous beam, I is constant throughout the length of the beam, and therefore the stress σ varies directly with the bending moment M . For a cantilever loaded at the tip, the maximum moment M is at the fixed support, where the support will be most likely to fail.

All three of these ideas put together suggest that the bending stress is maximum at the fixed end of a cantilever loaded at the free end, and that it is proportional to the entire length of the beam. The results in Section 5 give experimental backing to these predictions.

V. Results and Discussion

I. Comparative Data

The trials resulted in distinct and significant differences in performance between the two models. Table 1 below summarises the main figures.

Table I: Structural Performance Comparison of Model A (Central Support) and Model B (Cantilever)

Metric	Model A (Central Support)	Model B (Cantilever)	Variance
Maximum Load Capacity (kg)	1.80	0.45	−75%
Deflection Onset (% of max load)	~80%	~20%	−60 percentage points
Support Configuration	Centrally balanced	Single fixed end	N/A
Mechanical Advantage	High (counter-moments)	Low (concentrated stress)	N/A
Failure Mode	Gradual bending	Sudden joint fracture	N/A

II. Analysis of Load-Bearing Capacity

Model A was the centrally supported beam that could support up to 1.80 kg before it began to bend in a manner from which it could never recover. This is an indicator of a well-balanced support. When the loads are applied at both ends, they create clockwise and counterclockwise moments of equal magnitude around the central pivot, satisfying the rotational equilibrium condition $\Sigma\tau = 0$ with fairly low stresses within the structure. The tensile and compressive stresses are spread out through the fibres in the material, and they do not exceed the elastic limit throughout the load range, up to the point of failure.

The cantilevered beam, Model B, completely collapsed at only 0.45 kg—a reduction of about 75% of the load Model A could handle. This is consistent with the prediction from the bending moment equation. The force F in a cantilever is applied at the point farthest from the fixed joint and thus produces a bending moment $M = F \times d$ which must be resisted entirely by internal stress at

the fixed joint. That's because there's no other joint to help share the load and one joint has to take the reactive turning effect. The consequence is a high bending stress ($\sigma = MY/I$) at the fixed end, in which M now represents the total load force acting on the entire beam.

That 75% decrease is not only a variation of the material used here, it is a geometric and mechanical fact. When the support is shifted from the center to one end, the moment arm of the load goes from 0 in the balanced case to the full length of the beam which increases the bending moment at the critical section by a factor related to the ratio of beam length to the original moment arm. The measurable price of the floating aesthetic is this sudden build up of the bending moment.

III. Analysis of Deflection Behaviour

In addition to failure load, the two models also bent in drastically different ways during the process. Model A was able to be loaded to 80% of its load capacity without measurable, non-recoverable deflection, or without leaving the elastic range. That is the balanced distribution of moments provided by a central support that prevents any one cross-section from having to bear too much load until the total load approaches the yield of the material.

Model B began to show signs of sagging at about 20% of its load capacity. The steady increase in bending moment along the beam's length causes this early bending; even small loads are sufficient to cause stress measurable at the fixed joint. The cantilever is constantly in a state of being close to its stress limit for any load that is placed upon it, since the entire beam is an amplifier of the moment for each increment of added load. In practical architectural terms, this means that in a cantilevered structure, the maximum sag or deflection that can be seen by the occupants, and which can cause damage to the finishes, occurs at a much smaller percentage of its designed load than a centrally supported structure.

This directly impacts the safety factors required for a cantilevered design. In the case of cantilevered elements, the early sag and the manner of accumulation of failure risk at one joint indicate that much higher safety factors or stronger, higher-modulus materials such as structural steel or reinforced concrete are required to achieve the same serviceability performance [11].

IV. Architectural Implications

The results will be significant to actual architectural and structural practice. This 75% reduction in load bearing capacity seen here leaves no doubt about the structural price of the cantilevered aesthetic at the scale of one small, uniform beam using one material. This loss is typically controlled in one of three ways in actual buildings. The first is the incorporation of materials that are able to withstand the bending stress much more than normal construction materials, such as high strength materials including structural steel, post tensioned concrete or carbon-fibre composites. The second is to reduce the actual load that a cantilevered space needs to support, by using less dense finishes or restricting usage, or by designing a structure with low mass. The third is to modify the cantilever itself, particularly to taper towards the fixed support, thus collecting more material at the point of maximum bending moment [7].

This failure pattern, a sudden break at the fixed support as opposed to the gradual bending experienced by the Model A, suggests a further significant difference between the two. The centrally supported structures have a tendency to show signs of failure before they collapse, usually by sagging first. Cantilevered structures, particularly those that have fixed joints, can collapse quite suddenly and without much warning. In the real world, that difference is real, in terms of safety of the structure and safety for the people inside.

VI. Conclusion

This investigation proves by physical testing under control conditions that the mathematical price of a cantilevered aesthetic is

indeed significant and measurable reduction in the load bearing efficiency of the structure. If only the support position is altered, the maximum load capacity of a moving from centrally supported to a cantilevered beam is reduced by 75%, while the point at which the serviceability deflection starts moves forward by 60 percentage points. These findings are in accordance with the predictions of classical beam mechanics, namely the equations of moments, equilibrium and bending stress; they are also supporting these principles at the level of small, uniform models.

The practical takeaway is clear. There is an actual and known structural cost to cantilevering to achieve that floating appearance. It can be compensated for by improved materials, clever geometry, or reduced function loads, but it can't be eliminated. This efficiency loss must be taken into account and openly addressed in the calculation and the materials selected by the architects and structural engineers involved in cantilevered structures.

This research is a practical and field-tested example of moments and equilibrium in action for physics and structural engineering students. 75% efficiency loss is not a number on a page, it is the actual outcome of moving the point of a load from zero to the full beam length. This understanding is essential not only to safe design, but also to an appreciation of the need for high performance materials in some of the most impressive examples of contemporary architecture.

VII. Future Scope

This study provides a fundamental quantitative framework of the structural cost of cantilevered design. There are a number of aspects to the topic that warrant further investigation.

Dynamic Load Analysis: Only static vertical loading has been considered in this study. Real architectural cantilevers are also subject to dynamic loads such as wind pressure, seismic activity and the swaying caused by foot traffic on cantilevered floors. Further studies should be conducted to determine the variation in the 75% reduction in efficiency under static loads with dynamic loads, and especially if resonance at the fixed joint accelerates the onset of failure [12].

Material Fatigue and Creep: The long term performance of the fixed joint under constant load was not observed in this scenario. In actual structures, the stress concentrations at the fixed supports cause material fatigue and, in other materials such as timber and some polymers, creep with time. Continued testing of joints through a simulated building life would provide valuable information for cantilever design codes.

Tapered Geometry Optimisation: Theory states that a cantilever can be optimised by increasing the cross-sectional area towards the fixed end, to regain some of the efficiency lost by optimising for a uniform beam, by increasing the value of I in the high moment area. Future experiments should quantify this 75% loss and determine the taper shape that will provide the greatest load capacity per quantity of material.

Scale Effects and Material Variation: Small models were employed in this study with card-paper. Future studies should be conducted on the 75% efficiency ratio at various scales with a range of materials such as timber, steel and reinforced concrete to determine if the material non-linearity and scale effects alter the relationship. This could be done using finite element analysis validated with experimental results at various scales.

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