STRUCTURAL ENGINEERING

Comprehensive Guide to Castellated and Cellular Beam Design: AISC 360-16 and Design Guide 31 Standards

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In the evolving landscape of structural engineering, the drive toward material efficiency and architectural flexibility has led to the widespread adoption of expanded web members, specifically **castellated and cellular beams**. These structural components, often referred to collectively as **expanded beams**, represent a sophisticated method of optimizing steel sections. By taking a standard wide-flange (I-beam) and subjecting it to a strategic longitudinal cut along its web, followed by a re-welding process, engineers can significantly increase the depth and moment of inertia of the member without adding any additional steel weight. This guide provides an in-depth technical analysis of the design, fabrication, and application of these members, primarily focusing on the standards set forth in **AISC Design Guide 31: Castellated and Cellular Beam Design** and the **AISC 360-16 Specification**.

The Evolution and Engineering Philosophy of Expanded Beams

The concept of the castellated beam is not a modern novelty; it dates back to the mid-20th century. However, the publication of **AISC Design Guide 31 (DG31)** marked a pivotal moment in the standardization of their design. Historically, the design of these beams was governed by proprietary methods or older ASD (Allowable Stress Design) 9th Edition principles. With the advent of more complex computational modeling and the need for unified standards, DG31 provided a rigorous framework based on **Limit State Design**, adhering to the **2016 AISC Specification for Structural Steel Buildings**.

The fundamental philosophy behind expanding a beam's web is **structural optimization**. In a standard I-section, the material at the neutral axis contributes minimally to the moment-carrying capacity. By "splitting" the web and rejoining it to create a deeper section, the material is moved further from the neutral axis, exponentially increasing the section modulus (S) and the moment of inertia (I). This allows for longer spans and reduced deflections, which are critical in modern commercial office spaces and parking structures.

Defining Castellated vs. Cellular Profiles

While both member types follow similar fabrication principles, their geometric profiles differ significantly, impacting both aesthetics and structural performance:

- Castellated Beams: These are characterized by a series of hexagonal openings. The fabrication involves a "zig-zag" cut along the web. When the two halves are shifted and welded together, the resulting member has a deeper web with a sequence of hexagonal holes.
- Cellular Beams: These feature circular openings. The cut is typically a series of semi-circles. Cellular beams are often preferred for their aesthetic appeal and are increasingly used in exposed structural steelwork (AESS). From a structural standpoint, the circular opening provides a different stress distribution compared to the corners of a hexagon.

Technical Analysis of the Fabrication Process

The fabrication of a castellated or cellular beam is a precision-driven process that dictates the final structural properties of the member. The process follows these specific steps:

1. Profile Selection: A standard hot-rolled wide-flange section (the "root" beam) is selected based on the

required final depth and load capacity.

2. Web Cutting: A computer-controlled plasma or oxy-fuel torch cuts a continuous pattern along the length of the web. For castellated beams, this is a trapezoidal/zigzag pattern; for cellular beams, it is a series of circular arcs.
3. Shifting and Re-alignment: The two resulting halves (the "tees") are separated. One half is shifted longitudinally relative to the other.
4. Welding: The peaks of the two halves are aligned and welded together. This process typically uses Submerged Arc Welding (SAW) or Flux-Cored Arc Welding (FCAW) to ensure full penetration at the web post joints.

The resulting beam is typically **40% to 60% deeper** than the original root beam. The distance of the shift determines the "expansion ratio," which must be carefully calculated to balance the increased stiffness against potential local buckling of the web posts.

Structural Mechanics and Limit States

Designing expanded beams is significantly more complex than designing prismatic wide-flange beams. Because the web is no longer continuous, several unique **limit states** must be evaluated to ensure safety and serviceability. According to **AISC 360-16** and **Design Guide 31**, the following mechanisms are critical:

1. Vierendeel Bending

In a solid-web beam, shear is primarily carried by the web. In an expanded beam, the presence of the opening forces the shear to be transferred through the upper and lower "tees." This creates a local bending moment within the tees, known as **Vierendeel bending**. This is often the governing limit state for beams with large openings. The interaction between the local Vierendeel moment and the global bending moment must be checked at each opening.

2. Web-Post Buckling

The "web post" is the solid portion of the web between two openings. This post is subjected to intense horizontal shear and vertical compression. If the post is too slender or the openings are too large, the post may buckle out-of-plane or fail in shear. **Design Guide 31** provides specific formulas for calculating the critical buckling strength of these posts, often requiring the use of empirical factors derived from finite element analysis (FEA).

3. Vertical Shear and Horizontal Shear

The vertical shear capacity is limited by the sum of the shear capacities of the top and bottom tees at the opening. Additionally, the horizontal weld that joins the two halves must be capable of transferring the total horizontal shear required to maintain composite or non-composite action. Weld rupture is a catastrophic failure mode that must be prevented through rigorous design of the throat thickness.

4. Lateral-Torsional Buckling (LTB)

Because expanded beams are deeper and often have narrower flanges relative to their depth than standard sections, they are more susceptible to **Lateral-Torsional Buckling**. The LTB equations in AISC 360 Chapter F must be adjusted to account for the reduced torsional constant (J) and the varying moment of inertia along the beam's length.

Comparison of Structural Members

To understand why a designer would choose a castellated or cellular beam over a standard wide-flange or a open-web steel joist, consider the following technical comparison matrix:

Feature	Standard Wide-Flange (W-Shape)	Castellated / Cellular Beam	Open-Web Steel Joist (OWSJ)
Depth-to-Weight Ratio	Moderate	High (Optimized)	Very High
Vibration Performance	Excellent	Good (Stiffness helps)	Requires Careful Analysis
MEP Integration	Poor (Requires drilling/ cutting)	Excellent (Pre-existing holes)	Excellent (Open webs)
Aesthetics (AESS)	Industrial / Standard	Highly Architectural	Utility / Industrial
Fabrication Cost	Low	Moderate (Cutting/Welding)	High (Labor intensive)

Design Procedure per AISC 360-16 and DG31

The following step-by-step procedure outlines the typical technical workflow for an engineer designing an expanded beam:

Step 1: Preliminary Section Sizing

The engineer begins by selecting a root beam and a target depth. A common rule of thumb is a depth increase of 1.5 times the original. For example, a **W18x35**might be expanded into a 27-inch deep castellated beam. This preliminary sizing is based on the required span and estimated moment capacity.

Step 2: Geometry Definition

The geometry of the cut must be defined. Key parameters include:

- e: The length of the solid web post.
- a_o: The width of the opening.
- h_{open}: The height of the opening.
- $=RC The angle of the cut (typically 45 to 60 degrees for hexagonal castellations).

Step 3: Moment and Shear Evaluation

The global bending moment (M_u) and vertical shear (V_u) are calculated using standard structural analysis. However, these forces must be checked against the **net section** at the openings and the **gross section**at the web posts.

Step 4: Vierendeel Interaction Check

A critical check involves the interaction equation for Vierendeel bending. The designer must ensure that the combined effect of global moment and local tee bending does not exceed the yield strength of the steel:

Interaction Ratio "H (M_u / =TÕöâ' ² …e÷U÷FVR ¢ R ò ÕM_n_tee) "d 1.0

Step 5: Web Post Buckling and Stability

Using the guidance in **Design Guide 31 Section 3.3**, the stability of the web post is evaluated. If the post is too narrow, it may require reinforcing plates, though this is often avoided by adjusting the initial cut geometry to maintain economic efficiency.

Step 6: Serviceability (Deflection and Vibration)

Expanded beams are often used in long-span applications where deflection ($L/360$ or $L/240$) and floor vibrations are the governing factors. The **moment of inertia**used for deflection calculations is typically an effective moment of inertia (I_{eff}), which accounts for the flexibility introduced by the openings.

Practical Implementation and Economic Benefits

The primary economic driver for using castellated and cellular beams is the **reduction in building height** and **material savings**. In multi-story commercial buildings, the ability to pass mechanical, electrical, and plumbing (MEP) services through the beam openings—rather than beneath them—can reduce the floor-to-floor height by 8 to 12 inches per level. In a 20-story building, this can result in a total height reduction of nearly 20 feet, leading to massive savings in facade costs, elevator cabling, and HVAC ducting.

Integration with Composite Construction

Expanded beams are exceptionally efficient when used in **composite construction**. By welding shear studs to the top flange and pouring a concrete slab, the top tee of the expanded beam is braced against buckling, and the neutral axis shifts upward. This further enhances the moment capacity and stiffness of the system. **AISC 360-16** provides the framework for calculating the effective width of the concrete slab and the resulting composite section properties.

Case Study: Challenges and Troubleshooting

Despite their advantages, expanded beams present unique challenges that require careful engineering oversight. Below are common issues and their solutions:

Problem 1: Excessive Deflection in Asymmetric Sections

Cause: When different root beams are used for the top and bottom halves (to create an asymmetric section for composite design), the different stiffnesses can cause unusual deflection profiles.**Solution:** Use specialized software validated against **AISC DG31** to model the asymmetry and ensure accurate cambering during fabrication.

Problem 2: Web Post Weld Failure

Cause: Inadequate weld penetration or poor weld quality at the junction of the two tees can lead to shearing of the posts under heavy loads.**Solution:** Implement strict **Quality Assurance (QA)** and **Non-Destructive Testing (NDT)**, such as ultrasonic testing, on the web post welds. Ensure the weld throat thickness exceeds the required horizontal shear capacity.

Problem 3: Concentrated Load Crippling

Cause: Placing a heavy point load (such as a column or a large equipment mount) directly over an opening can cause local web crippling.**Solution:** Always align concentrated loads over **solid web posts**or provide vertical stiffeners to transfer the load directly to the flanges.

Future Outlook and Summary

The future of castellated and cellular beam design lies in the integration of **Automated Optimization Algorithms** and **Robotic Fabrication**. Modern structural software now allows engineers to run thousands of iterations to find the exact cut geometry that minimizes weight while meeting all limit states of **AISC 360-16**. Furthermore, the use of cellular beams is expanding into the realm of **long-span roof structures**for stadiums and airports, where their aesthetic lightness and high strength-to-weight ratio are unmatched.

In conclusion, the design of castellated and cellular beams is a sophisticated exercise in structural efficiency. By leveraging the principles found in **AISC Design Guide 31**, engineers can deliver projects that are not only economically superior but also architecturally striking. Understanding the nuances of Vierendeel bending, web post stability, and composite action is essential for any modern structural engineer looking to push the boundaries of steel construction. As sustainability and material reduction become central to the global building code, the role of expanded web members will only continue to grow in importance across the structural engineering profession.

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