

Chapter I

Introduction and Literature Review

1.1 Introduction

The primary advantage of castellated beams is the improved strength due to the increased depth of the section without any additional weight. However one consequence of the increased depth of the section is the development of stability problems during erection. To fully utilize the engineering advantage of castellated beams, erection stability must be considered.

Engineers are constantly trying to improve the materials and practices of design and construction. One such improvement occurred in the mid-1930's. An engineer working in Argentina, Geoffrey Murray Boyd, invented what was then called the Boyd beam (Knowles 1991). This name was later changed to castellated beam. The original patent described the invention as "...a specification related to improvements in built-up structural members, of the kind comprising two parts with pairs of projections extending towards one another and welded along a line of sinuous or toothed nature" (Knowles 1991). In simpler terms, castellated beams are created by cutting a saw tooth pattern in the web of a rolled "I" section the length of the span. Then the tips of the long cuts are welded together joining the two pieces, as illustrated in Figure 1.1. The name castellated comes from the appearance of the beam and its similarities with castle battlements.

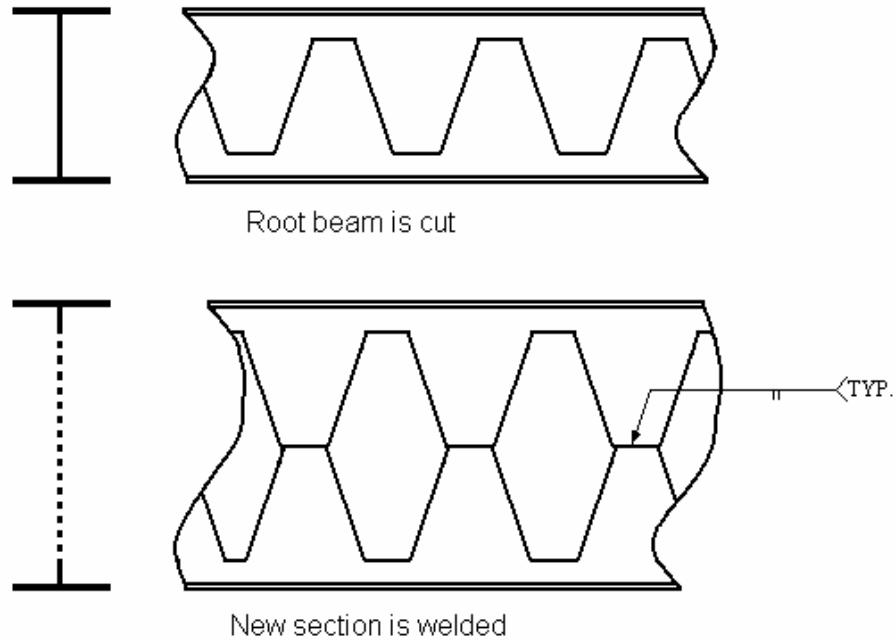


Figure 1.1 Fabrication Process of a Castellated beam

The primary advantage of this new section is the increased depth of the beam without increasing its weight. In some instances, the depth is increased as much as 50%. By increasing the depth of the beam, strong axis bending strength and stiffness are improved as the strong axis moment of inertia, I_x , and section modulus, S_x , are increased. Further, the castellations or holes also allow HVAC ductwork, plumbing pipelines, and electrical conduits to pass through them ultimately reducing the thickness of the floor assembly.

The advantages of castellated beams far outweigh the disadvantages. However, one disadvantage is the increased fabrication costs associated with the cutting and welding of the section. The Litzka Process has minimized this problem. Litzka Stahlbau of Germany devised a process and machinery that minimize the time consuming process of fabricating castellated beams.

Due to the unique mechanics of castellated beams, the design engineer must consider the holes and analyze the section accordingly. Since the invention of the castellated beam, materials and design methods have improved. With these improvements, castellated beams are being pushed to span much greater lengths, thus creating a demand for better understanding of castellated beams and how they react in the field. With the increase in span length, stability issues during erection have presented themselves and need to be examined. During erection the bracing that allows the castellated beam to reach its design strength is not present.

1.2 Scope of Research

The purpose of this research is to examine stability problems during the stage of construction when the permanent bracing that provides most of the stability to the castellated beam is not present. This stage of construction is present at the time of erection. Various solutions are evaluated to determine the critical unbraced length of the castellated beam during erection. The cross-sectional properties are adjusted to better model the contributions of the components of the castellated beam. The effective length factors are adjusted to account for the contribution of the connection on the stability of the castellated beam. Finally, laboratory testing was conducted to validate the use of and confirm the accuracy of the final procedure, variables, and cross-sectional properties proposed.

1.3 Terminology

Throughout this paper various terms will be used to discuss castellated beam components and testing results. This section introduces the reader to the definition of these terms and Figure 1.2 illustrates the terms.

- *Web Post*: The cross-section of the castellated beam where the section is assumed to be a solid cross-section.
- *Castellation*: The area of the castellated beam where the web has been expanded (hole).
- *Throat Width*: The length of the horizontal cut on the root beam. The length of the portion of the web that is included with the flanges.
- *Throat Depth*: The height of the portion of the web that connects to the flanges to form the tee section.
- *Expansion Percentage*: The percentage change in depth of the section from the root (original) beam to the fabricated castellated section.

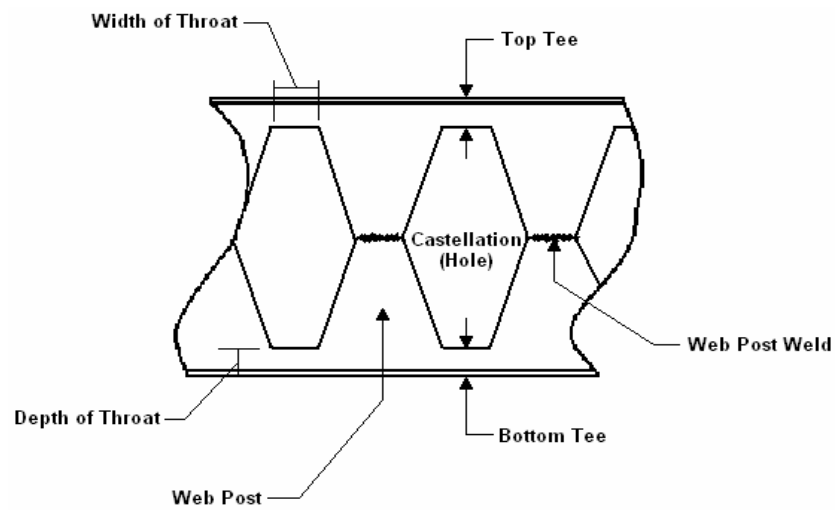


Figure 1.2 Components of a Castellated Beam

1.4 Literature Review

1.4.1 Castellated Beams

With the invention of castellated beams came the need to simplify and quicken the fabrication process. Boyer (1964) reviewed the Litzka process. Litzka Stahlbau of Germany developed this fabrication method to help make castellated beams more economical and increase their use. Boyer also selected several sections and compared them with their hot-rolled equivalent and found that the economic savings ranged from 11% to 22%. Not only are there economical advantages to castellated beams, but there are also performance advantages. Toprac, Altfillisch, and Cooke (1957) found that by expanding the shape of the rolled section the beam could carry 10% to 35% more moment.

Early methods of analysis of castellated beams neglected the web and tension flange in the calculation of section properties. This approach analyzes the compression flange as a strut. Kerdal and Nethercot (1982) found this to be too conservative and stated that the section properties should be calculated at the middle of a castellation or hole. This better represents the “real-life” response of the beam. They also found that if the cross-sectional properties are calculated in this manner, equations that predict the behavior of hot-rolled sections can be used for castellated beams for design.

With castellated beams being analyzed in this manner, the importance of the hole geometry becomes more relevant. Hosain and Speirs (1973) and Kerdal and Nethercot (1983) extensively studied the effects of hole geometry on the strength and failure modes of castellated beams. Hosain and Speirs found that

narrowing the throat width greatly improves the performance and produces a more optimal design. They also found that by shortening the web post weld, the castellated beam acts more like a solid rolled section. This is due to the susceptibility of castellated beams to secondary bending effects and what the authors refer to as reserve strength.

Kerdal and Nethercot (1983) stated that castellated beams should be designed as structures in themselves. They found that the only way to correctly analyze and fully understand castellated beams is to look at each component individually (See Figure 1.2). When this is done the beam will then be able to function properly and reach its intended design strength. Pattanayak and Chesson (1974) stated that too many idealizations are used to correctly analyze castellated beams. These idealizations cause all current methods for design to be overly conservative.

Kerdal and Nethercot (1984) determined that there are six failure modes for castellated beams;

1. Formation of a Vierendeel mechanism
2. Lateral-torsional buckling of the web post
3. Rupture of the welded joint
4. Lateral-torsional buckling of the entire span
5. Web post buckling
6. Formation of a flexure mechanism.

Kerdal and Nethercot (1984) conducted a series of ultimate strength tests and found that lateral buckling occurred in all the tests. The characterization of failure in the test specimens usually involved a combination of any of the six failure modes. The only way to evaluate the failure modes other than lateral buckling

was to provide adequate lateral bracing. The authors also found that the lateral bracing was required for the beams to reach their full strength.

There is not a prescribed design method for castellated beams and many engineers have tried to develop processes to help aid the use of castellated beams. Boyer (1964) used the Vierendeel truss analogy to develop some design tables that could be used for castellated beams. The Vierendeel truss analogy analyzes the castellated beam as if its geometry is comprised of components of a Veirendeel truss (See Figure 1.3). Kerdal and Nethercot (1983) found that being overly conservative was the price to pay for the tedious and complex nature of the design of castellated beams. They found that most applicable codes were as much as 40% conservative. The authors also stated that the then current practice of using design rules that govern beams with large holes is unacceptable however generally adopted.

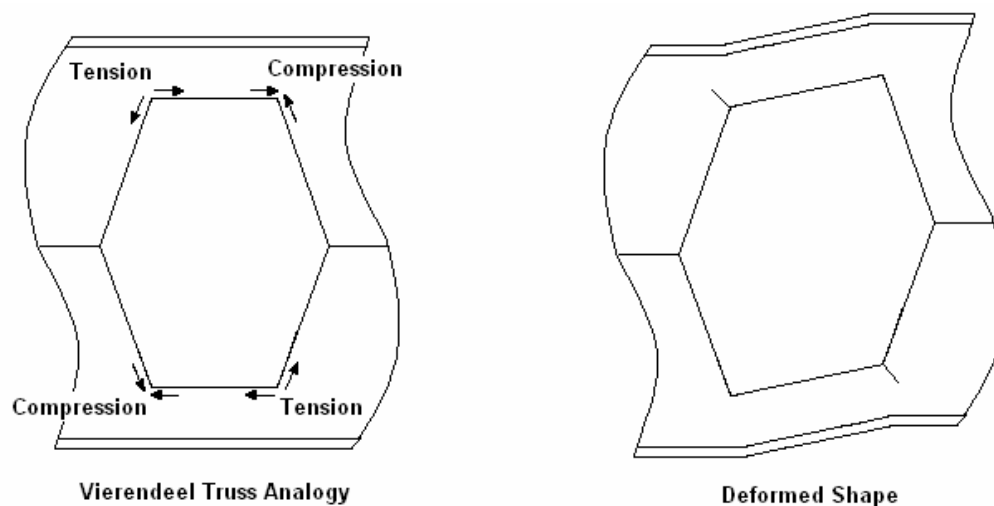


Figure 1.3 Vierendeel Truss Analogy

Hosain and Speirs (1973) analyzed castellated beams using plastic methods and found that this produced more realistic factors of safety than elastic methods. They found that the plastic method better utilized the reserve strength in the beam. Halleux (1967) used two methods for determining the strength of castellated beams. The first was a “static” approach, which produces a lower bound. In this approach the stress fields are examined in the member. Next a “kinematic” approach was considered, which produces more accurate but higher bounds by examining the performance of the beam using work principles.

Pattanayak and Chesson (1974) found that a minimum potential energy method of analysis is best. They found this form of analysis yields better results with fewer assumptions and produces equations that can be used in practice. The authors stated that using the energy approach best models the lateral instabilities associated with castellated beams.

Jackson (2002) examined the vibration and flexural strength of composite castellated beams. He found that the measured non-composite stiffness characteristics were closer to those associated with the gross cross-sectional properties for deep beams and net cross-sectional properties for shallower beams and the net properties should be used for calculating flexural strength. He also found that procedures in AISC Design Guide Series 11, by Murray, Allen, and Ungar (1997), for determining natural frequency in rolled sections could be used for composite castellated beams.

1.4.2 Stability and Lateral-Torsional Buckling

Clark and Hill (1960) compiled background research and information that is associated with beams and girders whose design is limited and controlled by lateral buckling. The authors reviewed elastic buckling equations and various coefficients that are present in those equations. Specifically, the authors examined the C_1 (also known as C_b), C_2 , and C_3 coefficients. The values of these coefficients are dependent on the boundary conditions and loading of the beam. The authors present a table with values of C_1 , C_2 , and C_3 for various end restraints and loading conditions. Also included in the paper is a collection and presentation of lateral buckling test data that had previously not been published.

Chen and Lui (1987) stated the importance of understanding lateral stability: "...if sufficient lateral bracing is not provided to the compression flange, out of plane bending and twisting of the cross section will occur when the applied loads reach a certain limit." This limit is referred to as the critical lateral-torsional buckling load. Chen and Lui also reviewed the importance of the location of the application of the load on beam stability (See Figure 1.4). In cases where the load is applied to the top flange of the beam, "...that force has a destabilizing effect, since it enhances the rotation of the cross section from its original deflected position.

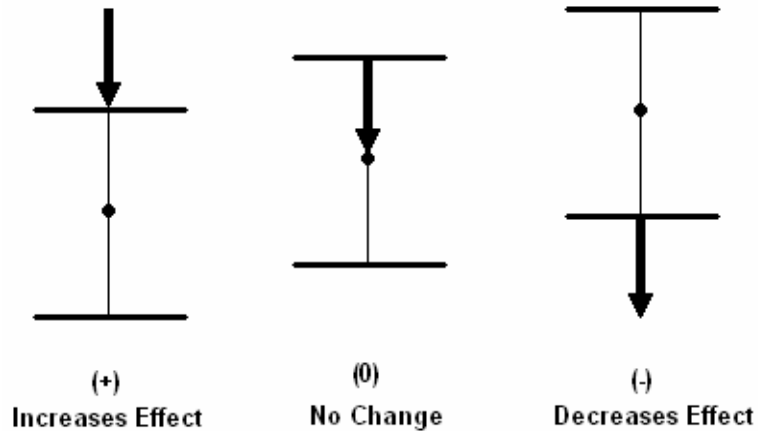


Figure 1.4 Location of Load Application

Galambos (1993) examined the bracing requirements of steel joists and light trusses during various stages of construction and service loading. He stated that like beams, joists are laterally stable once they are in their final service state and that special consideration should be paid to these members during construction and handling. Galambos explained the background of the Steel Joist Institute Specification (SJI 1994) for bridging and lateral bracing. He emphasized the importance for the structural engineer to understand the construction process associated with the design, and more specifically, the need to understand the stability of the member under self weight and weight of an erector. The SJI provision for determining the critical length was presented and Galambos reviewed the background of the derivation of this formula.

Salmon and Johnson (1996) explain that it is not possible for beams to attain perfect loading and there is a need to understand the lateral stability considerations of the beams being designed. This is due to the fact that no beam is “perfect”. The imperfections that are part of every beam cause the beam’s

reaction to load to be different than what is assumed in simplified analysis. The authors also derived the classical elastic lateral-torsional buckling solution.

In *Guide to Stability Design Criteria for Metal Structures*, Galambos (1998) stated that during construction steel beams are more likely to fail by lateral-torsional buckling because “braces are either absent or different in type from the permanent ones.” He defined lateral-torsional buckling as the limit state where the beam no longer only deflects in plane, but begins to deflect laterally and twists. During the development of lateral-torsional buckling, the load carrying capacity of the beam initially remains the same and then drastically reduces due to excessive deformations and material yielding. Galambos cited the following variables as the foundation of lateral torsional buckling:

- Type and position of loads
- Restraints at the ends and at intermediate locations
- Type of cross-section
- Continuity at supports
- Presence or absence of stiffeners at critical warping locations
- Material properties
- Magnitude and distribution of residual stresses
- Initial imperfections and loading
- Discontinuities of the cross-section (coping or holes)
- Interaction of local and overall buckling

Galambos also pointed out that elastic buckling is critical for long beams and particularly important during construction. Galambos compared the previous methods with the new method for calculating C_b and examined the effect of the location of load application on the stability of the beam.

There has been an extensive amount of research done on castellated beams and lateral-torsional buckling of beams. Past researchers have focused on service loading and composite construction of castellated beams. However the reaction of the castellated section during erection has not been examined.

1.5 Need for Research

The service strength of castellated beams is not the issue of this research. The ability of the castellated member to support its own weight and the weight of an erector until the continuous bracing of the floor deck is in place is the aspect under consideration. This is primarily a construction and constructability issue. Therefore various methods for modeling this unique situation are examined to better determine the number of and the required spacing of temporary bracing to ensure safety during construction.

1.6 Overview

An evaluation of existing provisions for determining the critical unbraced length of castellated beams is covered in Chapter II. The parameters of the formulation that is being evaluated are discussed. The reasoning behind the choices of modeling and evaluation processes used is also covered. This includes loading assumptions, end restraints, and construction issues. The cross-sectional properties are then assessed to explore the “real life” response of castellated beams.

The specimens used in the test verification are described in Chapter III. The test set-up and procedure used in testing the specimens are also reviewed. Included in this chapter are the loading, bracing, and connection details that are unique to this set-up.

The discussion and explanation of the results of the verification tests are covered in Chapter IV. These results are then compared to those of the lateral-torsional buckling solutions. Then the methods are compared to determine a viable method for estimating the stability of castellated beams.

A summary and the conclusions of this study are presented in Chapter V. Lastly, future areas of research are proposed. Supporting data is located in appendices.

1.7 Section Designation

The section designation description used by SMI Products, who supplied the test specimens, is illustrated in Figure 1.5. Section geometry and critical dimensions are identified in Figure 1.6. Two sections, CB24x26 and CB27x40, were used in the analytical evaluation and the experimental verification parts of this study.

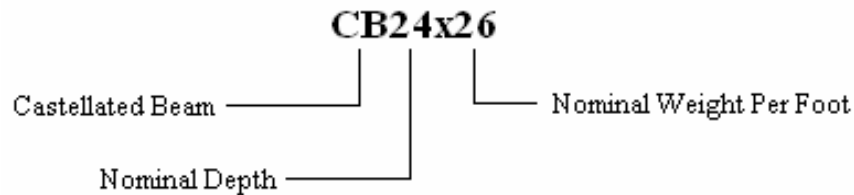


Figure 1.5 SMI Catalog Designation

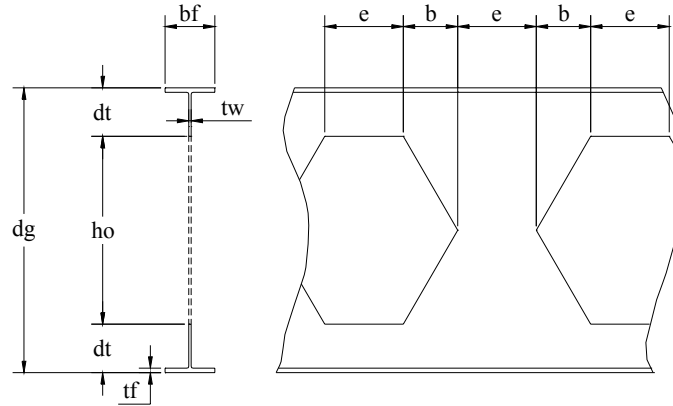


Figure 1.6 Critical Dimensions

The CB24x26 castellated beam section is fabricated from a W16x26 hot-rolled section. The nominal depth of a CB24x26 is 24 in., the weight per linear foot is 26 lb, and the expansion percentage is 32.8%. The measured dimensions of the CB24x26 section used in the testing are given in Table 1.1. These measured dimensions were used in all critical unbraced length evaluations.

Table 1.1 Measured Dimension of Specimen CB24x26

CB24x26 SECTION PROPERTY	MEASURED DIMENSION SIZE [in.]
e	6.250
b	4.500
h _o	15.188
t _f	0.344
b _f	5.603
t _w	0.251
d _g	23.375
d _t	4.125

The CB27x40 castellated beam section is cut from a W18x40 hot-rolled section. The nominal depth of this section is 27 in., the weight per linear foot is

40 lb, and the expansion percentage is 34.4%. The measured dimensions of the CB27x40 section are given in Table 1.2. These measured dimensions were used in all critical unbraced length evaluations.

Table 1.2 Measured Dimensions of Specimen CB27x40

CB27x40 SECTION PROPERTY	MEASURED DIMENSION SIZE [in.]
e	7.500
b	6.000
h_o	18.500
t_f	0.524
b_f	6.063
t_w	0.320
d_g	26.875
d_t	4.188