

# Castellated Beams—New Developments

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"CASTELLATED BEAM" is a name commonly used for a type of expanded beam. It is made by expanding a standard rolled shape in a manner which creates a regular pattern of holes in the web. The name is derived from this pattern of web holes, because castellated means "built like a castle, having battlements, or regular holes in the walls, like a castle".

Fig. 1 illustrates a castellated beam. It is made by separating a standard rolled shape into two halves by cutting the web in a regular alternating pattern as shown. The halves are rejoined by welding, after offsetting one portion so that the high points of the web pattern come into contact. Some design conditions make it advantageous to increase the depth even more. This is done by adding web plates between high points of the tee sections. These added plates are called "increment plates".

## BACKGROUND

Castellated beams have had occasional usage in this country for many years, during which time they were produced by simple hand procedures. Though these fabrication methods were not conducive to broad development, castellated beams have long been recognized as advantageous structural members. The pattern of holes in the web presents an attractive appearance for beams exposed to view. The web holes are becoming ever more functional with the increase of piping, conduits and ductwork in modern construction. The greatest advantage, however, is the economy effected by the increased load carrying capacity and stiffness.

In developing this structural member, the Mississippi Valley Structural Steel Co. carried on an extensive program of design investigation, production studies and economic comparisons. European production methods and product applications were reviewed, because on that continent castellated beams have been used extensively for many years. This development took place in

Europe because of the limited number of sections available from European mills and because of the high ratio of material cost to labor cost.

The investigation was primarily directed toward the Litzka process and equipment which was developed by Litzka Stahlbau of Bavaria, Germany. Study and evaluation of this process led to the conclusion that it is particularly adaptable to large volume production and automatic methods; therefore the equipment and the rights for its use were acquired. The component items of Litzka equipment were imported and are now in operation at the company's Decatur, Ill., plant.

The development of efficient production processes has opened a broad new field of economical applications of castellated beams. In the last few years such members have been used as various types of structural elements in many different kinds of buildings.

## ASSUMPTIONS FOR ANALYSIS

Castellated beams generally are used as flexural members. However, due to the nature of the section, a beam size cannot be selected solely on the basis of the usual simple procedure of applying the flexure formula to the total beam bending moment. A castellated beam

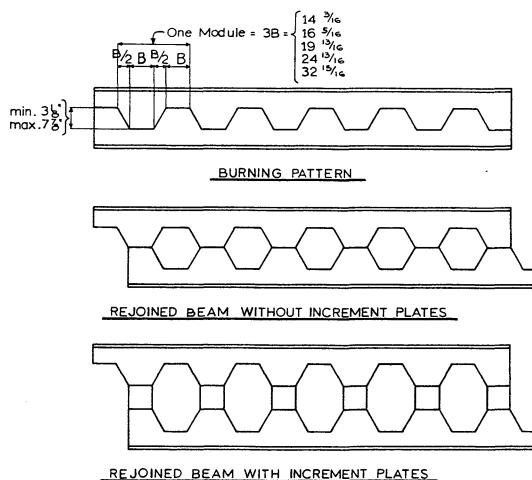


Fig. 1. Castellated beams

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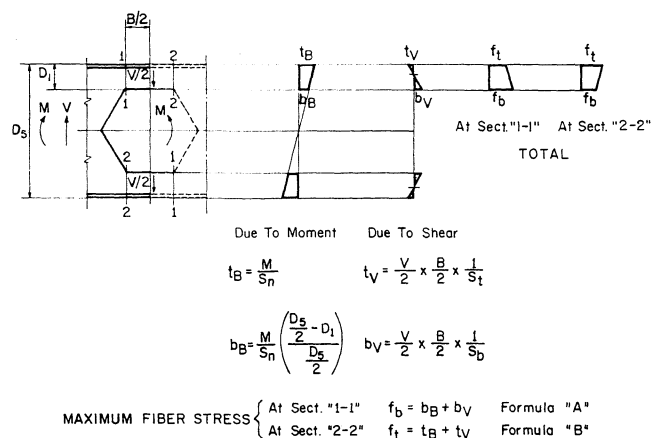


Fig. 2. Fiber stresses

performs like, and may be analyzed as, a Vierendeel truss. In such a member the longitudinal fiber stresses, which govern the beam section used, are influenced both by beam bending moment and vertical shear.

The basic design of a castellated beam consists of analyzing the effect of the forces and calculating the stresses illustrated in Fig. 2. Maximum longitudinal fiber stresses occur in the tee section. These stresses may be readily computed on the basis of the following assumptions which are well verified:

1. Vertical shear divides equally between the upper and lower tees.
2. For bending in the tees due to shear, there are points of contraflexure at the vertical centerline through each opening.
3. Fiber stresses distribute as illustrated and can be computed by the formulas shown.

As illustrated in the stress distribution diagrams in Fig. 2, maximum longitudinal fiber stresses can occur at the inner edge of the tee web,  $f_b$ , or at the back of the tee,  $f_t$ . Maximum  $f_b$  would occur at Section 1-1 and be computed by Formula A. Maximum  $f_t$  would occur at Section 2-2 and be computed by Formula B. A castellated beam section is most efficiently used when  $f_t$  is the governing stress. However this is not always possible, particularly on short spans.

There is an element which adds considerable work to the design of castellated beams. That is, the location of the maximum fiber stress is unknown; it can occur at any point along the length of the beam. Fiber stress  $f_b$  will be at its optimum in areas of higher shear; fiber stress  $f_t$  will be at its optimum in areas of high moment. On simple span beams carrying uniform load, the location of maximum fiber stress can be at any point between the end of the beam (high shear) and mid-span (high moment).

## DEVELOPMENT OF BEAM LOAD TABLES

It is conceivable that a formula could be established to solve directly for the critical stress of a castellated beam section; however, such a formula would be exceedingly complex. The most practical method for designing a castellated beam is to start with a specific beam section and compute its capacity. That simple statement, however, covers quite a sizeable amount of calculating, since it is necessary to compute many different stress conditions for each beam. Because of this, it was decided by Mississippi Valley to devise a series of efficient castellated beam sections and to calculate and publish their load capacities for various spans. This has resulted in the publication *Design Data for Castellated Beams*.<sup>1</sup>

In making design calculations for the castellated beam load tables, the capacities of about 500 different beams were computed for some 20 span lengths. Since this involved determining the fiber stress at many points along each beam, about 500,000 stress calculations were required and a computer program was obviously a real benefit.

To calculate the beam capacities, a simple span beam was considered carrying a unit uniform load. The computer program determined stresses at each of 100 points along the length of the beam and selected the maximum stress and its location. From this maximum stress for unit load, the beam capacity for any particular allowable stress was readily calculated. In addition to computing the longitudinal fiber stresses, shear stresses and deflections were also determined. These analyses were made for each beam section on each span considered.

The load tables give precise data for the selection of castellated beams over a wide range of uniform load conditions on simple spans. The load tables may also be used to select castellated beams for certain special concentrated load conditions.

## DESIGN CRITERIA AND PROCEDURES

There are conditions, however, which will require the designer to compute the stresses and capacity of a castellated beam. This may be required for irregular concentrated loads, for cantilever beams, or when there are special web holes. Under such special conditions the designer should select a trial castellated beam section by judgment and use of the load tables, and then compute its stresses using Formulas A and B.

The maximum longitudinal fiber stress generally governs the selection of a beam section, but there are other stress conditions which must be examined and controlled. These are lateral buckling, local buckling, web buckling and web bending and shear stresses.

1. Design Data for Castellated Beams, Mississippi Valley Structural Steel Co., 111 West Washington St., Chicago 2, Ill.

Lateral torsional buckling should be investigated for the limitations imposed by AISC Specification Section 1.5.1.4.5. As with any beam, the fiber stress must be kept within these limitations, either by the choice of section or by compression flange bracing. Of course, if the compression flange is continuously supported laterally by a deck or slab, stress reduction need not be considered.

Local buckling will not constitute a problem if the provisions of Specification Sect. 1.9 are met.

Web buckling of a castellated beam due to the vertical shear should be investigated. Formula C gives the allowable unit stress in the solid web section. This formula is a modified column formula and has been verified by experimental work.

$$f_v \text{ (psi)} = \frac{18,000}{1 + \frac{1}{2,666.75} \left( \frac{D_s - 2D_1}{T_2} \right)^2} \quad \text{Formula C}$$

The allowable vertical shear is the allowable unit stress given by this formula multiplied by the cross-sectional area of the solid web panel at its least section. If the vertical shear at any solid web in the beam exceeds this value, then a stiffener will be required for as many panels as the shear is in excess of the allowable. Usually a single vertical bar stiffener added on one side of each solid web section is sufficient web reinforcement. In general, castellated beams without increment plates do not require stiffeners except for conditions of heavy loading.

Bending and shear stresses in the web elements functioning as the verticals of the Vierendeel system should also be checked because in some cases they become critical. The web stresses can be readily computed by the formulas shown in Fig. 3.

The web bending stress on plane X-X may possibly exceed the allowable  $0.6 F_y$  when deep increment plates are used or for special cases when enlarged web holes

$$V' = \frac{\frac{V_1}{2} \times \frac{3B}{2} + \frac{V_2}{2} \times \frac{3B}{2}}{\frac{D_s}{2} - H_1} = \frac{3B}{4} \times \frac{V_1 + V_2}{\frac{D_s}{2} - H_1}$$

$$\text{If } V_1 = V_2 \quad V' = \frac{3B \times \frac{V}{2}}{\frac{D_s}{2} - H_1} \quad V_C = \frac{V'}{B \times T_2}$$

$$M_{x-x} = V' \times \frac{D_4}{2}$$

Fig. 3. Web stresses

are required. When this occurs the web must be reinforced with a vertical bar on each edge of the increment plate.

In rare cases, the shear stress  $V_c$  exceeds the allowable stress of  $0.4 F_y$ . For this condition the web may be reinforced by means of a bar or doubler plate welded flat against the web.

Methods of reinforcing for these special stress conditions are shown in Fig. 4.

Methods of analysis are based primarily upon studies and research conducted at the University of Texas. Further verification of designs has been made by test programs conducted at Washington University in St. Louis and the University of Missouri. In the most recent tests at the University of Missouri, some beams designed for heavy loading and having enlarged web holes were tested; results gave good verification of design procedures.

#### FABRICATION

The fabrication of castellated beams is a comparatively simple series of operations when adequate handling

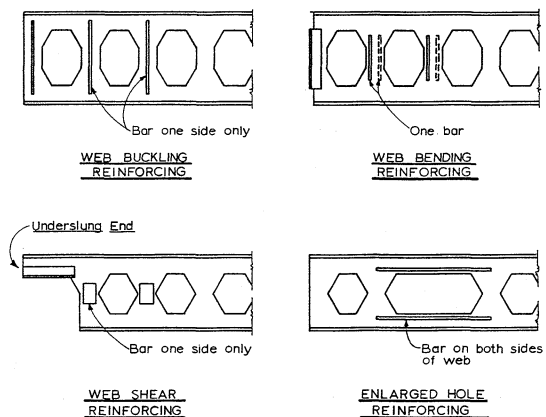


Fig. 4. Types of reinforcement

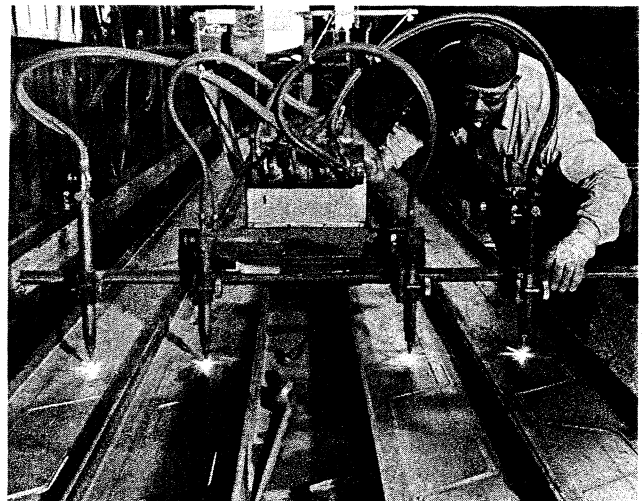


Fig. 5. Webs being split to a predetermined pattern

and controlling equipment is used. At Mississippi Valley Structural Steel Co. beams are split by burning two or more at a time, depending upon their depth. Splitting is performed by using a component of the Litzka equipment shown in Fig. 5. This is an electrically propelled buggy which runs on a fixed track. The buggy has built-in burning patterns that can be adjusted to any one of five standard longitudinal "module" dimensions and to any half-opening height from  $3\frac{1}{8}$  to  $7\frac{7}{8}$  in.

The split beams are lifted from the burning table onto a roll conveyor that feeds into the Litzka joining unit. One beam at a time is fed into this unit with web horizontal, as shown in Fig. 6.

The Litzka joining unit is actually a heavy-duty set of rolls which properly positions the two half-beams for rejoining by welding. The rolls remove the curvature of the tee sections caused by the burning and produce a castellated beam either to a straight alignment or with a specified camber. The beam does not move constantly through the Litzka joining unit but stops as required for welding each web section. Welds are made using  $\text{CO}_2$  shielded welding process with cored wire electrodes.

Using air cylinder actuated copper back-up strips, 100% welds are produced for most web thicknesses. Usually this is considerably more weld than required.

The welded castellated beam moves from the Litzka machine onto a set of powered rolls, and is in turn

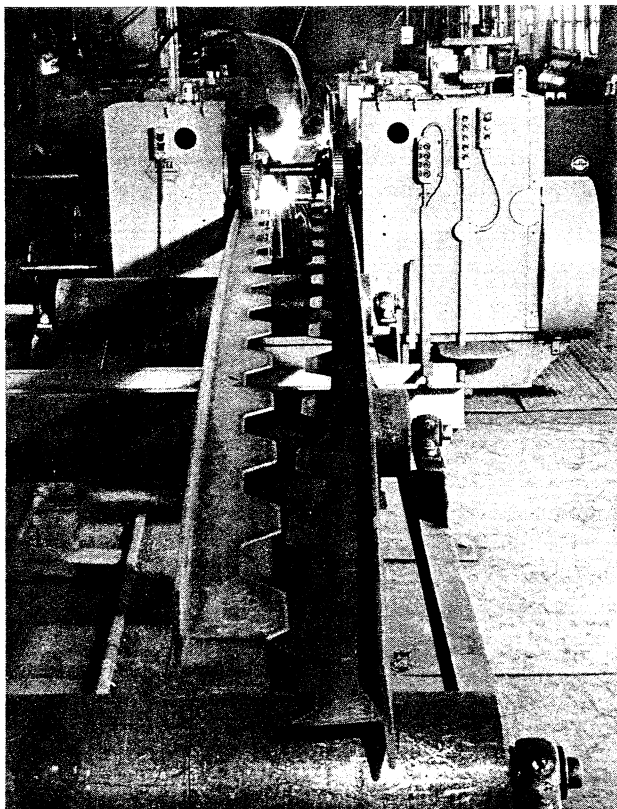


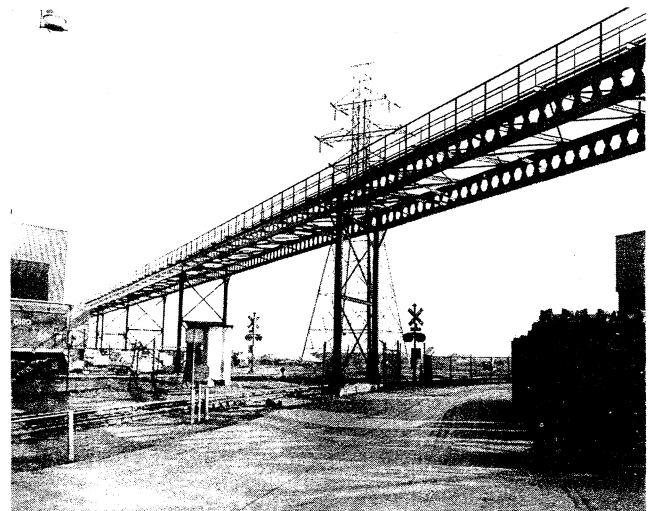
Fig. 6. Split sections feeding into the joining unit



a. Connection detail



b. Industrial building



c. Pipe bridge

Fig. 7. Examples of castellated beam installations

CASE I		CASE II	
Data: Span = 35 ft Load = 1500 lbs per ft Deflection limits = $1/360 = 1.167$ in.		Data: Span = 45 ft Load = 1000 lbs per ft Deflection limits = $1/360 = 1.5$ in.	
21 WF 68 Load: 1828 lbs per ft @ 24 ksi but $\Delta = 1.45$ in. 1470 lbs per ft when $\Delta = 1.167$ in. <b>OK</b>  Weight = 2380 lbs Cost = \$231 (9.7¢ per lb)	25.9 × 50-3 (18 WF 50) Load: 1542 lbs per ft @ 22 ksi  $\Delta = \text{OK}$  Weight = 1750 lbs Cost = \$198 (11.3¢ per lb)	24 WF 76 Load: 1388 lbs per ft @ 24 ksi but $\Delta = 2.095$ in. 995 lbs per ft when $\Delta = 1.5$ in. <b>OK</b>  Weight = 3420 lbs Cost = \$327 (9.6¢ per lb)	28.7 × 55-3 (21 WF 55) Load: 1123 lbs per ft @ 22 ksi  $\Delta = \text{OK}$  Weight = 2475 lbs Cost = \$272 (10.9¢ per lb)
Savings per beam, \$33 or 14 percent		Savings per beam, \$55 or 17 percent	

CASE III		
Data: Span = 60 ft Load = 800 lbs per ft Deflection limits = None		
27 WF 84 Load = 940 lbs per ft @ 24 ksi  Weight = 5040 lbs Cost = \$478 (9.48¢ per lb)	29.0 × 68-3 (21 WF 68) Load = 809 lbs per ft @ 22 ksi  Weight = 4080 lbs Cost = \$427 (10.46¢ per lb)	37.8 × P <sub>12</sub> 55.1-4 (18 WF 50) Load = 809 lbs per ft @ 22 ksi  Weight = 3305 lbs Cost = \$375 (11.2¢ per lb)
Savings per beam, \$51 or 11 percent and \$102 or 22 percent		

Fig. 8. Cost comparisons

laterally removed from these rolls onto a set of accumulating skids. At this point, the finish fabrication operations, which may include squaring of ends, welding on end connection angles, stiffeners and other details, or drilling holes, are performed by conventional methods.

#### APPLICATIONS AND ECONOMICS

Castellated beams have been used in a wide variety of applications, such as roof beams and rafters in both simple span and cantilever construction, floor beams and girders for heavy as well as light floor loads, tier buildings, rafter portions of rigid frames, pipe bridges, girts and other special applications. These uses take advantage of the increased strength and the economy of castellated beams. They also demonstrate the interesting appearance and the functional use of the web holes. Even the increased depth is at times advantageous as in the case of spandrels or other special architectural fea-

tures. Some of these are shown in Fig. 7.

The economy of castellated beams is one of their most important advantages. The savings effected depend on such factors as span, loading and depth requirements, so no single flat percent of savings can be stated. Fig. 8 shows some cost comparisons of castellated beams with solid beams. These are typical load conditions on spans of 35, 45 and 60 ft, which illustrate that savings can be considerable.

Even though the castellated beam is an ideal choice for many situations, it would be wrong to contend that it is the best solution in every case. There are some instances in which loads are too small, the spans too short, or the depth limitations too restrictive, to bring out the economy of castellated beams. However, the efficiency and economy of castellated beams has been well established and, for beams on most spans carrying medium to heavy loads, their use merits consideration.