Analysis of Stress Distribution and Failure Behavior of Cellular Beams

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Abstract

This paper presents an overview of recent research on cellular beams, or steel beams with circular expanded sections. Expanded web beams are common steel I-beam sections that have been adapted by adding web openings down the length of the span. The addition of these cells results in a beam of the same weight as the root beam but stronger and deeper due to the increased web depth. These added openings, however, also result in a different stress distribution within the web and new failure modes associated with the beam. Recent experimental research of coped cellular beams has shown that these non-composite beams often fail in one of three ways: 1) by buckling of the first web post, 2) by buckling of the region between the cope at the end connection and the first web opening (referred to as the $e'$ region), or 3) by a combination of $e'$ region buckling and web post buckling. A linear elastic finite element analysis for service loading conditions and a nonlinear buckling analysis were performed in parallel with the experimental testing program. The analyses were correlated with the experimental data.

Introduction

Cellular beams are steel beams with circular web openings. They are formed by cutting two semicircular sections through the web of a common steel I-beam section. Once the two cuts are completed, the halves are then separated, shifted and welded together with one other to form a new, deeper, stiffer, stronger section known as an open-web expanded steel beam. The resulting beam is deeper than the original I-beam, resulting in a larger section modulus. This process is illustrated in Figure 1.

Due to their design and construction advantages, engineers are increasingly utilizing open web sections in their designs. Design advantages include a reduced weight per unit length of beam and an improved flexural stiffness (larger section modulus) resulting from the increased depth, thus allowing longer spans, which provide for a more open floor plan. Construction advantages include the ability to run utilities through the openings, which can save several inches of floor-to-floor height. The open webs also provide aesthetic advantages when used in structures with exposed beams. Open web sections are considered to be particularly economical in structures that have medium to high design loads over medium to long spans. Recent applications of open web beams range from commercial and industrial buildings to parking garages. (Hennessey, et. al., 2004)

There are two types of open web beams: castellated beams with hexagonal openings, and cellular beams with circular web openings. The circular web openings are commonly referred to as cells. The recent increase in usage of castellated and cellular beams highlights the need for additional research. Present design standards for open web beams in the United States remain non-uniform. This incomplete treatment of castellated beams in design codes is, in part, a result of the limited research on these types of beams. With the exception of Ward, 1990 and Surtees and Liu, 1995, which studied cellular beams, prior research on these beams primarily involved simply supported castellated beams without end copes. (See,
for example, Boyer 1964; Blodgett 1966; Hosain and Speirs 1973; and Redwood and Demirdjian, 1998.)

These papers involved a minimal number of test specimens, making it difficult to determine how indicative
the test results are of true castellated beam behavior and the applicability of these results to cellular beams.

For construction purposes, the beam may be coped, that is, a corner of the beam may be removed
so that the expanded beam will fit into an adjoining column. The removed material (see Figure 2) is called
the cope. The copes in this paper are distinguished by their horizontal dimension. The distance from the
edge of the cope to the edge of the first cell is termed the $e'$ distance. For significant cope sizes, $e'$ can
become relatively small and may affect the failure mode of the beam. This region is illustrated in Figure 2,
below.

**Figure 1. Manufacture of a cellular beam**

**Figure 2. Cell, cope and $e'$ for a cellular beam**
Procedure

The goals of this study were to determine the elastic stress distribution around the interior cells or openings of the beam and the failure behavior of coped cellular beams under loading and boundary conditions more commonly found in practice. To accomplish this, 18 ASTM A570 Grade 50 steel non-composite open web expanded beams with varied cope geometries and depths were tested in parallel with the analyses. All specimens spanned 15.0625-ft. (180.75-in.).

The beams were tested in a self-reacting frame. The support conditions for each specimen consisted of a double angle bolted connection utilizing two 4-in. x 4-in. x 3/8-in. angles bolted to the flange of a W10x26 stub column. The beams were bolted to the double angle connection using four ¾-in. bolts at each end. In order to prevent rotation of the specimen about the longitudinal axis, lateral bracing was provided at the ends and the third points of the span for both the top and bottom flanges. All specimens were subjected to loads along the width of the flange and spaced at 6-in. along the span. The load was applied using a manual two-speed hydraulic pump at a rate of approximately 1 kip/minute. Loading continued until an approximate 10% decrease from the maximum load was observed.

For each beam in the experimental program, load, vertical deflection and strain were recorded. Strain gage location was determined using the initial finite element models. Vertical deflection was measured at four points along the span of each beam with linear variable-differential transformers (LVDT). One LVDT was placed under each connection and at the quarter-span and mid-span of each beam. Strains were measured throughout the $e'$ region and at various points along the beam using strain rosettes. Yielding of the steel beam was mapped visually using a lime wash on the non-instrumented side of the beam. A cellular beam prepared for testing is shown in Figure 3.

![Figure 3. Cellular beam in self-reacting test frame](image)

Finite Element Models

In parallel with the testing, finite element (FE) models were constructed in the ANSYS program for each of the tested beams. Since the goals were two-fold, two separate models of varying complexity were constructed.
Figure 4 shows the model used to determine the elastic stress distribution around the interior cells. As can be seen from the figure, the beam was modeled as symmetric about its mid-length with out-of-plane constraints applied to the top and bottom flanges at the end and the third-point to model the lateral bracing in the experiments. Since the focus of this model was the stress distribution around the inner cells, particularly the second and third cells which are significantly removed from the beam ends, the double angle connection to the stub beam was replaced by pinned boundary conditions at each of the four bolt locations. A linear elastic isotropic material model (elastic modulus, $E = 29 \times 10^6$ psi and Poisson’s ratio, $\nu = 0.3$) was used.

![Linear elastic finite element model used to determine the stress distribution around the interior cells](image)

Figure 5 shows the model used for the nonlinear failure analysis. A bilinear isotropic material model (elastic modulus, $E = 29 \times 10^6$ psi, tangent modulus, $E_T = 60 \times 10^3$ psi) with von Mises yield criterion (yield strength, $F_y = 55 \times 10^3$ psi) was used for the steel to model the nonlinear material behavior of the beam. The material properties used in the models were determined through tensile tests of coupons taken from the test beams. Since the primary objective of this analysis was to determine beam failure behavior in the $e'$ and first web post regions, significant attention was focused on properly modeling the connection of the beam to the loading frame. For the model, the two 4-in. x 4-in. x 3/8-in. angles were included. The beams were connected to the double angles via a simplified bolt model. This bolt model coupled the nodes of the beam and the angles at the bolt locations such that these nodes would displace in all directions as a single unit. Contact without friction was then defined between the beam and the angles. The backs of the angles, which were attached to a stub column in testing, were fixed in the model. A close-up view of this end condition is given in Figure 6.

![Figure 4. Linear elastic finite element model used to determine the stress distribution around the interior cells](image)
Figure 5. Nonlinear finite element model used to for coped beam failure analysis

Figure 6. Close-up of end boundary conditions
To model the applied load, pressure loads were applied every 6-in. along the span across the elements of the top flange. Pressure loading was chosen so that the applied force would remain normal to the flange regardless of flange rotation, which reflected the experimental conditions. Because all loading was all in the vertical direction, two 10-lb. perturbation forces out of the plane and normal to the web were applied in the $e'$ region and first web post to ensure that when the models became unstable, buckling would ensue. An eigenvalue buckling analysis completed in the ANSYS program (Hennessey, et. al., 2004) was conducted to determine the locations of the perturbation force application. Once all the boundary conditions were specified, the model was solved using a large displacement static analysis. Load was applied incrementally until the model became unstable.

**Model Correlation:**

Strain gage data taken in the $e'$ region were compared to the FEA strain results to ensure correlation between the model and experimental results. The FEA strain results correlated well with the experimental strains. Additionally, the load-deflection behavior of the model was compared to experimentally obtained data. For the linear elastic model, experimental mid-span vertical deflection at service load was compared to analytical deflections. The average value difference between the experimental and analytical deflections at the calculated design load was within 0.05-in. For the nonlinear model, the full load-deflection plot was used for correlation. A typical load-deflection plot, comparing the finite element model (LB 2-2 Model) with two corresponding experimental specimens (LB 2-2A and LB 2-2B), can be seen in Figure 7. Close correlation between analytical and experimental results is evident at design loads, and correlation was also close at the failure load, with only three of the eighteen specimens experiencing more than a 0.1-in. difference in vertical deflection at failure.

![Figure 7. Experimental and analytical load-deflection data](image)

Finally, analytically predicted failure loads were compared to experimental values. The analytical models accurately predict experimental failure loads and failure modes, with only one specimen exhibiting more than a 10% difference between analytical and experimental failure loads. In most cases, the failure loads were predicted within 5%. It is important to note that all failures occurred at levels significantly above design loads. Full correlation data can be found in Reither, 2005, Hennessey, 2004 and Dionisio, 2005.
Analysis Results & Discussion

Stress Distribution:

Due to shear flow around the cells, tangential stress gives the best overall picture of the stress field around the cell. A comparison of experimental stresses to finite element stress results as a function of angular position around the cell for the second and third cells from the end is given in Figure 8. It is clear from this figure that the stress varies greatly depending on the angular location. What’s more, for this loading configuration, the maximum stress magnitude and location vary from cell to cell.

![Stress Distribution Diagram](image)

**Figure 8.** Tangential stress results around the second and third cells.

Failure Analysis:

As stated before, the failure mode of the beam can be related to the $e'$ distance on the beam. All specimens in the experimental program failed in some combination of $e'$ region buckling and buckling of the first web post. This combination buckling can be seen in Figure 9. Because these two buckling modes occurred almost simultaneously, it was difficult to determine visually the dominant failure mode. However, with the analytical specimens it is possible to determine the interaction between the two buckling modes and to differentiate which region precipitated the beam’s failure. Failure modes for three cellular beams, varying only by cope size, are shown in Figure 10, where the out-of-plane buckling locations observed during analytical modeling are illustrated for the specimens. The graphs to the left of each of the FE displacement plots give the load and magnitude of the out-of-plane deflection and the degree of interaction between the buckling modes in the $e'$ region and the first web post. For each model shown, out-of-plane deflections are graphed at four locations: the $e'$ region (Point A), the bottom of the first web post (Point B), the middle of the first web post (Point C), and the top of the first web post (Point D). The locations of the points shown in the graphs are identified on the associated beam model.

![Failure Analysis Diagram](image)

It is clear from the out-of-plane displacement plot on the left that the participation of $e'$, and thus the failure mode of the beam, is directly related to the $e'$ distance.
Figure 9. Failure due to combined $e'$ and web post buckling.
Figure 10. Combined buckling mode for a cellular beam with a 3.5-in, a 5.5-in. and a 7-in. cope

Conclusion

This paper details the analytical work conducted to determine the stress distribution and failure behavior of non-composite, coped cellular beams. Finite element analysis is an extremely useful tool in the design and analysis of cellular beams. FEA enables a more complete view of the stress distribution around the cells that would otherwise require extensive strain gaging of the region to determine. This more complete view shows the changing nature of the distribution both around the cell and along the span. Further, the nonlinear buckling analysis enabled the determination of the effect of $\epsilon'$ on the ultimate failure mode of the beam.
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References