

DEFLECTIONS OF COMPOSITE BEAMS WITH WEB OPENINGS

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Abstract: Procedures for calculating the deflections of composite beams with web openings are described. Initially, a matrix formulation is used. Modeling assumptions are verified by comparison with experimental data, and recommendations for practical application of the matrix analysis procedure are made. The results of the comparison are used to develop a design aid for estimating the maximum deflection of beams with web openings, and an expression for calculating the deflection across a web opening. The work demonstrates that, in most cases, a single web opening effect has little effect on the total deflection of a composite beam. There are, however, important cases where the effect can be significant. The effects of an opening and its shear deflections are of the same order. Ignoring both the web opening and shear deformation can lead to significant error. The matrix stiffness method, the design aid, and closed form equations provide reasonable estimates of both total deflection and deflection across an opening.

INTRODUCTION

Most multi-story steel buildings use composite members consisting of a concrete deck integrally connected to a steel beam. The depth of the floor system can be reduced if web openings are used to pass utilities through the steel sections. The result is reduced building height and overall cost savings. The introduction of web openings, however, can significantly affect beam behavior by increasing both the total deflections and the differential deflections across the openings. In most cases, the influence of a single web opening is small, but for those cases where the increase in deflections is unacceptable, a procedure capable of accurately predicting the deflections is needed.

Since the early 1970s, a number of procedures have been developed to calculate deflections for flexural members with web openings. These methods address steel beams (ASCE 1971; McCormick 1972; Donahy 1980), and one method covers both steel and composite beams (Donahy and Darwin 1984; Donahy 1987). The first three procedures require calculation of the deflection due to the web opening; the total deflection is then obtained by adding this deflection to the deflection of the beam without an opening. The fourth method directly calculates the total deflection.

Web openings reduce the stiffness of a member in an opening by (1) lowering the gross moment of inertia at the opening; (2) eliminating strain compatibility between the top and bottom steel flanges above and below the opening; and (3) reducing the cross-sectional area available for carrying shear. The lower gross moment of inertia results in increased curvature at openings subjected to bending. The elimination of strain compatibility and the loss of material for carrying shear result in differential torsional (or Vierendeel) deflections between the ends of openings subjected to shear. The use of reinforcement at an opening can reduce the gross moment of inertia and, thus, limit the increase in curvature. Reinforcement has much less effect on the Vierendeel deflections.

This paper describes procedures for finding both total and differential deflections of composite beams with web openings.

(e.g., Fig. 1). The procedures can be used for steel beams as well. The methods represent an extension of the work by Donahy and Darwin (1986) and Donahy (1987). Initially, a matrix formulation is used. Modeling assumptions are verified using comparisons with experimental data, and recommendations for the practical application of the matrix analysis are made. The results of the comparison are used to develop a design aid for conservatively calculating the maximum deflection of beams with web openings and an expression for calculating the deflection across a web opening. Full details of the study are presented by Benítez et al. (1990).

MATRIX ANALYSIS

Deflections are calculated using the stiffness method of matrix analysis. The top and bottom steel at an opening, as well as the unapertured sections adjacent to the opening, are modeled using uncoupled 6 degrees of freedom (DOF) beam elements. The local element stiffness matrix, $[K_e]$, is (Stern 1970)

$$[K_e] = \frac{EA}{L} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{E I_x}{L^3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

in which E = modulus of elasticity; $\beta = \eta(1 + \nu)$; $\eta = EA_s/G$; A_s = effective shear area; A = gross transformed area for axial deformation; L = element length; and I = moment of inertia of the transformed section.

The element is capable of incorporating shear deformations, as well as axial and bending deformations. Shear deformations can be neglected by setting $\eta = 0$.

$[K_e]$ is derived considering bending of a beam about its own neutral axis. For the nonperforated portion of the beam, the local and global DOF are coincident. Thus, the local and global element stiffness matrices, $[K_e]$ and $[K_g]$, are identical.

At an opening, the neutral axes of the top and the adjacent nonperforated section are not coincident. Therefore, the local DOF for the top and bottom steel do not correspond to the global DOF for the structure. By assuming that the webs ad-

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