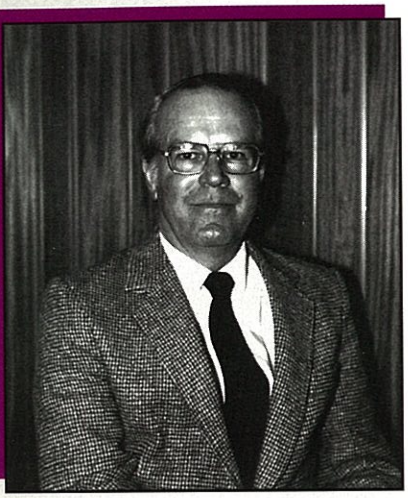
Composite Beams With Slab Openings

A procedure to more efficiently use steel framing



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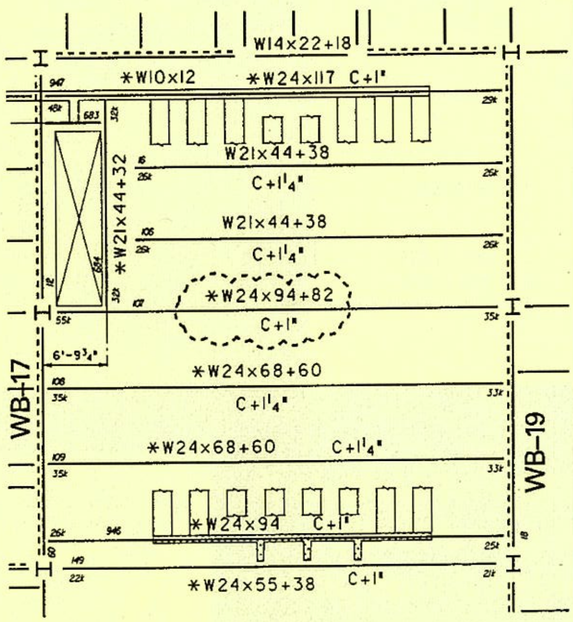
While composite simple span beams, consisting of a concrete slab on steel beams with welded stud shear connectors, are commonly used in steel-framed buildings, current U.S. design specifications do not provide guidance to the engineer concerning the effects of slab openings on the design of composite beams. Engineers manually designing such beams generally estimate an effective slab width based on individual judgment.

Figure 1



Shown is a portion of a framing plan for a new 10-story Courthouse in Boston. The highlighted beam (W24x94, F_Y 36, + 82 studs) has a large slab opening at one end, and is composite with a 3.25-in. lightweight concrete slab over a 2-in. steel deck. We overrode our in-house CADD program to use a full slab effective width of 94 in. The CADD program otherwise would have used a width of 55 in., resulting in a W24x117 (FY 36) beam with 34 studs.

CAD programs are now being used to design entire floors with hundreds of composite beams, and generally assess effective slab width of a beam with one or more adjacent slab openings based on the least width of concrete at any point along a beam unless the engineer overrides manually. Such an approach can lead to a conservative result with steel beams heavier than necessary (see Figure 1).

Parametric Study

A theoretical study was performed, in which a one-bay wide metal deck supported slab was represented by plate type finite elements connected to a 40-ft. span uniformly loaded W24x55 steel beam. Slab openings of various sizes and locations were modeled for a base-line case "A" with no openings and 12 others. Figure 2 shows the model and one such case, case "B". The lateral restraint provided by adjacent slab spans was approximated by modeling lateral "springs" at each edge of the slab.

With no openings, the AISC ASD and LRFD Specifications allow a slab effective width of L/4, or 120 in., for this study. For case "B" shown in Figure 2, a conservative approach would be to use 30 inch effective width. This would require a heavier beam, for strength. The proposed design method leads to a mid-span effective width of 60 in., and allows use of the W24x55 beams. Results for the study for case "B" are shown in Figure 3.

The study shows how slab longitudinal compressive stresses (at slab mid-thickness) vary across the width, the magnitudes of slab transverse tensile forces, and a comparison of midspan compressive stress and deflection for these cases to base line case "A" with no slab openings.

The study showed that the openings cause slab in-plane shear and bending stresses, which often will require some additional slab reinforcement. The proposed design method provides a simplified approximation of these in-plane bending stresses in the transverse direction.

Proposed Design Procedure

The proposed effective slab width guidelines are based on limiting the tangent of the horizontal angle alpha between the near-beam opening edge and the edge of the effective slab width, which thus limits the slab shear stress. See Figure 4 for parameters of a general case of one or two large openings. Figure 5 shows parameters of the special case of a slab opening contained within the normal slab effective width. Unless slab reinforcing is much heavier than the normally used welded wire fabric, tangent alpha is limited to 0.25. The rationale for this is that the AISC ASD and LRFD Specifications implicitly allow this angle by prescribing slab effective width of L/8 in a distance of L/2 or less between end of beam and point of maximum bending moment.

Figure 2

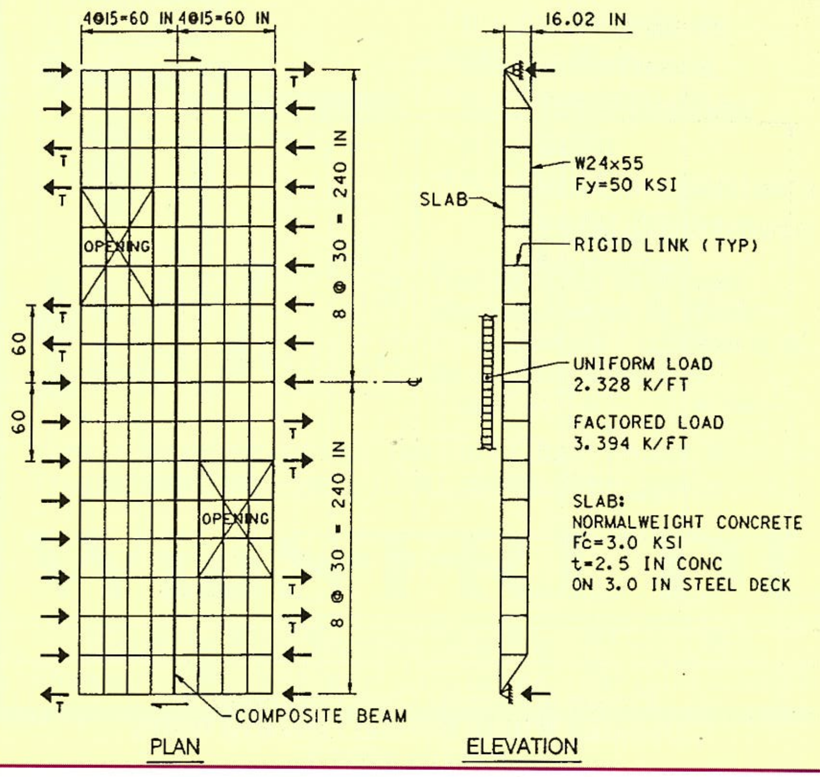


Figure 3

TWO 45"x90" OPENINGS

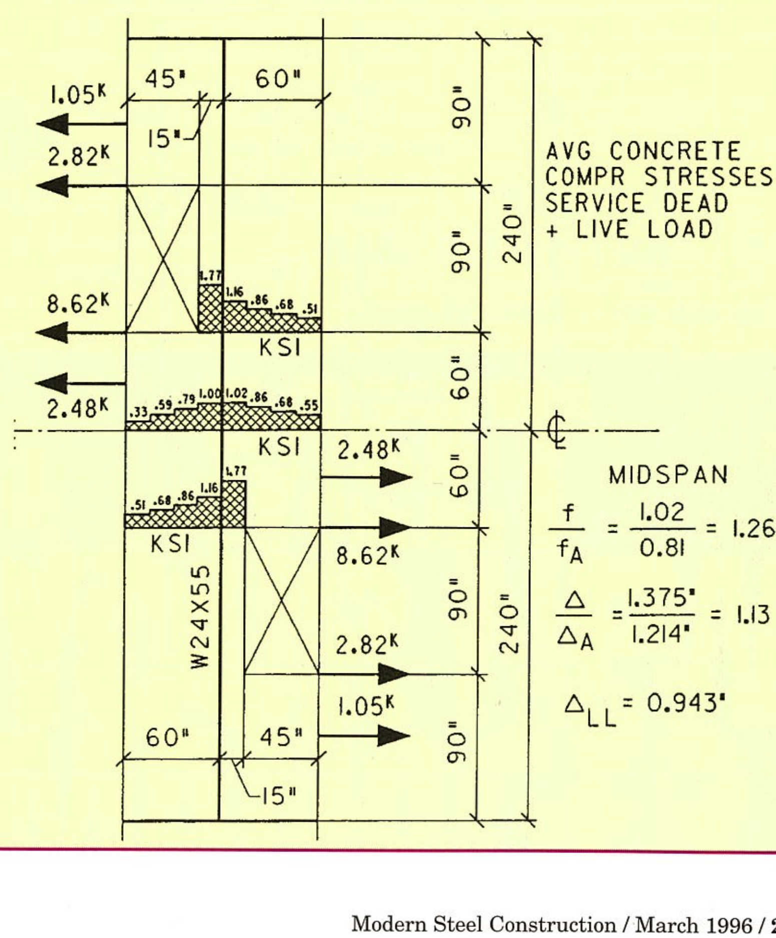


Figure 4: General Case Parameters

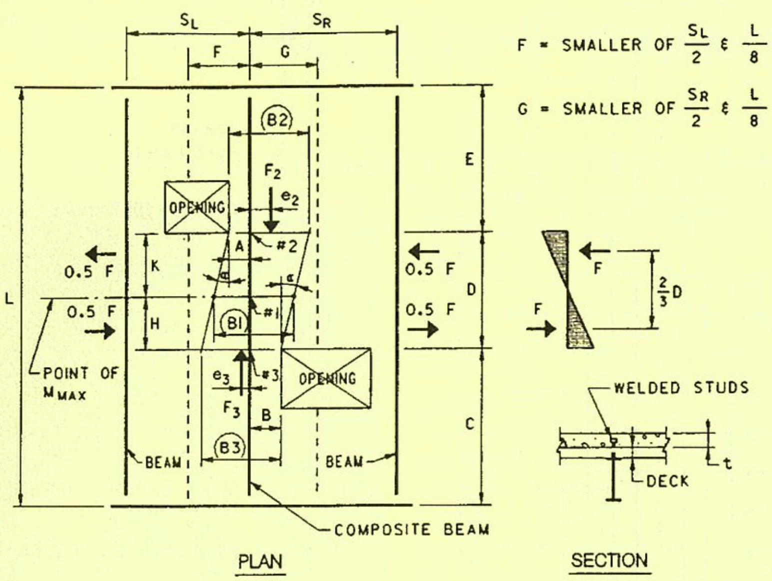
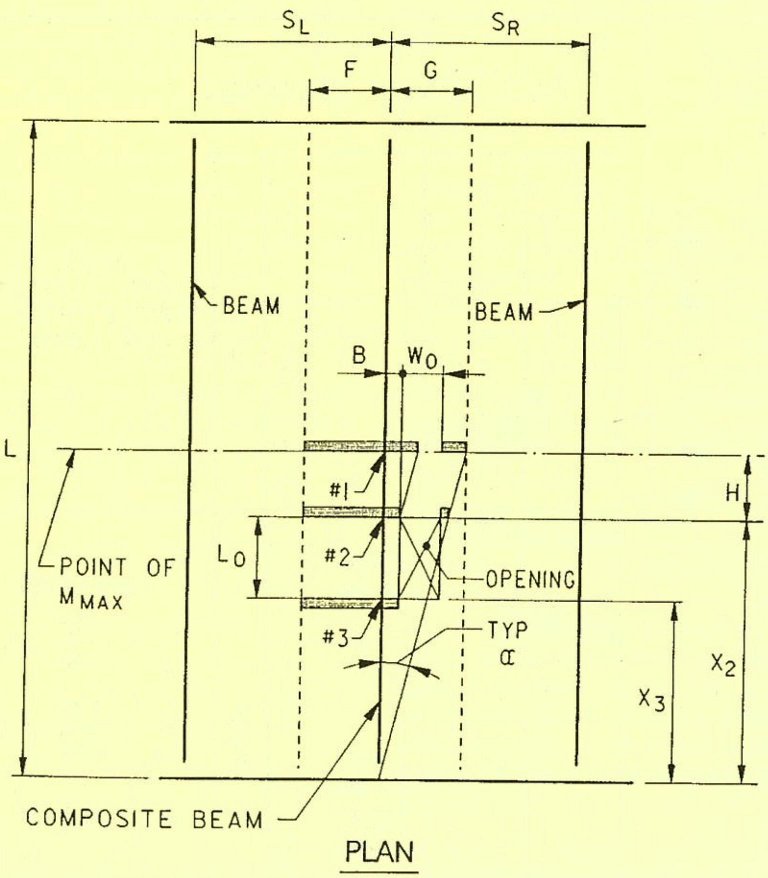


Figure 5: Special Case Parameters— Opening Within Normal Effective Width



If the engineer wishes to provide heavier slab reinforcing and to use tangent alpha larger than 0.25, the following iterative approach is suggested, based on the alternative formula from ACI Building Code Commentary Par. Rl 1.7.3:

Tan $\alpha = (V_n/A_c)/F_{cu}$, in which F_{cu} = average concrete compressive stress at factored load, $V_n/A_c = 0.8F_yA_{vf}/A_c + K_l$, and A_{vf} must be $>200A_c/F_y$ for inch and psi units, and K_l = 400 psi for normalweight concrete, or K_l = 250 psi for sand-lightweight concrete. This is an iterative process since F_{cu} is dependent on the effective width, which depends on tan α.

Limitations

- The proposed design procedure is applicable to simple span composite beams, loaded so as to have maximum bending moment near midspan, and having one or two slab openings as shown in Figure 4 or Figure 5.
- There shall be at least one essentially opening-free slab span on each side of the span containing the opening(s).
- Dimensions A and B (from composite beam) must be not less than steel beam half flange width.
- Openings do not overlap, so dimensions H and K (from point of maximum moment) are each greater than zero.

Neglecting Slab Openings.

The effects of slab openings may be neglected when:

- All openings are located at the end(s) of the beam, not farther from the support than one-eighth the distance from end support to point of maximum moment.
- Distance from center of beam web to edge of nearest opening is not less than the larger of L/80 and 6 in.

Procedure for General Case of Figure 4

1. Check strength of composite beam at M_{max}, generally midspan, for concrete effective flange width B_1, using ASD or LRFD.

$B_1 = A + B + \tan\alpha\,(H + K) \leq F + G$. Use $\tan\alpha = 0.25$ unless special slab shear reinforcing permits use of a larger angle. If strength is found inadequate, revise beam size or F_y, or opening sizes or locations, or slab thickness or strength. Determine number and spacing of shear studs.

2. Check beam moment capacity at points #2 and #3 and compare to the design moments. For LRFD, use ΣQ_n = lesser of Σ shear capacity of studs between the point and support, and $0.85\,F'_c\,b\,t$. Use $B_2 = A + B + \tan\alpha\,(H + K) \leq A + G$. and B_3 = the same but $\leq B + F$. If necessary, revise number or spacing of shear studs.

3. Calculate approximate inplane slab bending stresses as follows.

A. Calculate F_2 = slab average axial force at point #2, determined by calculating ΣQ_n between point #2 and end of beam. Take eccentricity of F_2 as e_2 = center of beam web to center of width B_2, and compute $M_{e2} = F_2\,e_2$.

B. Similarly, calculate F_3, e_3 and M_3 at point #3. Take eccentricity of F_3 as e_3 = center of beam web to center of width B_3, and compute $M_{e3} = F_3\,e_3$.

C. Using M_e = the larger of M_{e2} and M_{e3}, compute $F = 1.5\,M_e/D$, and compute maximum transverse concrete stress: $f_c = 4\,F/D_t$. For the opening in lower right of Figure 4, there is slab compression on the left side and slab tension on the right side. Assume a 50%-50% ratio. Conservatively provide slab reinforcing to resist this tension, placing it in a zone near the opening oriented at 90 degrees to beam axis.

4. Deflection of the beam is increased due to the slab openings. Sufficient accuracy is provided by using a constant composite beam stiffness equal to the average of the three effective flange widths calculated in steps 1 and 2.

Procedure for Special Case of Figure 5.

1. Check strength of composite beam at M_{max}, generally midspan, for concrete effective flange width B_1 using ASD or LRFD. $B_1 = F + G + H \tan \alpha - W_o \leq F + G$. Use $\tan \alpha = 0.25$ unless special slab shear reinforcing permits use of a larger angle. If strength is found inadequate, revise beam size or F_y, or opening sizes or locations, or slab thickness or strength Determine number and spacing of shear studs.
2. Check beam moment capacity at points #2 and #3 and compare to the design moments. For LRFD, use ΣQ_n = lesser of Σ shear capacity of studs between the point and support, and $0.85 F'_c b t$.
   Use $B_2 = F + X_2 \tan \alpha - W_o$, but $\leq F + G - W_o$. Use $B_3 = F + X_3 \tan \alpha - W_o$, but $(F + B) \leq B_3 \leq (F + G - W_o)$. If necessary, revise number or spacing of shear studs.
3. For smaller width openings, say $W_o \leq 0.70$ G. extra slab reinforcing is not needed. For larger opening widths, calculate approximate slab in-plane tranverse tensile stress in a manner similar to Step 3 of the Figure 4 general case procedure.
4. Estimate beam deflection by using a constant composite beam stiffness based on an average effective slab width $B_{av} = (B_{full}/2 + B_1/4 + B_2/4)$, where B_{full} = the full effective width allowed by AISC Specifications.

CONCLUSIONS

Based upon a limited parametric study and engineering judgment, guidelines have been presented for design of simple span composite beams with adjacent slab openings, where there is at least one opening-free slab span on each side of the span containing the openings. The effect of such openings may be neglected when the openings are close to the beam end support, extend no more than one-eighth the distance to the point of maximum moment, and are at least L/80 or 6 in. from center of beam web. Where the slab openings cannot be neglected, a design procedure has been proposed which includes guidelines for design of slab reinforcing to resist tensile stresses induced in the slab transverse to the beam axis.