Effective Width of Composite L-Beams in Buildings

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ABSTRACT

The latest AISC design specifications permit the use of wider effective widths for steel-concrete composite exterior beams (or L-beams) than previous editions. This sometimes results in more flexible beams which quite often support deflection-sensitive nonstructural components. An analytical study of composite L-beams was conducted within a practical range of span and spacing for buildings. Both the conventional stress-based and rational stiffness-based definitions of effective width were considered. Effective widths were computed from the results of finite element analysis of three-dimensional models permitting longitudinal slip between the concrete slab and the steel beam. It was concluded that the AISC effective width criteria for L-beams tends in an unconservative direction; a stiffness-based formula dependent on the spacing/span ratio is proposed.

INTRODUCTION

In 1986 AISC issued the first edition *Manual of Steel Construction LRFD*. Included in this volume was a new LRFD specification introducing in Chapter 1 a limit-state design method for composite beams. Benefits of the LRFD method included more consistent reliability and marginally lighter steel framing. However, the Specification adopted significant changes to the formulas for effective width which were carried into the 9th edition ASD manual published in 1989. The previous 1978 Specification called for two different ways of computing effective width: one for interior, or "T-beams," and one for exterior, or "L-beams."[11] After 1986, the same formula was used for both interior and exterior beams.[12] Formulas for effective width b_e at the interior side of a composite L-beam are shown in Equations 1 and 2.

8th edition (1978):

$$b_e = (\text{lesser of } l / 12 \text{ or } s / 2 \text{ or } 6t_s) + b_f / 2 \tag{1}$$

LRFD (1986), ASD (1989):

$$\text{lesser of } b_e = l / 8 \text{ or } b_e = s / 2 \tag{2}$$

where

l is the beam span,
s is the beam spacing, and
b_f is the flange width of the steel beam.

The 1978 Specification did not recognize the contribution of the "short" exterior slab edge beyond the flange of the steel beam. The 1986 Specification permits the consideration of all concrete in the slab up to the exterior edge. While the historic development of effective width theory is not fully known, the 1986 change was intended to simplify composite beam design[7] and was not a manifestation of any physical testing or analytical study.[17] In 1977 Iyengar wrote that the behavior of composite beams having a floor slab on only one side of the steel beam was an area of uncertainty requiring investigation.[9] Despite the subsequent code changes, this represents the first paper discussing composite L-beams published in the United States since Iyengar's remarks.

EFFECTIVE WIDTH: T-BEAMS VS. L-BEAMS

The idea of effective width allows one to account for shear lag in the compression of the concrete. Shear lag occurs when the compressive stresses in the concrete slab reach their maximum at the steel beam centerline and diminish with distance from it. The effective width concept permits the use of a uniform compressive distribution over a smaller area of concrete than provided by the center-to-center spacing of floor beams. In design, larger effective widths bring about greater bending moment capacity and stiffness; smaller effective widths in turn supply less bending moment capacity and stiffness. To be sure, the final design of a composite beam entails consideration of a number of factors and no single one like effective width will influence every design. Nonetheless, the combination of LRFD and the increased dimension of effective width as computed from Equation 2 can lead to the use of smaller steel beams. Although the LRFD manual provides lower-bound moments of inertia for use in checking deflection, the ASD manual still uses the transform or effective moment of inertia based on the same effective width used to compute stress. For T-beams this has remained largely inconsequential because the strength limit state usually controls. But L-beams, which often support long-term superimposed dead loads at the building envelope, may show inferior performance. This results from overestimation of stiffness where deflection is critical. L-beams occur in virtually every

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constructed building using composite floor framing. Figure 1 shows a typical composite L-beam.

The serviceability limit state holds particular importance for composite L-beams. Because both exterior cladding and interior finishes rely on the exterior floor beam for support, proper estimation of vertical deflection and related longitudinal slip at the steel-concrete interface is necessary.[4] This becomes even more crucial when the exterior building finishes consist of heavy masonry, which triggers long-term inelastic concrete strain and corresponding beam deflection. Many exterior building finishes tolerate only very small deflections without cracking and other adverse effects on weathertightness.[3]

Composite L-beams possess a number of features that distinguish them from T-beams. Only one of these, effective width, is discussed here in detail. Other characteristics remain important to designers who might not always consider their significance. First, many L-beams specified according to present standards may not develop the full ultimate moment assumed in design. Loss of shear connector capacity can occur when the unconfined exterior edge of the slab fractures and becomes ineffective.[10] Second, the fact that an L-beam, when taken as a free body, has no axis of symmetry implies torsional behavior. Composite L-beams actually behave like structural angles constrained to bend in one direction.[15] The continuity of the concrete slab provides this constraint by absorbing lateral shear and moment developed by the L-shape in bending. The rigidity of the slab-beam connection is crucial to this behavior. Third, longitudinal shear transfers from shear studs to concrete in only one plane through the slab, as opposed to T-beams where concrete resists longitudinal shear on both sides of the steel beam. Slab reinforcement with proper anchorage in the exterior edge may be required solely for the purpose of resisting excessive shear in the concrete.[4]

Some researchers, notably Adekola,[1] have questioned the theoretical basis of effective widths in composite beam design. Adekola suggests that stress-based effective widths of the kind commonly used in engineering practice are incorrect.

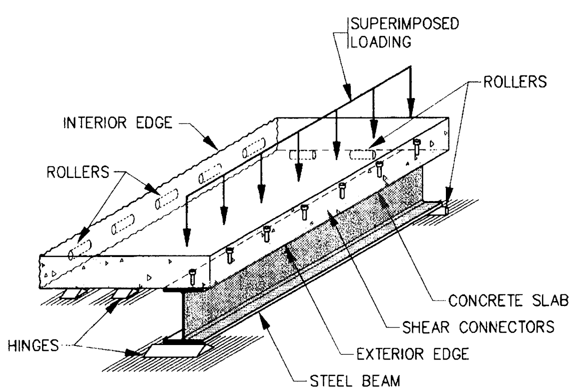

Fig. 1. A composite L-Beam.

He asserts that effective widths based on stress tend to increase with a lesser degree of composite action, a behavior contrary to intuition and rigorous mathematical proof.[1] Adekola's recommendations for "deflection-based" (or stiffness-based) effective width have been regarded as too conservative in practice. One study expressing such a sentiment was published in 1985 by Vallenilla and Bjorhovde. Their paper studies only T-beams. It concludes that effective widths proposed for the LRFD specification are conservative.[16]

The limits on effective width of L-beams used before 1986 were devised from limited existing test data and practical observations of shear lag theory. Documented examination of them came in 1968 when Hagood *et al.* tested assemblies of three beams each. That paper pronounced the AISC specification for L-beams "reasonable" in comparison to the standards for T-beams which were said to be "conservative."[6] The 1968 research examined only a limited number of assemblies which covered a large range of spans and spacings. Since that time, other researchers have eliminated slab thickness as a factor influencing the effective width of T-beams. Today the acknowledged factors influencing effective width include span, spacing, degree of shear connection, and pattern of loading.[5] Results from much of the research conducted on uniformly loaded composite T-beams have been applied to composite beams which do not exhibit the T profile and which do not support uniformly distributed loads. It has been shown that the effective width of the compression flange varies significantly in the vicinity of point loads.[5] Present AISC effective width criteria apply without distinction to T-beams, L-beams, partial T/partial L beams, uniformly loaded beams, and point-loaded girders.

OBJECTIVE AND SCOPE

The research for this paper attempted to tie together what is known about the effective width of composite L-beams and to apply this information to ordinarily constructed building designs. Knowing a range of beam spans and spacings typically used in constructed buildings (as opposed to bridges) permitted the analysis to be focused more precisely. With this information in hand, models pertinent to L-beams in buildings could be fashioned. The models then served as the basis for a finite-element computer analysis. From the analysis results, stiffness-based and stress-based effective widths were computed and studied according to criteria established by previous researchers of composite beams.[5,6,8] The accumulated information from past research, the statistical results, and the study of analytical models allow new design rules for effective width to be proposed. The rules remain exclusive to the range of spans and spacings of L-beams used in building design.

RANGE OF SPANS AND SPACINGS

To find a practical range of spans and spacings that is commonly constructed in buildings, records of a typical New

England steel fabricator and those of a Boston-area structural engineering firm were reviewed. Spans and spacings for one or more typical framing conditions in each building were recorded and statistically analyzed to find a spacing/span ratio and a confidence interval appropriate to describe floor beams in buildings. The number of repetitions of a design in a single building was not considered because it would skew the data toward larger structures, when a variety of building sizes was examined.

A total of 45 different beam designs representing 30 different buildings yielded a mean spacing/span ratio of 0.33. Table 1 lists the s/l ratio of the designs reviewed. This sample includes a variety of building uses, sizes, and designers. Because of sufficient sample size, a normal distribution was used. The 95 percent confidence interval for this same ratio fell between extremes of 0.30 and 0.38. The 99 percent confidence interval fell between extremes of 0.28 and 0.40. Thus very close spacing of beams (less than 25 percent of span length) does not represent typical building construction in this sample population. Very wide beam spacing (more than 40 percent of span length) also seems to be unusual. Specimens tested in Hagood's research had s/l ratios of 0.35, 0.50, and 0.70. Specimens examined by Heins and Fan[8] for bridges, in contrast, ranged from s/l of 0.06 to 0.24.

DESIGN OF BEAM MODELS

Only L-beams were examined. The ratio of spacing to span chosen for this study encompassed a range of 0.25 to 0.50 in order to cover the widest possible number of practical framing situations. A composite L-beam design corresponded to each of six conditions of spacing to span ratio: 0.25, 0.30, 0.35, 0.40, 0.45, 0.50. The beams all simulated exterior floor beams

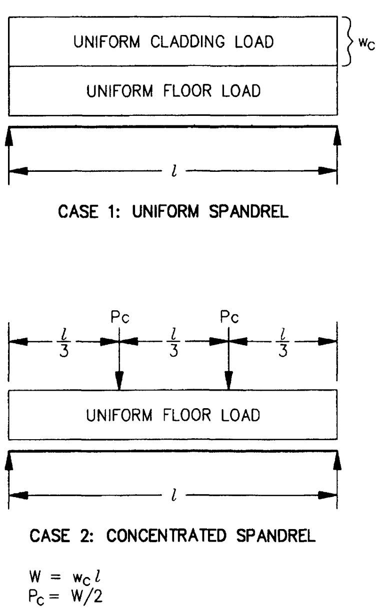

Fig. 2. Patterns of loading.

supporting some kind of building cladding. Each was sized using an LRFD design. All supported uniformly distributed floor loads, which is to say that no floor loads were applied in the manner of a beam reaction. Cladding loads were applied in two ways, as illustrated in Figure 2. In the first case, the cladding weight was distributed over the entire length of the beam. In the second case, the cladding weight was divided into two point loads applied near the third points of the span. Table 2 lists the beam designs and their loading characteristics.

ANALYSIS PROCEDURE

Six composite L-beams were analyzed as three-dimensional solid finite element models using the ANSYS program.[2] Eight node elastic isoparametric "brick" elements simulated concrete and steel. Elements of this type produce displacement in three directions. To accurately model slip between concrete slab and steel beams, two-node inelastic force-deflection elements represented shear connectors.[2] These elements made up the only connection between concrete and steel capable of transmitting force parallel to the long axis of the beam. The nonlinear behavior of the shear connectors was described by the formula[13]

$$Q = Q_u(1 - e^{-18\delta})^{0.4} \tag{3}$$

relating interface shear force Q to longitudinal slip δ, where Q_u is the ultimate shear connector capacity as computed from LRFD Equation 15-1. Figure 3 graphically illustrates the force-deflection releationship of the shear connector elements. This suggests that load capacity reaches its maximum only after substantial deformation. The elements representing shear connectors were given values of Q_u appropriate to ¾-in. diameter headed shear studs. Other connections between slab and beam, such as those at tack welds fastening metal deck to the beam, were simulated by linked nodes. The model was arranged to maintain equal vertical and lateral displacements

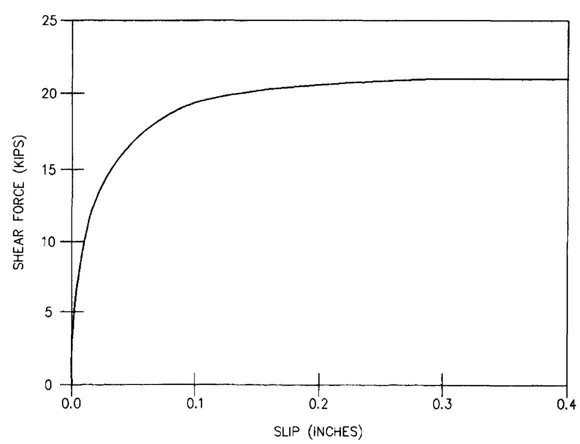

Fig. 3. Load-deflection behavior of shear stud.

Table 1. Beam Span and Spacing Data								
Design	Building	s/l	Design	Building	s/l	Design	Building	s/l
1	1	0.23	16	13	0.31	31	20	0.24
2	2	0.19	17	14	0.30	32	20	0.33
3	3	0.41	18	15	0.26	33	21	0.33
4	3	1.20	19	15	0.40	34	21	0.50
5	4	0.30	20	15	0.29	35	22	0.28
6	5	0.23	21	15	0.32	36	23	0.33
7	6	0.23	22	16	0.33	37	24	0.32
8	7	0.28	23	16	0.28	38	25	0.33
9	8	0.25	24	17	0.31	39	25	0.29
10	9	0.53	25	17	0.23	40	26	0.33
11	10	0.33	26	17	0.35	41	27	0.33
12	11	0.33	27	18	0.24	42	28	0.50
13	11	0.50	28	19	0.29	43	28	0.45
14	12	0.29	29	19	0.20	44	29	0.33
15	13	0.22	30	19	0.21	45	30	0.33

Table 2. Model and Loading Characteristics								
Case	Span s (ft.)	Spacing l (ft.)	s/l	Steel Beam	Deck Height (in.)	Slab Cover (in.)	Number of Studs	Total Load Applied (kips)
1	35	8.75	0.25	W24×62	3.0	2.5	51	40.53
2	30	9.00	0.30	W16×31	3.0	3.0	19	41.85
3	25	8.75	0.35	W12×14	3.0	2.5	13	22.95
4	20	8.00	0.40	W10×19	2.0	3.0	14	20.62
5	15	6.75	0.45	W8×13	2.0	2.5	10	28.65
6	10	5.00	0.50	W8×10	1.5	2.5	10	4.68

at pairs of linked nodes. Longitudinal displacement was permitted beween individual linked nodes.

Boundary conditions were likewise similar for all models. The bottom flange of the typical steel beam was simply supported at its end nodes. The concrete slab had vertical supports at the ends of the beam span and horizontal supports along the length of its interior edge. This left the entire L-section capable of vertical displacement. As pictured in Figure 4, rigid supports were used for horizontal restraint at the interior edge because of the large stiffness of concrete floor slabs in their own plane. All slabs had an "exterior" edge of six inches measured from the centerline of the steel beam. At the interior side of the steel beam, slab thickness was reduced to the amount of concrete above steel deck. The deck itself was not included in the models.

Material properties reflected industry standards. Young's modulus E was set to 29,000 ksi for steel and 3,500 ksi for 4,000 psi normal weight concrete. Poisson's ratio was 0.3 for steel and zero for concrete. The zero value indicates the concrete's inability to strain laterally when longitudinal cracks occur in the slab.[14] Isotropic behavior was assumed for both materials.

Service loads of the type discussed above were imparted to the top surface of the concrete slab. Uniform floor and cladding loads were applied as a series of constant forces to nodes in the slab directly over the steel beam. Concentrated cladding loads were applied as additional forces at the third points of the span. No loads were applied in the plane of the slabs or to the bottom flange of the steel beams. It has been shown by others[5] that shear lag behavior is not greatly affected by intensity of loading; thus the service load effective width should be similar to that experienced at ultimate load. All loads were superimposed on the fully hardened composite section. The models assumed neither initial downward deflection nor upward camber in the steel beam.

Values of compressive stress parallel to the beam span were read from ANSYS output data for individual elements at midspan. A postprocessor which produced both averaged and unaveraged contour plots of the slab surface permitted visual verification of shear lag patterns A sectional view of midspan longitudinal stress countours also was examined.

RESULTS OF ANALSIS

Table 3 shows results for each of the six beams and their two

Table 3. Effective Widths, Inches					
Case	**Spandrel**	**Stress Eff. Width**	**Deflection Eff. Width**	**LRFD AISC Eff. Width**	**8th Edition AISC Eff. Width**
1	Uniform	53	39	59	42
2	Uniform	51	25	51	36
3	Uniform	44	22	44	29
4	Uniform	39	17	36	24
5	Uniform	29	10	29	19
6	Uniform	21	5	21	14
1	Concentrated	53	39	59	42
2	Concentrated	50	27	51	36
3	Concentrated	45	22	44	29
4	Concentrated	41	18	36	24
5	Concentrated	30	10	29	19
6	Concentrated	21	6	21	14

load cases. Effective widths were determined from the output data in two different ways. First, the longitudinal compressive stress at the top of the slab was averaged over the individual element widths to approximate the area under the plot of compressive stress versus slab width. Once this area was found, a rectangle equivalent in area was constructed using the peak compressive stress. The width of this rectangle is the stress-based effective width. A second method used the midspan beam deflection computed in the ANSYS analysis. Using known loads and traditional equations for deflection under the patterns of loading imposed on the model, an effective moment of inertia was computed. From this effective moment of inertia, the effective slab width was derived using the parallel-axis theorem. Stiffness-based effective width is highly influenced by the amount of slip between the concrete slab and the top flange of the steel section. Effective slab width in both circumstances was computed at a number of sections along the span of the composite beam. All effective widths computed represent the total value including concrete on both sides of the beam flange.

When calculated at intervals along the beam span, both stress-based and stiffness-based effective widths exhibited significant variation. As Figure 5 demonstrates for a single example, stress-based effective widths showed a characteristic parabolic shape leading to a peak at midspan. The shape of this curve corresponds to the shape of stress contours observed using the ANSYS postprocessor. Stiffness-based effective widths, when plotted along the beam span, show a definite flattening at the peak value, suggesting a more constant effective width over the length of the beam. Table 3 clearly indicates that stress-based effective widths are larger than the corresponding stiffness-based effective widths.

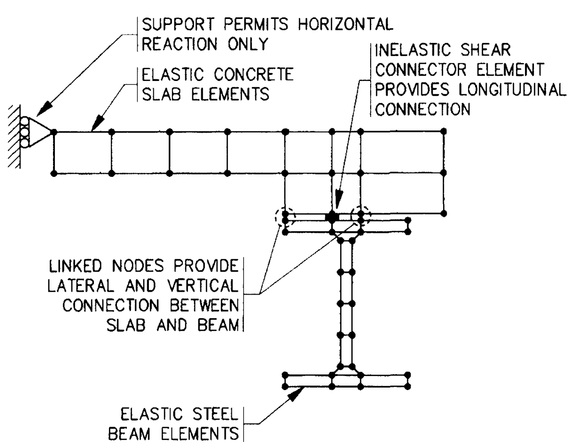

Fig. 4. Typical cross-section through model.

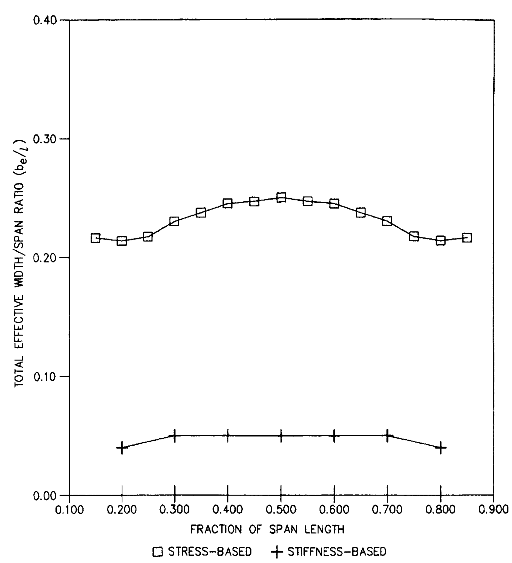

Fig. 5. Variation of effective width (Case 6—uniform spandrel load pattern).

It has been traditional to compare effective widths of different beams by normalizing both b_e and s by the beam span, l. In this investigation, normalized stress-based effective widths b_e/l tend to increase with normalized spacing s/l. In contrast, deflection-based values of b_e/l decreased with increasing s/l. These opposite tendencies are illustrated in Figure 6. Effective widths of L-beams computed by two different methods diverge with greater spacing. At large s/l, therefore, the difference between stiffness-based and stress-based methods becomes more significant. While AISC rules for effective width are not directly related to stress, they appear to follow the same trends as the stress-based effective widths.

To examine the importance of composite behavior, the b_e/l values were plotted against a measurement of steel-concrete interaction. The measurement used was the ratio of midspan deflection to maximum slip at the steel-concrete interface. Slip was read directly from the computer output as the longitudinal stretch of shear connector elements. The maximum value invariably occurred at the ends of the L-beams. The deflection/slip ratio ($\Delta_{max}/\delta_{max}$) increases with increasing interaction between the steel beam and the concrete slab. Figure 7 indicates that Adekola's reservations about stress-based effective widths may contain some validity as they decrease with increasing interaction. Stiffness-based effective widths, on the other hand, tend to increase as the degree of interaction increases. At low levels of interaction, stress-based effective widths significantly overestimate stiffness of the composite section.

The pattern of loading imparted by the exterior cladding of the simulated L-beams did not appear to influence the peak value of effective width for either method of calculation. Effective width values and stress contour shapes seemed to be only slightly distorted in the immediate vicinity of the point loads. As no point loads were introduced at midspan, the midspan value remained relatively unchanged. This investigation used service loads of the kind expected in buildings, including cladding loads. Thus, cladding loads applied in a non-uniform distribution do not undermine AISC code requirements for effective width. It is important to emphasize, however, that other types of point loads, notably from supported columns and floor beams, can impart unusually large forces that other research has shown will change the effective width by as much as 25 percent.[5]

A regression analysis of the results shown in Figure 6, modified to eliminate the contribution of the 6-in. exterior slab edge, produced equations for stress-based and stiffness-based effective widths on one side of the beam centerline.

$$\text{Stress-Based: lesser of } b_e = 0.11l + 0.05s \text{ or } s/2 \quad (4)$$

$$\text{Stiffness-Based: lesser of } b_e = 0.13l - 0.16s \text{ or } s/2 \quad (5)$$

When $b_e < b_f$, it is recommended for practical purposes that composite action not be assumed. Figure 6 shows clearly that the data points, which serve as the basis for the two formulas, diverge as s/l increases. Figure 7 indicates that the data points also diverge with increasing interaction. Equations 4 and 5 represent the portion of total effective width contributed by the interior floor slab. The usefulness of the exterior slab edge can be regarded as an open question. Its concrete certainly resists high compressive stress compared to that of the interior slab. However, the construction details now prevalent raise questions about the behavior of this concrete at ultimate moment. Additional testing and theoretical research are needed to determine the best way to construct such elements. For now, it will suffice to say that designers should use their

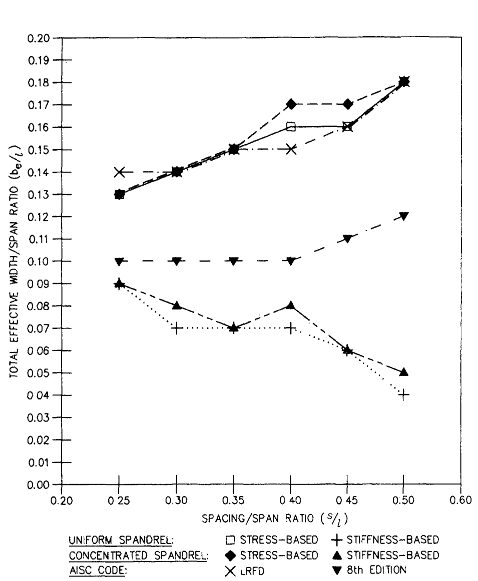

Fig. 6. Total effective width/apsc vs. spacing/span.

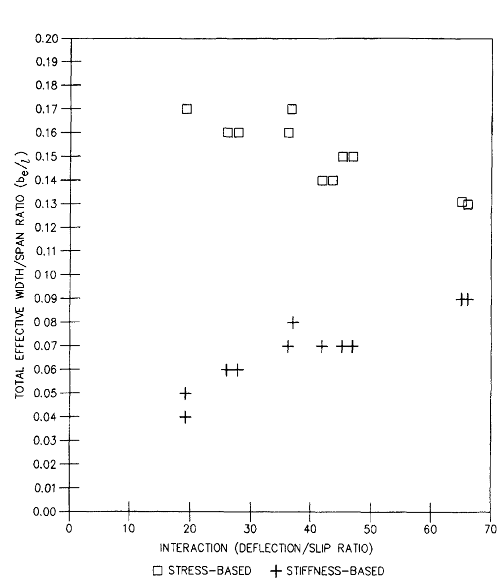

Fig. 7. Total effective width/span vs. interaction.

judgment with respect to confinement of shear connectors and the transfer of compressive stress from the beam flange to the concrete slab.

From this study, it appears that the recent simplified standard for effective width moved in a direction less conservative than many consider to be warranted. Even though effective width is a more complicated function of the span and spacing than past or present codes suggest, the 1978 AISC specification offered a more conservative value. It also recognized a distinction between T-beams and L-beams. Equation 5 above provides a conservative value for L-beams alone based upon the aspect ratios normally found in building construction. It takes account of stiffness and tends in a direction supported by theory. Figure 8 illustrates a comparison among various standards for effective width at the interior side of a composite L-beam. It is clear that Equation 5 offers the lowest value in nearly every case.

CONCLUSIONS

1. Composite L-beams and T-beams differ in many substantial respects. Further investigation of composite L-beams with steel deck is warranted to confirm that their overall behavior corresponds to the assumptions implied in current design specifications. Many of these standards simply extend the findings of research on composite T-beams.
2. The spacing to span ratio of composite beams in constructed buildings is most often between the values of 0.25 and 0.5.
3. According to the conventional stress-based definition, effective widths of composite L-beams tend to increase with wider spacing. Effective widths computed from a stiffness-based definition tend to decrease with wider beam spacing. At wide spacings, designers should exercise greater conservatism when estimating stiffness using a stress-based effective width.
4. Effective widths of composite L-beams based on stress tend to decrease with increasing interaction between steel and concrete, a trend not consistent with intuitive expectations. In contrast, effective widths based on stiffness tend to increase with increasing interaction. These findings are consistent with Adekola's observations for interior (or T-shaped) beams.
5. A stiffness-based effective width is recommended for design of uniformly loaded composite L-beams according to the formula $b_e = 0.13l - 0.16s$. This formula provides the portion of effective width at the interior side of the steel beam centerline.
6. For a uniform floor load on an exterior L-beam, pattern of cladding load does not appear to have an influence on the effective width at midspan.

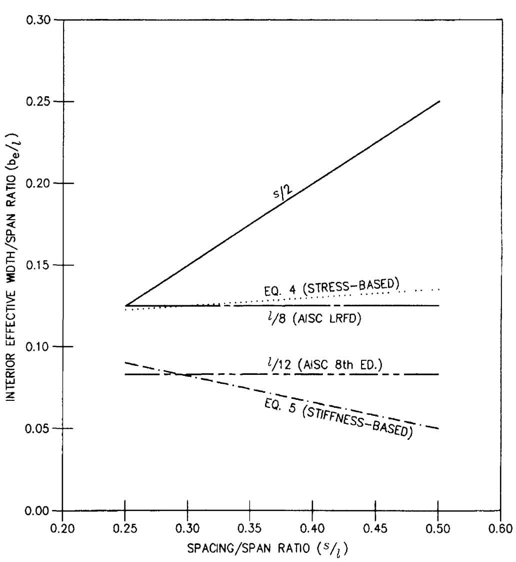

Fig. 8. Comparison of effective width formulas.

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NOMENCLATURE

b_e Effective concrete flange width, inches
b_f Steel beam flange width, inches
l Beam span length, inches
Q Load on a single shear connector, kips
Q_u Ultimate load of a single shear connector, kips
s Beam spacing, inches
t_s Slab thickness, inches
z Longitudinal slip between slab and beam, inches
δ Deformation of shear connector, inches
Δ Vertical beam deflection, inches

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