The Economies of LRFD in Composite Floor Beams

MARK C. ZAHN

The AISC Load and Resistance Factor Design (LRFD) Specification represents the state-of-the-art approach in the U.S. for routine structural steel design.[1] Based on a reliability, ultimate strength theory, use of the LRFD Specification may have an economic advantage over the current 8th Edition AISC *Manual of Steel Construction*,[2] Allowable Stress Design (ASD) Specification. An economic advantage of reduced weight of building elements, while meeting all strength and serviceability requirements, is sure to exist. One major building element where the full economy of LRFD could be realized is in composite floor beam construction. A comprehensive study is thus warranted.

The purpose of this paper is to report the findings of an in-depth comparative design study between the recently published LRFD and the established ASD Specifications for simply supported composite floor beams. The results are based on a direct beam weight comparison of over 2,500 composite beam designs and shear stud requirements using A36 steel.

DESIGN CONSIDERATIONS

The design of any structural member must meet both strength and serviceability requirements. Strength criteria is met by allowable stress limits using the ASD approach and by member resistance, or capacity, using the LRFD approach. The differences in design methodologies will be illustrated by applicable specification sections and equations.

Serviceability requirements in this study include: (1) limiting live load deflections to 1/360 of the beam span L and (2) limiting the floor vibration induced by a heel drop impact load. The upper limit range of slightly perceptible to distinctly perceptible as reported by Murray[3,4] was selected for this investigation. This corresponds to a response rating R of 2.75. Floor vibration perceptibility was of particular interest. With a savings in beam weight expected using the LRFD Specification, a fundamental question arises. With all design parameters and serviceability requirements being equal, will an LRFD composite beam have both an acceptable floor vibration response rating and an economic advantage over an ASD composite beam design? A direct economic comparison, using dollars and cents, is outside the scope of this paper because of many varying factors. However, by making a comparison of beam weight and shear stud requirements of each design, an indirect cost comparison on a quantitative basis can be made.

Mark C. Zahn is a Structural Engineer with Chris P. Stefanos Associates, Inc., Consulting Structural Engineers, Oak Lawn, Illinois.

DESIGN PARAMETERS

Several basic assumptions are common to each design method: (1) only wide flange sections which meet the compact section criteria of ASD Specification 1.5.1.4.1 and LRFD Specification Sect. B5.1 are used, (2) beams are considered to have continuous lateral support of their compression flange during construction, (3) metal deck ribs run perpendicular to the beam span, (4) construction live loads are included for unshored construction and (5) dead load deflections are not limited; it is assumed that beam cambering during fabrication could be provided for in either design method and would not be a significant factor in this study.

Loading, type of construction, spacing, and span parameters were selected to envelope each controlling design criteria of strength and serviceability. Spans range from 10 ft to 45 ft; beam spacings range from five ft to 10 ft.

Two load conditions have been studied with both shored and unshored construction types considered. Each load condition uses minimum slab and metal deck depths in order to investigate the minimum potential savings between the ASD and LRFD design approaches. Representing a "common" load case a live load of 100 psf with a dead load of 50 psf was selected. This load case has a total slab thickness of 4 in., 1-½ in. metal deck, 3,000 psi concrete strength and a live load to dead load ratio of two. On the heavier side a live load of 250 psf, dead load of 60 psf, total slab thickness of 6 in., 3-in. metal deck, and 4,000 psi concrete strength is used. This second loading condition has a live load to dead load ratio greater than four.

Table 1. ASD/LRFD Shape List

W 8×10	W 8×24	W21×44	W27× 94	W36×160
W10×12	W16×26	W18×46	W30× 99	W36×170
W 8×13	W 8×28	W21×50	W27×102	W36×182
W10×15	W14×30	W24×55	W30×108	W36×194
W12×16	W16×31	W21×57	W30×116	W33×201
W10×17	W14×34	W18×60	W33×118	W36×210
W 8×18	W18×35	W24×62	W33×130	W33×221
W12×19	W16×36	W24×68	W36×135	W36×230
W 8×21	W14×38	W24×76	W33×141	W36×245
W14×22	W18×40	W27×84	W36×150	W36×260

Wide flange sections range from W8 × 10 to W36 × 300 for this investigation. Considering all of the shapes commonly used for beam members, a reduced list of 50 shapes was selected and arranged according to increasing weight. This reduced data base is necessary to eliminate duplicate weight shapes and assure an economical design. For example, W14 × 30 and W12 × 30 are of equal weight; however, because of the greater depth, the W14 × 30 section is a part of the design section data base. Depth of beam was not an imposed limitation on beam selection.

DESIGN METHODOLOGY

Each composite beam shape is chosen from respective computer data files for ASD and LRFD design using an IBM PC/AT computer. Each file contains the same shapes and order of selection (Table 1). Properties required for calculating transformed sections are taken from the 8th Edition AISC Manual. The LRFD data file contains moment capacity values ϕM_n and ϕM_p, neutral axis and resultant compressive force locations *Y1* and *Y2* respectively, and shear connector strength ΣQ_n associated with the above values. This information is from Part 4 of the 1st Edition LRFD Manual, Composite Beam Selection Tables.

Three areas of composite beam design have undergone noteworthy changes in developing the LRFD approach from the ASD approach. The first area which has been revised is the determination of effective width. LRFD Sect. I3.1 defines $b_{eff}/2$ for interior beams as the minimum of: (a) one-eighth of the beam span center line to center line of supports, or (b) one-half the distance to the center line of adjacent beams. ASD Section 1.11.1, on the other hand, gives, for interior beams, the following definition for $b_{eff}/2$ as the minimum of: (a) one-eighth of the beam span, (b) one-half the distance to the center line of adjacent beams or (c) eight times the slab thickness plus one-half the beam flange width. By reviewing these criteria it is seen that for smaller beam spacing effective widths will be equal with both methods. However, as the spacings increase the slab thickness criterion of the ASD approach will control and give a smaller effective width for ASD beams. This requires a larger beam shape to meet ASD requirements. Recent studies[5,6] have indicated the established ASD slab thickness criterion is conservative as applied to interior beams and that the LRFD effective width definition is much more realistic.

The second, and most striking, change is in bending of both shored and unshored construction. Based on the assumptions previously stated, the ASD Specification limits the allowable steel fiber stress for shored construction to $0.66\,F_y$ (Sect. 1.5.1.4.1) and the allowable concrete compressive stress to $0.45\,f'_c$ (Sect. 1.11.2.2). For unshored construction an allowable steel flange tension stress of $0.89\,F_y$ is indirectly applied[7] by ASD Specification Sect. 1.11.2.2: $S_{tr} = (1.35 + 0.35\,M_{LL}/M_{DL})S_s$. S_s is the section modulus of the steel beam alone at its bottom flange, M_{LL} and M_{DL} are the live load and dead load moments respectively, and S_{tr} is the maximum transformed section modulus for which unshored construction is permitted. The LRFD approach relies on load factors, 1.6 live load and 1.2 dead load and resistance factors ϕ. The criteria of factored required strength by analysis must be less than or equal to the member design resistance, more simply $R_u \leq \phi R_n$. Using compact sections and full lateral support composite beams may develop the maximum resistance of the steel section from a plastic stress distribution (LRFD Sects. I3.2 and F1.3). By Sect. F1.2 and I3.2 and Part 4 of the LRFD Manual ϕ is equal to 0.9 for noncomposite action (prior to concrete set during unshored construction) and 0.85 for composite action. Having factored moments from analysis, the engineer selects a section which provides a resistance ϕM_n equal to or exceeding that required. Composite beam design aids are provided in the LRFD Manual. Part 4 gives ϕM_p, ϕM_n, I_{LB}, *Y1*, *Y2*, and ΣQ_n values as defined previously. For a complete explanation of the development and use of this design aid the reader is referred to Refs. 1 and 8.

The third noteworthy difference in design methods involves the effective moment of inertia used for deflection calculations. As noted, the LRFD composite beam design aid in Part 4 of the Manual contains values of lower bound moment of inertia (I_{LB}). These values represent a transformed moment of inertia using an equivalent area of concrete which is effective in compression and based on the transfer of horizontal shear force.[8] It is obvious deflection calculations using I_{LB} may differ considerably from those of ASD which permits the full concrete thickness for moment of inertia values.

Shear requirements on the web area A_w have not been revised significantly. The familiar ASD Specification Sect. 1.5.1.2.1 gives the allowable shear as $V_{all.} = 0.4\,F_y A_w$. This same format applies to the LRFD Specification Sect. F2 defining the shear resistance as $\phi R_n = \phi\ 0.6\ F_y\ A_w$ for compact sections with no stiffeners, where ϕ equals 0.9.

RESULTS

The analysis comparing composite beam designs and the potential savings between the LRFD and ASD Specifications focuses on four major areas: (1) strength, (2) floor vibration response, (3) deflection, and (4) shear connector requirements. The results are presented as a series of graphs with accompanying discussion. To include graphs for each load case, type of construction, and beam spacing would mean including over 70 graphs—a total well beyond the intent of this report. Therefore, graphs have been selected which best represent the overall results.

Consider first the criteria of strength only. With all other limitations removed, designs by each method can be compared for beam weight savings in its most basic form. Figure 1a illustrates a plot of beam weight, based on strength only, for each approach vs. span length. This graph represents an eight foot beam spacing, shored construction, and the heavy loading condition as described previously and gives a reasonable representation of the overall results. With only minor modifications, this graph could represent any load case, construction type and beam spacing. In all cases, there is a region in the lower span lengths which has very little or no difference in beam weight by either specification. As span length increases to 20 or 22 ft, the margin of difference between sizes increases slightly and, in general, will decrease at the 20- or 22-ft span length. This area, 13 to 22 ft, exhibits a reduction in beam weight using LRFD ranging from two to seven percent. Past the 22-ft span, LRFD consistently gives reduced weights over the ASD design approach. Increased strength associated with the LRFD approach is illustrated in Fig. 1b. It can be seen that a greater strength is developed when considering the full section as effective with a plastic stress distribution. Thus, under the LRFD approach, strength requirements can be met with a lighter, more economical section. In only a few cases, design beam weights were equal at random span lengths and in no case is an LRFD beam design heavier than an ASD beam design. Figure 1a shows weight reductions as high as 15%. Overall, based on strength only, reductions reached a maximum of 45%. This is only the first indication of the savings possible during the LRFD Specification.

The addition of floor vibration response rating and deflection limitations gives very noteworthy results. All calculations, for each design method, follow the procedure by Murray[3,4] with a damping of 4% and a weight term, for the purpose of this investigation, which includes dead load plus full live load. Interesting results occurred for the load case using 100 psf live load and 50 psf dead load (having minimum slab and deck depths). For span lengths less than 23 feet, vibration rating was of great significance (due to the reduced total weight and reduced moment of inertia terms) and is the controlling factor for beam selection. With this in mind, it is easily understood that there will be no difference in beam weights using the LRFD or ASD approaches up to 23 foot spans. Beyond 23 feet, however, strength becomes the controlling factor and a substantial savings in weight is seen. Figures 2a and 3a show the relationships between the two design methods for the load case of 100 psf LL and 50 psf DL. Spacing and type of construction are noted on each figure. Figures 2b and 3b are plots of the percent reduction

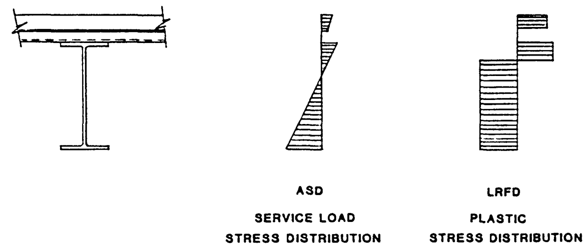

Figure 1b

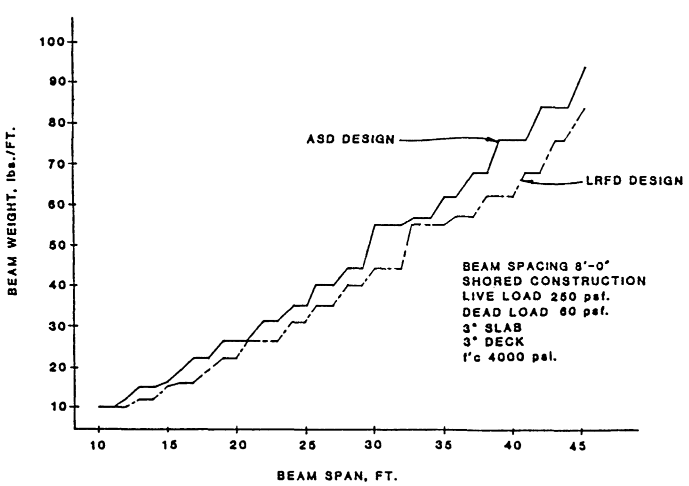

Fig. 1a. ASD/LRFD composite beam design comparison

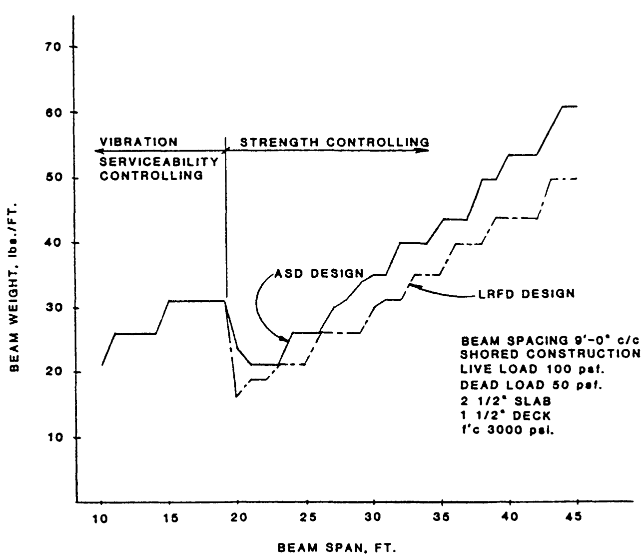

Fig. 2a. ASD/LRFD composite beam design comparison

in beam weight, or savings, versus span length associated with Figs. 2a and 3a. Savings in weight reach as high as 30% for the shored condition (Fig. 2) and as high as 37% for the unshored condition (Fig. 3). Savings are, therefore, not limited to one type of construction. Figures 4a and 4b give a similar result for the heavier load case. However, in the shorter span region vibration is not a controlling factor and equal weights in this area are seldom encountered. In fact, for the span lengths between 10 and 16 ft, savings are the greatest and approach 40%.

The third item in this study is deflection. With the introduction in the LRFD approach of the Lower Bound Moment of Inertia (I_{LB}) concept, a direct comparison of live load deflection is inconsequential. I_{LB} values can be as

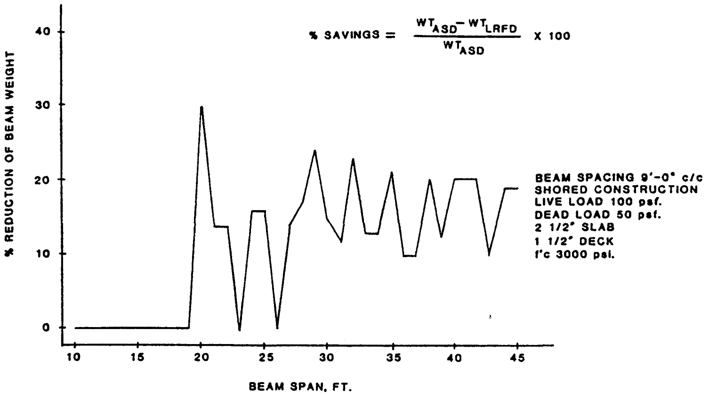

Fig. 2b. ASD/LRFD composite beam weight savings

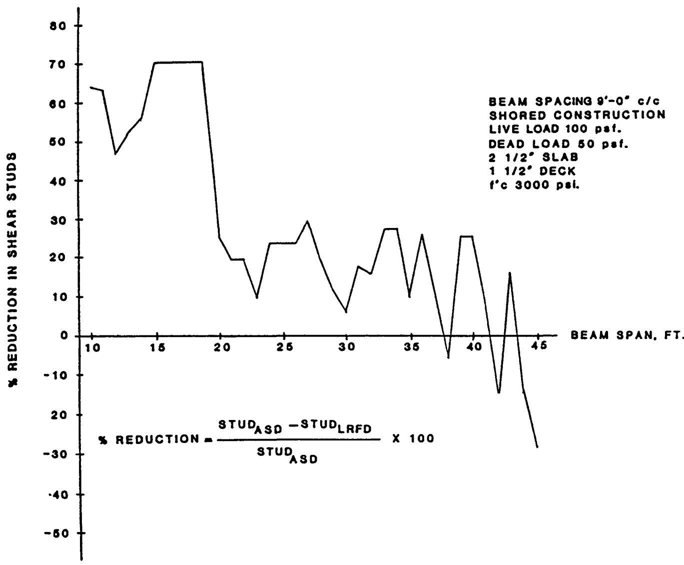

Fig. 2c. ASD/LRFD shear stud comparison

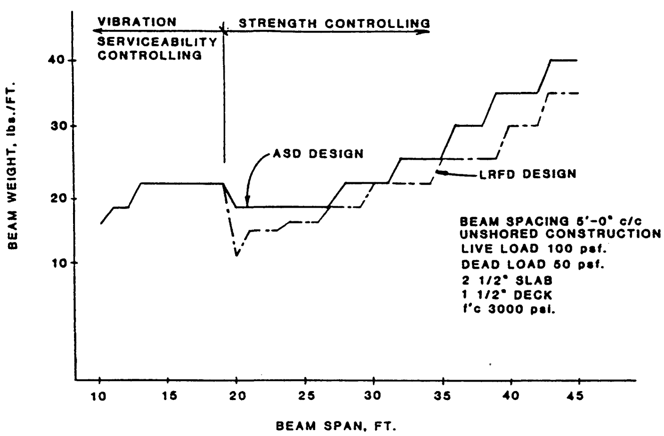

Fig. 3a. ASD/LRFD composite beam design comparison

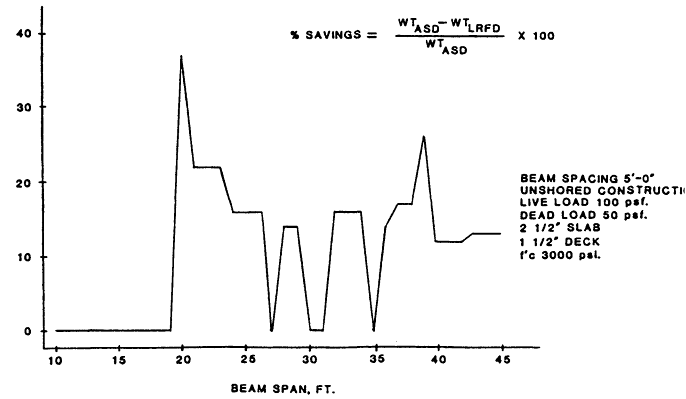

Fig. 3b. ASD/LRFD composite beam weight savings

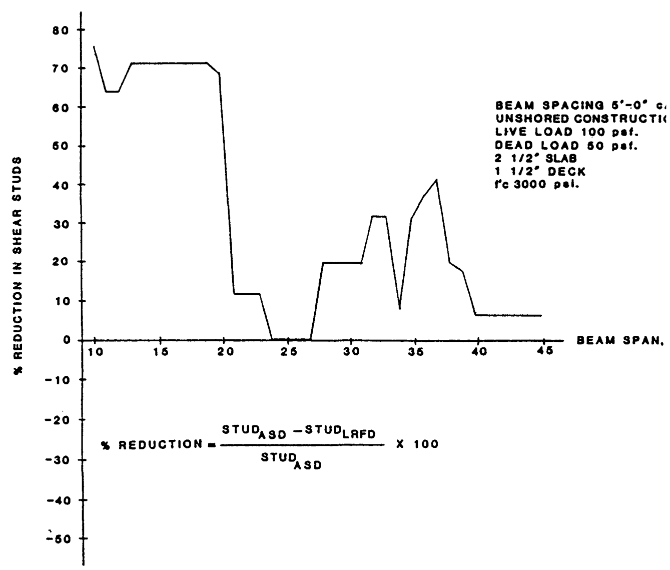

Fig. 3c. ASD/LRFD shear stud comparison

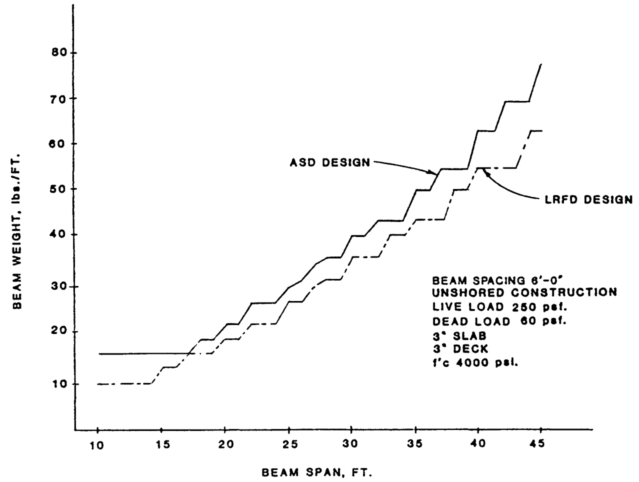

Fig. 4a. ASD/LRFD composite beam design comparison

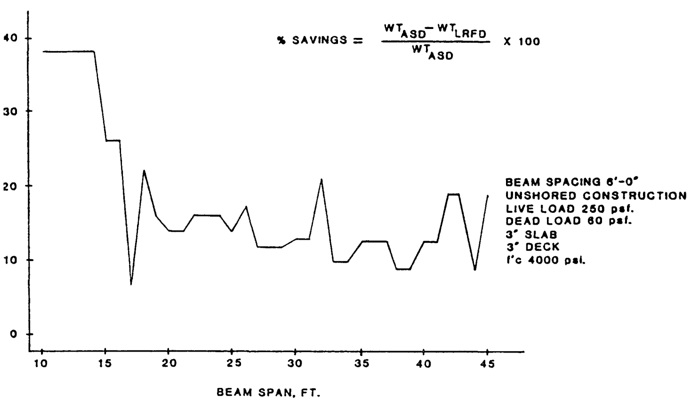

Fig. 4b. Composite beam weight savings

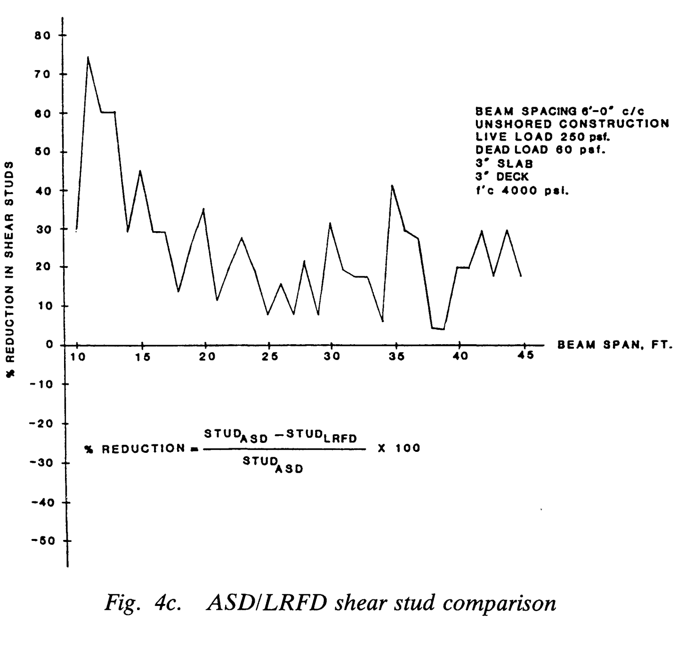

Fig. 4c. ASD/LRFD shear stud comparison

much as 50% less than the transformed moment of inertia for the same size section by the ASD approach. It is worth noting, however, in no case did the live load deflection criteria of *L/360* cause a heavier section to be selected. And, studies by Vallenilla and Bjorhovde have suggested the ASD Specification procedure underestimates actual deflections.[6] Furthermore, Ref. 6 suggests the LRFD concept gives more realistic results for interior beams. Live load deflections which correspond to Fig. 3 range from 0.01 in. to 1.4 in. by LRFD and 0.01 in. to 1.02 in. by ASD. Dead load deflections range from 0.01 to 1.55 in. by LRFD and 0.01 to 1.29 in. by ASD.

The fourth area of interest is shear-stud connector requirements. The established ASD Specification defines the horizontal shear force for simply supported beams as the smaller of $V_h = 0.85 f'_c A_c/2$ (Formula 1.11-3) or $V_h = A_s F_y/2$ (Formula 1.11-4). In these formulas, A_s is the area of the steel section and A_c is the area of concrete within the effective width. LRFD is quite similar in format to ASD, but extends the approach of ASD Formula 1.11-3 to an ultimate state and considers only the effective area of concrete which is in compression. This area may not include the full concrete depth. LRFD horizontal shear force is covered in Sect. I5.2 of the LRFD Manual. Composite Beam Selection Tables in Part 4 tabulate horizontal shear force requirements ΣQ_n based on neutral axis and compressive force locations *Y1* and *Y2*. Typical results of the percent change in connector requirements from ASD to LRFD are shown in Figs. 2c, 3c and 4c. For the 100-psf live load with 50-psf dead load cases of Figs. 2c and 3c, three distinct ranges of span length are worth noting. For span lengths between 10 and 20 ft, the differences in connector requirements are primarily due to the differences in design methodologies. For this minimum deck and slab depth condition, the controlling ASD shear force is Formula 1.11-3. The ASD specification permits using the full depth of concrete above the metal deck for calculating A_c. On the other hand, because vibration is the controlling factor in this region, the LRFD beam is relatively inefficient for composite action and develops only a very small effective concrete depth. This explains the wide margin of difference between the ASD and LRFD shear-stud requirements. Type of construction is not a factor. As the span length increases to 40 ft there is a consistent reduction in shear studs required by LRFD over ASD beams. These reductions reach as high as 40% for closely spaced beams (Fig. 3c) and as high as 30% for larger spacings (Fig. 2c). From 40 to 45 ft, the ASD approach requires increasingly fewer studs over the LRFD approach, as beam spacing increases from 5 to 10 ft. In this upper range of spans, the sharp decline in margin of difference is again attributed to methodology. Two factors are important on the ASD side; the effective depth and the effective width b_{eff}. As stated previously, the ASD criteria of eight times the total slab depth criteria will control in Fig. 2c. Therefore, ASD formula 1.11-3 controls. Stud requirements for LRFD, however, will be controlled by LRFD

Sect. I5.2 Eq. 2: $A_s F_y$. Thus, the margin of difference will decrease as span and spacing increases. In some cases, as shown in Fig. 2c, ASD may require fewer studs over LRFD. It should be noted, however, that a lighter section may be used by the LRFD approach over the ASD method and an overall economy may be realized.

The heavier load case of Fig. 4 does not follow this same pattern. With few exceptions, span lengths of 10 to 20 ft show a significant reduction (up to 60%) in shear studs using LRFD. Between 20 and 45 ft, the reduction varies from 0 to 33%. Greatest reductions are shown in the 24- to 27-ft, 30- to 33-ft and 38- to 41-ft areas; Fig. 4c represents this behavior. In no case did the ASD require fewer studs than the LRFD approach for this load condition.

Further investigation has been completed using a 3-in. metal deck, 2½-in. slab, and the (100 psf LL)/(50 psf DL) condition. In both the shored and unshored cases, the behavior exhibited follows that shown in Fig. 4. As in Figs. 4a and 4b, the greatest savings in beam weight occur over spans ranging from 10 to 25 ft. In spans from 25 to 45 ft, a consistent savings of 15% occurs. Shear stud reductions peak in the shorter spans and level off to 20% for spans ranging from 25 to 35 ft.

The full economies of LRFD in composite floor beam construction cannot be realized without addressing the relative cost differential between the ASD and LRFD methods on the final composite beam design. Preliminary results of this study show that, when using minimum slab and deck parameters without regard to fire protection rating by the structure, there is an average savings of up to 6% for span lengths between 10 and 18 ft, 15% for span lengths between 18 and 30 ft and 14% for span lengths between 30 and 45 ft. These findings are based on a fabricated and erected cost per pound of steel to cost per shear stud connector ratio of 1:3.75.

CONCLUSION

This investigation has shown the recent 1st Edition *Load and Resistance Factor Design Manual of Steel Construction* does have an economic advantage over the 8th Edition *Manual of Steel Construction* in composite floor beam construction. For span lengths of 10 to 20 ft with a 100-psf live load and 50-psf dead load condition, minimum slab and deck depths, vibration serviceability is the controlling factor regardless of the design method used. As spans increase to 38 ft, designs by the LRFD approach consistently give lighter beam weights and require fewer shear connectors for full composite action. Beyond 38 ft, lighter beam weights are evident with a moderate increase in shear connectors. Preliminary results of a cost comparison study indicate savings average 6% to 15% for span lengths ranging from 10 to 45 ft. Serviceability has not been compromised using the LRFD approach. All designs meet the *L/360* live load deflection limitation commonly used in design. LRFD deflections are slightly higher than those using the ASD method of transformed section properties. It should be noted, however, previous studies indicate the ASD approach currently underestimates actual composite beam deflections.

Based on this investigation, the Load and Resistance Factor Design approach to composite floor beam construction will have a substantial overall savings in material costs without compromising serviceability. In addition, the introduction of *ILB* in the LRFD Manual for deflection calculations gives a much more realistic and reliable account of live load deflections.

ACKNOWLEDGMENTS

Appreciation is due Elizabeth Reardon, Structural Engineer with Sargent & Lundy Engineering, for her programming contribution and floor vibration criteria input. Thanks also to Lynn Echlin for typing this manuscript.

REFERENCES

1. *American Institute of Steel Construction, Inc.* Load and Resistance Factor Design Manual of Steel Construction *1st Ed., 1986, Chicago, Ill.*
2. *American Institute of Steel Construction, Inc.* Manual of Steel Construction *8th Ed., 1980, Chicago, Ill.*
3. *Murray, Thomas M.* Acceptability Criterion For Occupancy-Induced Floor Vibrations *AISC Engineering Journal, 2nd Qtr., 1981, Chicago, Ill. (pp. 62–69).*
4. *Murray, Thomas M.* Design to Prevent Floor Vibrations *AISC Engineering Journal, 3rd Qtr., 1975, New York, N.Y. (pp. 82–87).*
5. *American Society of Civil Engineers* Structural Design of Tall Buildings *Vol. SB, 1979 (pp. 620–627).*
6. *Vallenilla, Cesar R. and R. Bjorhovde* Effective Width Criteria for Composite Beams *AISC Engineering Journal, 4th Qtr., 1985 (pp. 169–175).*
7. *Gaylord, Edwin H. and C. N. Gaylord* Design Of Steel Structures *2nd Ed., McGraw-Hill, Inc., 1972 (pp. 346–347).*
8. *Zahn, Cynthia J.* LRFD Design Aids: Plate Girders and Composite Beams *AISC National Engineering Conference Proceedings, 1986, Chicago, Ill. (pp. 37–8 through 37–15).*