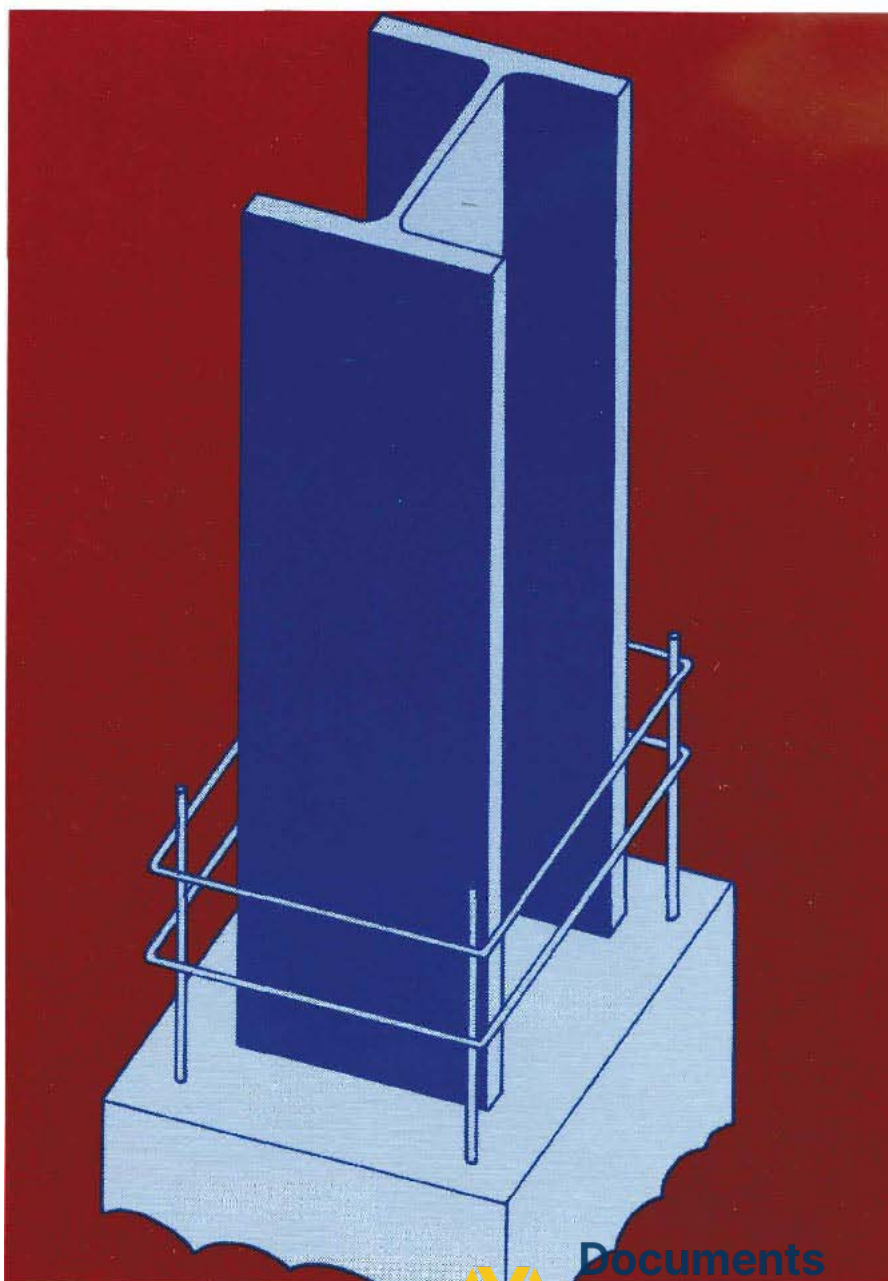




Steel Design Guide Series

Load and Resistance Factor Design of *W-Shapes* *Encased in Concrete*



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Load and Resistance Factor Design of W-Shapes Encased in Concrete (None -Table Version)

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PREFACE

This booklet was prepared under the direction of the Committee on Research of the American Institute of Steel Construction, Inc. as part of a series of publications on special topics related to fabricated structural steel. Its purpose is to serve as a supplemental reference to the AISC Manual of Steel Construction to assist practicing engineers engaged in building design.

The design guidelines suggested by the authors that are outside the scope of the AISC Specifications or Code do not represent an official position of the Institute and are not intended to exclude other design methods and procedures. It is recognized that the design of structures is within the scope of expertise of a competent licensed structural engineer, architect, or other licensed professional for the application of principles to a particular structure.

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LOAD AND RESISTANCE FACTOR DESIGN OF W-SHAPES ENCASED IN CONCRETE

INTRODUCTION

Structural members comprised of steel shapes in combination with plain or reinforced concrete have been utilized by engineers for many years. Early structures simply took advantage of the protection that the concrete afforded to the steel shapes for resistance to fire and corrosion. But research on the strength of such members was conducted in the early 1900s,¹ and design provisions were formulated by 1924.² More recently, with the advent of modern composite frame construction in high rise buildings, engineers developed new rational methods to take advantage of the stiffening and strengthening effects of concrete and reinforcing bars on the capacity of encased steel shapes.

This Guide presents design tables for composite columns, developed under the sponsorship of the American Institute of Steel Construction (AISC) as an aid to the practicing structural engineer in the application of the AISC Load and Resistance Factor Design (LRFD) Specification for Structural Steel Buildings.³ The information presented supplements that found in the AISC LRFD Manual.⁴ Background on the LRFD criteria for composite columns may be found in References 5 and 6. Engineers interested in Allowable Stress Design (ASD) are encouraged to consider the procedure developed previously by the Structural Stability Research Council (SSRC).⁷ The SSRC procedure is not presently included in the AISC ASD Specification.⁸

The reader is cautioned that independent professional judgment must be exercised when data or recommendations set forth in this Guide are applied. The publication of the material contained herein is not intended as a representation or warranty on the part of the American Institute of Steel Construction, Inc.—or any person named herein—that this information is suitable for general or particular use, or freedom from infringement of any patent or patents. Anyone making use of this information assumes all liability rising from such use. The design of structures should only be performed by or under the direction of a competent licensed structural engineer, architect, or other licensed professional.

SCOPE

This Guide is specifically for composite columns comprised of rolled wide flange shapes encased in reinforced structural concrete with vertical deformed reinforcing bars and lateral ties. Composite columns are defined in Section I1 of the

LRFD Specification as a "steel column fabricated from rolled or built-up steel shapes and encased in reinforced structural concrete or fabricated from steel pipe or tubing and filled with structural concrete." Further, the Specification requires in Section I2.1 that the cross sectional area of the steel shape comprise at least four percent of the total composite cross section. The Commentary to the Specification states that when the steel shape area is less, the column should be designed under the rules for conventional reinforced concrete columns.

Part 1 of this Guide includes a discussion of composite frame construction, practical uses of composite columns, their advantages and limitations, and a review of important practical design considerations. A summary of the pertinent LRFD rules is presented and compared to other methods. A set of suggested design details is given in Part 2, showing placement of reinforcing bars and ties, as well as treatment of joints and base plates. Five design examples are given in Part 3 to illustrate how the tables were derived and how they are applied. Finally, a comprehensive set of tables is presented in Part 4 to assist the designer in the rapid selection of the most economical section to resist required values of factored load and moment.

PART 1: USE AND DESIGN OF COMPOSITE COLUMNS

Composite Frame Construction

Although engineers since the 1930s have encased structural steel shapes in concrete for fireproofing and corrosion protection, it was not until the development and popularity of modern composite frame construction in the 1960s that composite columns again became a common and viable structural member type. The late Dr. Fazlur Khan, in his early discussions of structural systems for tall buildings, first proposed the concept of a composite frame system^{9,10} utilizing composite columns as part of the overall wind and earthquake resisting frame. Since that time composite frame construction has been adopted for many high rise buildings all over the world. Its usage, with the composite column as the key element, is well documented in the work of the Council on Tall Buildings and numerous other publications.¹¹⁻¹⁵

The term "composite frame structure" describes a building employing concrete encased steel columns and a composite floor system (structural steel and concrete filled steel deck).

The bare steel columns resist the initial gravity, construction, and lateral loads until such time as the concrete is cast around them to form composite columns capable of resisting the total gravity and lateral loads of the completed structure. In a composite frame building, the structural steel and reinforced concrete combine to produce a structure having the advantages of each material. Composite frames have the advantage of speed of construction by allowing a vertical spread of the construction activity so that numerous trades can engage simultaneously in the construction of the building. Inherent stiffness is obtained with the reinforced concrete to more easily control the building drift under lateral loads and reduce perception to motion. The light weight and strength obtained with structural steel equates to savings in foundation costs.

Traditionally in steel framed buildings or reinforced concrete buildings, stability and resistance to lateral loads are automatically provided as the structure is built. Welded or bolted moment connections are made or braces are connected between columns in a steel building immediately behind the erection of the steel frame to provide stability and resistance to lateral loads. Shear walls, or the monolithic casting of beams and columns, provide stability and resistance to lateral loads soon after the concrete has cured for reinforced concrete buildings. However, for composite frame structures, the final stability and resistance to design lateral loads is not achieved typically until concrete around the erection steel frame has cured, which typically occurs anywhere from a minimum of six to as much as 18 floors behind the erection of the bare steel frame. This sequence of construction is shown-schematically in Fig. 1. Thus, as discussed subsequently, *temporary*

lateral bracing of the uncured portion of the frame will typically be required.

Practical Uses of Composite Columns

Practical applications for the use of composite columns can be found in both low rise and high rise structures. In low rise structures such as a covered playground area, a warehouse, a transit terminal building, a canopy, or porte cochere, it may be necessary or desirable to encase a steel column with concrete for aesthetic or practical reasons. For example, architectural appearance, resistance to corrosion, or protection against vehicular impact may be important. In such structures, it may be structurally advantageous to take advantage of the concrete encasement of the rolled steel shape that supports the steel roof structure by designing the member as a composite column resisting both gravity and lateral loads.

In high rise structures, composite columns are frequently used in the perimeter of "tube" buildings where the closely spaced columns work in conjunction with the spandrel beams (either steel or concrete) to resist the lateral loads. In some recent high rise buildings, giant composite columns placed at or near the corners of the building have been utilized as part of the lateral frame to maximize the resisting moment provided by the building's dead load. Composite shear walls with encased steel columns to carry the floor loads have also been utilized in the central core of high rise buildings. Frequently, in high rise structures where floor space is a valuable and income producing commodity, the large area taken up by a concrete column can be reduced by the use of a heavy encased rolled shape to help resist the extreme loads encountered in tall building design. Sometimes, particularly at the bottom floors of a high rise structure where large open lobbies or atriums are planned, a heavy encased rolled shape as part of a composite column is a necessity because of the large load and unbraced length. A heavy rolled shape in a composite column is often utilized where the column size is restricted architecturally and where reinforcing steel percentages would otherwise exceed the maximum code allowed values.

Advantages, Disadvantages, and Limitations

Some of the advantages of composite columns are as follows:

1. Smaller cross section than required for a conventional reinforced concrete column.
2. Larger load carrying capacity.
3. Ductility and toughness available for use in earthquake zones.
4. Speed of construction when used as part of a composite frame.
5. Fire resistance when compared to plain steel columns.
6. Higher rigidity when part of a lateral load carrying system.
7. Higher damping characteristics for motion perception in tall buildings when part of a lateral load carrying system.

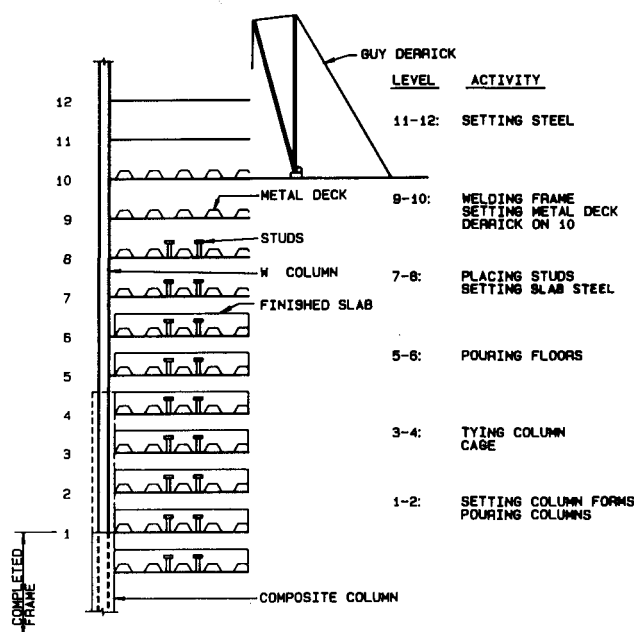


Fig. 1. Composite-frame construction sequence.

8. Stiffening effect for resistance against buckling of the rolled shape.

There are also, of course, some disadvantages and limitations. In high rise composite frame construction, design engineers sometimes have difficulty in controlling the rate and magnitude of column shortening of the composite column with respect to adjacent steel columns or shear walls. These problems are exacerbated by the wide variation in construction staging often experienced in the zone between the point where the steel erection columns are first erected and the point where concrete is placed around the steel to form the composite column. This variation in the number of floors between construction activities has made it difficult to calculate with accuracy the effect of column shortening. Creep effects on the composite columns with respect to the all-steel core columns, or between shears walls, can also be troublesome to predict for the designer. The net effect of these problems can be floors that are not level from one point to another. One solution to these problems has been the measurement of column splice elevations during the course of construction, with subsequent corrections in elevation using steel shims to compensate for differences between the calculated and measured elevation.

As with any column of concrete and reinforcing steel, the designer must be keenly aware of the potential problems in reinforcing steel placement and congestion as it affects the constructability of the column. This is particularly true at beam-column joints where potential interference between a steel spandrel beam, a perpendicular floor beam, vertical bars, joint ties, and shear connectors can all cause difficulty in reinforcing bar placement and lead to honeycombing of the concrete. Careful attention must be given to the detailing of composite columns by the designer. Analytical and experimental research is needed in several aspects of composite column design. One area requiring study is the need, or lack thereof, of a mechanical bond between the steel shape and the surrounding concrete. Several papers^{16,17} have discussed this question, but additional work is required to quantify the need for shear connectors with a practical design model for routine design office use. There presently is a question about transfer of shear and moment through a beam-column joint. This concern is of particular importance for seismic regions where large cyclical strain reversals can cause a serious degradation of the joint. Initial research has been completed at the University of Texas at Austin²⁴ and is ongoing at Cornell University on physical test models to study various joint details in composite columns.

Practical Design Considerations

Fire Resistance

Composite columns, like reinforced concrete columns, have an inherent resistance to the elevated temperatures produced in a fire by virtue of the normal concrete cover to the reinforcing

steel and structural steel. It is standard practice to provide a minimum of one and one-half inch of concrete cover to the reinforcing steel of a composite column (concrete cover is specified in ACI 318-89 Section 7.7.1).¹⁸ Chapter 43 of the Uniform Building Code states that reinforced concrete columns utilizing Grade A concrete (concrete made with aggregates such as limestone, calcareous gravel, expanded clay, shale, or others containing 40 percent or less quartz, chert, or flint) possess a four-hour rating with one and one-half inch cover. A four-hour rating is the maximum required for building structures.

Tables of fire resistance rating for various insulating materials and constructions applied to structural elements are published in various AISI booklets^{19,20,21} and in publications of the Underwriters Laboratory, Inc.

Longitudinal Reinforcing Bar Arrangement

Composite columns can take on just about any shape for which a form can be made and stripped. They can be square, rectangular, round, triangular, or any other configuration, with just about any corresponding reinforcing bar arrangement common to concrete columns. For use in composite frame construction, however, square or rectangular columns

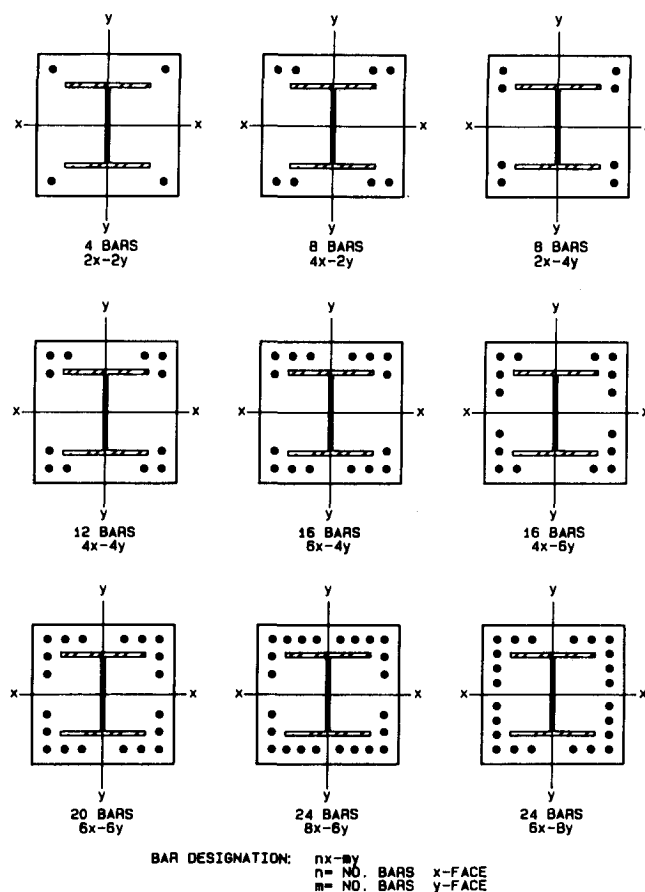


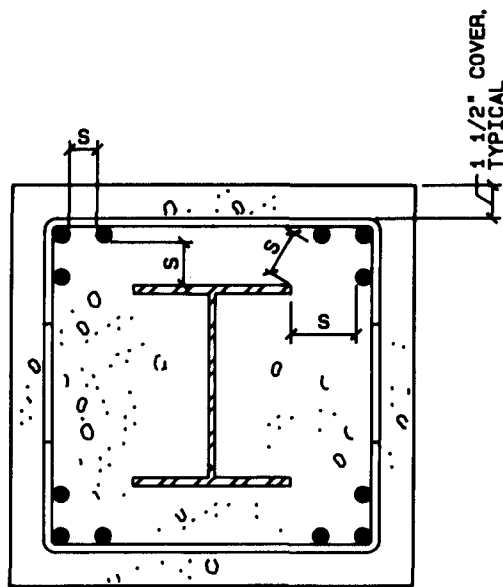
Fig. 2. Longitudinal bar arrangement in composite columns.

are the most practical shape, with bar arrangements tending to place the vertical reinforcing bars at or near the four corners of the column. Figure 2 shows preferred arrangements which allow spandrel beams and a perpendicular floor beam to frame into the encased steel shape without interrupting the continuous vertical bars. Such arrangements also generate the maximum design capacity for the column.

Although there are no explicit requirements for longitudinal bar spacing in the LRFD Specification, it is advisable to establish minimum limits so that concrete can flow readily in spaces between each bar and between bars and the encased steel shape.

Minimum spacing criteria will also prevent honeycombing and cracks caused by high bond stresses between bars. Past experience with reinforced concrete columns has shown that the requirements established by the ACI 318 Code have provided satisfactory performance. These spacing and cover requirements have been used in the formulation of this design aid and as diagramed in Fig. 3 and listed below:

1. Minimum concrete cover over vertical bars and ties shall be 1½-in. (LRFD Specification, Section I2.1.b).
2. Clear distance between longitudinal bars shall not be less than 1½ bar diameters or 1½-in. minimum (ACI 318-89 Section 7.6.3).



S=CLEAR DISTANCE BETWEEN BARS OR CLEAR DISTANCE BETWEEN ANY BAR AND FACE OF W SHAPE

$S \geq 1 \frac{1}{2}d_b$ OR $1 \frac{1}{2}"$, WHICHEVER IS GREATER

d_b = BAR DIAMETER

Fig. 3. Composite column cover and bar spacing requirements.

3. The clear distance limitations apply also to contact lap splices and adjacent bars (ACI 318-89 Section 7.6.4).
4. Clear distance between longitudinal bars and steel shape shall be 1½ bar diameters or 1½-in. minimum.

Ties

Reinforcing steel cages (longitudinal bars and ties) must usually be set after and around the steel column. Because the steel column is erected in an earlier erection sequence, only open U-shaped ties are suitable for composite columns. Ties are used to provide lateral stability of the longitudinal bars and confinement of the concrete. The requirements of the LRFD specification and certain requirements of the ACI 318-89 code not specifically addressed by the LRFD specification should be satisfied as follows:

1. The cross sectional area of the tie shall be at least 0.007 square inches per inch of tie spacing (LRFD Specification I2.1.b).
2. The spacing of the ties shall not be greater than two-thirds of the least dimension of the cross section (LRFD Specification I2.1.b).
3. The spacing of ties shall not be greater than 16 longitudinal bar diameters or 48 tie bar diameters (ACI 318-89 Section 7.10.5.1).
4. Ties shall be at least #4 in size for #11, #14, #18, and bundled longitudinal bars, and #3 in size for all other bars (ACI 318-89 Section 7.10.5.1).
5. Ties shall be arranged such that every corner and alternate bar shall have lateral support provided by a corner of a tie, with an inclusive angle of not more than 135° and no bar shall be further than 6 inches clear on each side along the tie from such a laterally supported bar (ACI 318-89 Section 7.10.5.3).
6. A lap splice of two pieces of an open tie shall be at least equal to 1.3 times the tensile development length for the specified yield strength (ACI 318-89 Section 12.13.5).

Suggested details for composite column ties are shown in Typical Details 1, 2, and 3 of Part 2.

Longitudinal Reinforcing Bar Splices

The requirements for splicing vertical longitudinal reinforcing bars for composite columns shall follow the same rules as apply for conventional reinforced concrete columns as specified in Chapter 12 of the ACI 318-89 Code. Several additional comments should be made for composite columns. First, additional vertical longitudinal restraining bars (LRFD Specification I2.1.b) should be used between the corners where the continuous load carrying bars are located in composite frame construction. These bars usually cannot be continuous because of interruption with intersecting framing members at the floor line. They are often required to satisfy the spacing requirements for vertical longitudinal bars shown as follows:

The cross section area of longitudinal reinforcement shall be at least equal to 0.007 square inches per inch of bar spacing (LRFD Specification I2.1.b).

Second, it is suggested that, in high rise composite frame construction, the vertical bar splices be located at the middle clear height of the composite column. This point is usually near the inflection point (zero moment) of the column where the more economical compression lap splices or compression butt splices may be used. The more expensive tension lap or tension butt splices may be required if splices are made at the floor line.

A suggested composite column splice detail is shown in Typical Detail 1 of Part 2.

Connection of Steel Beam to Encased Wide Flange

In composite frame construction, steel spandrel beams and/or perpendicular floor beams often frame into the composite column at the floor level. Sometimes these beams will be simply supported floor beams where conventional double-angle framed beam connections (LRFD Manual, Part 5) or single-plate shear connections may be utilized. More often, however, the steel spandrel beams will be part of the lateral load resisting system of the building and require a moment connection to the composite column. Practicality will often dictate that the larger spandrel beam (frequently a W36 in tall buildings) be continuous through the joint with the smaller erection column (often a small W14) interrupted and penetration welded to the flanges of the spandrel beam. To increase the speed of erection and minimize field welding, the spandrel beam and erection column are often prefabricated in the shop to form "tree columns" or "tree beams" with field connections at the mid-height of column and midspan of spandrel beam using high strength bolts. See Typical Detail 5, Part 2.

The engineer must concern himself with the transfer of forces from the floor beams to the composite column. For simply supported beams not part of the lateral frame, the simplest method to transfer the beam reaction to the composite column is through a standard double-angle or single-plate shear connection to the erection column. It is then necessary to provide a positive shear connection from the erection column to the concrete along the column length to ensure transfer of the beam reaction to the composite column cross section. The simplest method to accomplish this is by the use of standard headed shear connectors, preferably shop welded to the wide flange column. For moment connected spandrel beams, the beam shear and unbalanced moment must be transferred to the composite column cross section. Different transfer mechanisms have been tested at the University of Texas at Austin.²⁴

Several suggested details are shown in Details 1 and 2 of Part 2.

Shear Connectors

As discussed in the previous section, it is necessary to provide a positive shear connection transfer from the floor beam to the encased steel column when the beam connection is made directly to the encased steel column. It is likely that a significant portion of this reaction can be transferred in bond between the encased section and the concrete as reported in Reference 14. An estimate of this value can be made from Equation 5 of Reference 16 which is based on the results of a limited number of push tests in which a steel column is encased in a concrete column.

$$P_{sl} = \frac{3.6b_f(0.09f'_c - 95) l_e}{k}$$

where

P_{sl} = allowable load for the encased shape, lb

b_f = steel flange width of encased shape, in.

f'_c = concrete compressive strength, psi

l_e = encased length of steel shape, in.

k = constant ≈ 5

Converting to an average ultimate bond stress " u ," using only the flange surfaces as being effective and applying a safety factor of five as reported in the tests.

$$u = \frac{P_{sl} \times 5}{4b_f l_e} = \frac{3.6 \times b_f (0.09f'_c - 95) l_e}{5} \times \frac{5}{4b_f l_e}$$

$$u = 0.9 (0.9f'_c - 95), \text{ average ultimate bond stress, psi}$$

Consider a typical case of a W14x90 encased column in 5,000 psi concrete with a floor-to-floor height (h_o) of 13 feet. The average ultimate bond stress is

$$u = 0.9 (0.09 \times 5,000 - 95) = 320 \text{ psi}$$

The ultimate shear force that could be transferred by bond is

$$= u \times h_o \times 4b_f = \frac{320 \times (13 \times 12) \times (4 \times 14.5)}{1,000} = 2,895 \text{ kips}$$

These results indicate that typical floor reactions on the composite column could be easily transferred by bond alone.

The above discussion considered the case where axial load alone is transferred from the encased steel section to the concrete. For beam-columns where high bending moments may exist on the composite column, the need for shear connectors must also be evaluated. Until such time as research data is provided, the following simplistic evaluation may be made. Assume a situation where a composite column is part of a lateral load resisting frame with a point of inflection at mid-column height and a plastic neutral axis completely outside the steel cross section (similar to Fig. 4 except for plastic neutral axis location). An analogy can be made between this case and that of a composite beam where shear connectors are provided uniformly across the member length

between the point of zero moment and maximum moment. The ultimate axial force to be transferred between the encased steel column and the concrete over the full column height is $2AF_y$, where A is the steel column area and F_y is its yield strength. Assuming a bond strength is available in this case similar to the case of the push test discussed above, then shear connectors would theoretically be required when $2AF_y$ is greater than the ultimate bond force. In the previous example, assume an A36 W 14×90 erection column is used. Then,

$$2AF_y = 2 \times 26.5 \times 36 = 1,908 \text{ kips}$$

This is less than the available shear transfer from bond, which was calculated as 2,895 kips

Again, it is shown that bond stress alone can transfer the shear between the encased shape and the concrete, assuming no loss in bond occurs as a result of tensile cracking at high moments.

The composite beam-column design tables presented in Part A assume a nominal flexural strength based on the plastic stress distribution of the full composite cross section. To validate this assumption, the LRFD specification commentary in Section 14, requires a transfer of shear from the steel to the concrete with shear connectors. Therefore, until further research is conducted on the loss of bond between the encased steel section and the concrete, and until more comprehensive push tests are run, the following suggestions are made with regard to shear connectors on composite columns:

1. Provide shear connectors on the outside flanges where space permits. Where space does not permit, provide shear connectors on the inside flange staggered either side of the web.
2. Provide shear connectors in sufficient quantity, spaced uniformly along the encased column length and around the column cross section between floors, to carry the

greater of the following minimum shear transfer forces as applicable:

- a. The sum of all beam reactions at the floor level.
 - b. Whenever the ratio of the required axial strength to the factored nominal axial strength, $P_u / \phi_c P_n$, is less than 0.3, a force equal to F_y times the area of steel on the tensile side of the plastic neutral axis in order to sustain a moment equal to the nominal flexural strength of the composite cross section. The ratio 0.3 is used as an arbitrary value to distinguish a composite column subjected to predominantly axial load from one subjected to predominately moment. Consideration must be given to the fact that this moment is reversible.
3. The maximum spacing of shear connectors on each flange is suggested to be 32 inches.

If minimum shear connectors are provided according to the guidelines identified herein, it is reasonable to assume compatibility of strains between concrete and encased steel to permit higher strains than 0.0018 under axial load alone. This strain level has been identified in Reference 7 and LRFD Commentary, Section 12.1, as a point where unconfined concrete remains unspalled and stable. Therefore, a slight increase in the maximum usable value of reinforcing steel stress from 55 ksi, corresponding to 0.0018 axial strain, to 60 ksi, the yield point of ASTM A615 Grade 60 reinforcing steel, would seem to be justified. Such an approach has been adopted in this Guide. The use of shear connectors also allows the full plastic moment capacity to be counted upon when $P_u / (\phi_c M_n)$ is less than 0.3 (LRFD Commentary, I4) instead of the reduction specified in LRFD Specification, Section 14.

Suggested details for shear connectors on composite columns are shown in Typical Details 1 and 2 of Part 2.

Base Plate

Normally a base plate for the encased steel column of a composite column is specified to be the minimum dimension possible to accommodate the anchor bolts anchoring it to the foundation during the erection phase. In doing so, the base plate will interfere the least possible amount with dowels coming up from the foundation to splice with the longitudinal vertical bars of the composite column. The design engineer must provide dowels from the composite column to the foundation to transmit the column load in excess of the allowable bearing stress on the foundation concrete ($\phi_c \times 0.85 \times f'_c$) times the effective bearing area (the total composite column area less the area of the encased wide flange column base plate). In some cases, depending on the base plate size, it may be necessary to add additional foundation dowels to adequately transmit the load carried by the concrete of the composite column. A typical base plate detail is shown in Typical Detail 4, Part 2. A composite column base plate example is included as Example 5, Part 3.

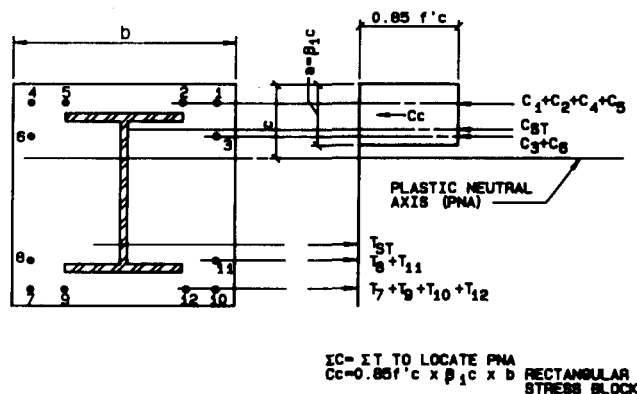


Fig. 4. Plastic stress distribution in composite columns.

Erection and Temporary Wind Bracing During Composite Frame Construction

Historically, a structural steel erector is accustomed to working with a steel framed structure that is stabilized as the frame is constructed with moment connections or permanent cross bracing. Composite frames many times are not stable and not fully able to carry lateral loads until after the concrete is poured and cured many floors behind. Because of this fact, it is incumbent on the engineer-of-record to state the assumptions of bare steel frame stability in the contract documents. Either he designs and details the necessary temporary bracing on the drawings or requires the erector to engage a structural engineer to provide it. The engineer-of-record is the most appropriate person to provide this service by virtue of his knowledge of the loads and familiarity with the overall structure. Additional discussions about the design responsibility of steel frames during erection may be found in the AISC Code of Standard Practice.²² A discussion of composite frames during erection may be found in Reference 15.

Load and Resistance Factor Design (LRFD) of Composite Columns

To qualify as a composite column under the LRFD Specification design procedure, the following limitations must be satisfied as defined in Section 12.1:

1. The cross sectional area of the steel shape, pipe, or tubing must comprise at least four percent of the total composite cross section.
2. Concrete encasement of a steel core shall be reinforced with longitudinal load carrying bars, longitudinal bars to restrain concrete, and lateral ties. Longitudinal load carrying bars shall be continuous at framed levels; longitudinal restraining bars may be interrupted at framed levels. The spacing of ties shall be not greater than two-thirds of the least dimension of the composite cross section. The cross sectional area of the transverse and longitudinal reinforcement shall be at least 0.007 in.² per inch of bar spacing. The encasement shall provide at least 1½-in. of clear cover outside of both transverse and longitudinal reinforcement.
3. Concrete shall have a specified compressive strength f'_c of not less than 3 ksi nor more than 8 ksi for normal weight concrete, and not less than 4 ksi for lightweight concrete.
4. The specified minimum yield stress of structural steel and reinforcing bars used in calculating the strength of a composite column shall not exceed 55 ksi.

The required design strength P_u of axially loaded composite columns is defined in the LRFD Specification, Section E2, with modification of certain terms according to Section I2.2. These rules are summarized as follows:

$$P_u = \phi_c P_n, \text{ required axial strength}$$

$$P_n = A_s F_{cr}, \text{ nominal axial strength} \quad (\text{E2-1 modified})$$

For $\lambda_c \leq 1.5$,

$$F_{cr} = (0.658\lambda_c^2) F_{my} \quad (\text{E2-2 modified})$$

For $\lambda_c > 1.5$,

$$F_{cr} = \frac{0.877}{\lambda_c^2} F_{my} \quad (\text{E2-3 modified})$$

$$\lambda_c = \frac{Kl}{r_m \pi} (F_{my} / E_m)^{1/2} \quad (\text{E2-4 modified})$$

ϕ_c = resistance factor for compression = 0.85

A_s = gross area of steel shape

F_{my} = modified yield stress

$$= F_y + c_1 F_{yr} (A_r / A_s) + c_2 f'_c (A_c / A_s), \text{ ksi} \quad (\text{I2-1})$$

E_m = modified modulus of elasticity

$$= E + c_3 E_c (A_c / A_s), \text{ ksi} \quad (\text{I2-2})$$

F_y = specified yield stress of structural steel column, ksi

E = modulus of elasticity of steel, ksi

K = effective length factor

l = unbraced length of column, in.

r_m = radius of gyration of steel shape in plane of buckling, except that it shall not be less than 0.3 times the overall thickness of the composite cross section in the plane of buckling, in.

$$A_c = \text{net concrete area} = A_g - A_s - A_r, \text{ in.}^2$$

$$A_g = \text{gross area of composite section, in.}^2$$

$$A_r = \text{area of longitudinal reinforcing bars, in.}^2$$

$$E_c = \text{modulus of elasticity of concrete} = w_c^{1.5} (f'_c)^{1/2}, \text{ ksi}$$

$$w_c = \text{unit weight of concrete, lbs./ft}^3$$

$$f'_c = \text{specified compressive strength of concrete, ksi}$$

$$F_{yr} = \text{specified minimum yield stress of longitudinal reinforcing bars, ksi}$$

$$c_1 = 0.7$$

$$c_2 = 0.6$$

$$c_3 = 0.2$$

The interaction of axial compression and flexure in the plane of symmetry on composite members is defined in Section H1.1, H1.2, and I4 as follows:

For $P_u / \phi_c P_n \geq 0.2$,

$$\frac{P_u}{\phi_c P_n} + \frac{8}{9} \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0 \quad (\text{H1-1a})$$

For $P_u / \phi_c P_n < 0.2$,

$$\frac{P_u}{2\phi_c P_n} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) \leq 1.0 \quad (\text{H1-1b})$$

P_u = required compressive strength, kips

P_n = nominal compressive strength, kips

M_u = required flexural strength, kip-in.

M_n = nominal flexural strength determined from plastic