

Load Transfer in Composite Construction

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ABSTRACT

In order for dissimilar materials to act in a composite manner, forces must be transferred between the materials so that they achieve a state of internal equilibrium with one another. Previous editions of the American Institute of Steel Construction (AISC) Specification briefly address load transfer; however, these provisions are quite limited in scope and clarity. The 2010 AISC Specification significantly expands load transfer requirements in a new section. Clear guidance is now provided for the allocation of forces between steel and concrete sections as well as for force transfer mechanisms used for composite members. This paper reviews the new AISC provisions, discusses their application, and provides a brief technical background to the new headed stud anchor provisions as they relate to load transfer.

INTRODUCTION

Significant updates and revisions to the composite design provisions of the AISC Specification have been made over the last several code cycles. Specifically, the 2005 AISC Specification for Structural Steel Buildings, ANSI/AISC 360-05 (AISC, 2005), included a wealth of new information and design provisions related to the design and detailing of composite columns including cross-sectional strength models, tension and shear provisions, and local buckling effects (Leon et al., 2007). However, one significant concept which has remained relatively unchanged through these revisions is that of load or force transfer. With the 2010 AISC Specification for Structural Steel Buildings, ANSI/AISC 360-10 (AISC, 2010), hereafter referred to as the AISC Specification, the provisions for force transfer have been greatly expanded to address the limitations on scope and perceived lack of clarity in previous versions of the Specification.

Force transfer is the concept of balancing forces within a member such that dissimilar materials can achieve a state of internal equilibrium and act in a composite manner. The revisions made for the 2010 AISC Specification address several key issues: the introduction of external force to the composite member, allocation of this force to various components of the composite member, determination of the required internal longitudinal shears to be transferred to achieve this force allocation, and the mechanisms

by which this shear transfer can take place. The primary goal of this paper is to summarize the application of each of these issues within the context of composite column design. The approaches presented here may also be applied for load transfer to other composite members such as composite walls. Additionally, during the development of these provisions, supplemental research was performed to investigate the use of steel headed stud anchors (commonly referred to as shear studs) for longitudinal shear transfer in composite columns and other composite components. A secondary goal of this paper is to discuss the implications of this research within the context of composite column force transfer.

OVERVIEW OF DESIGN PROCEDURE

The design procedure for analyzing force transfer requirements for composite columns is presented in a flow-chart in Appendix A to help visualize the process described below.

The first step of the procedure is to determine through analysis the required external load applied to the column utilizing either LRFD or ASD load combinations, depending on which design method is to be implemented. Once the applied external load is calculated, the configuration of the connection delivering this load to the composite column is examined to determine if the entire load is delivered to the steel, concrete, or both materials concurrently. Next, the required longitudinal shear force to be transferred between the materials to reach force equilibrium of the cross section is calculated. Finally, the mechanism used to transfer the longitudinal shear is chosen to allow the strength of the mechanism to exceed the required longitudinal shear as follows:

$$\begin{aligned} \phi R_n &\geq V'_r \quad (LRFD) \\ R_n/\Omega &\geq V'_r \quad (ASD) \end{aligned} \tag{1}$$

where:

- R_n = nominal strength of longitudinal shear transfer mechanism, kips (N)
- V'_r = required longitudinal shear force to be transferred, kips (N)
- ϕ = resistance factor for use with LRFD level load combinations – varies depending on force transfer mechanism used
- Ω = safety factor for use with ASD level load combinations – varies depending on force transfer mechanism used

The major steps involved in the design procedure, including force introduction, determination of longitudinal shear, and strength determination of the allowable longitudinal shear transfer mechanisms, are described in detail within each of the subsequent sections. Where possible, the relevant equations from the AISC Specification are presented to aid the reader in understanding their application.

FORCE INTRODUCTION AND LOAD ALLOCATION

Composite columns are typically categorized as filled composite columns, also known as concrete-filled tubes (CFTs), and encased composite columns, also known as steel-reinforced concrete (SRC) columns. These columns can be loaded by external forces through means of direct connection to the steel member, to the concrete encasement or fill, or to both materials concurrently. For example, in an SRC column, a beam could be attached to the steel shape only via extended shear tabs, as indicated in Figure 1(a). Similarly, external forces could be applied via concrete only, as indicated in Figure 1(b); or a cap plate could engage both materials concurrently, as indicated in Figure 1(c).

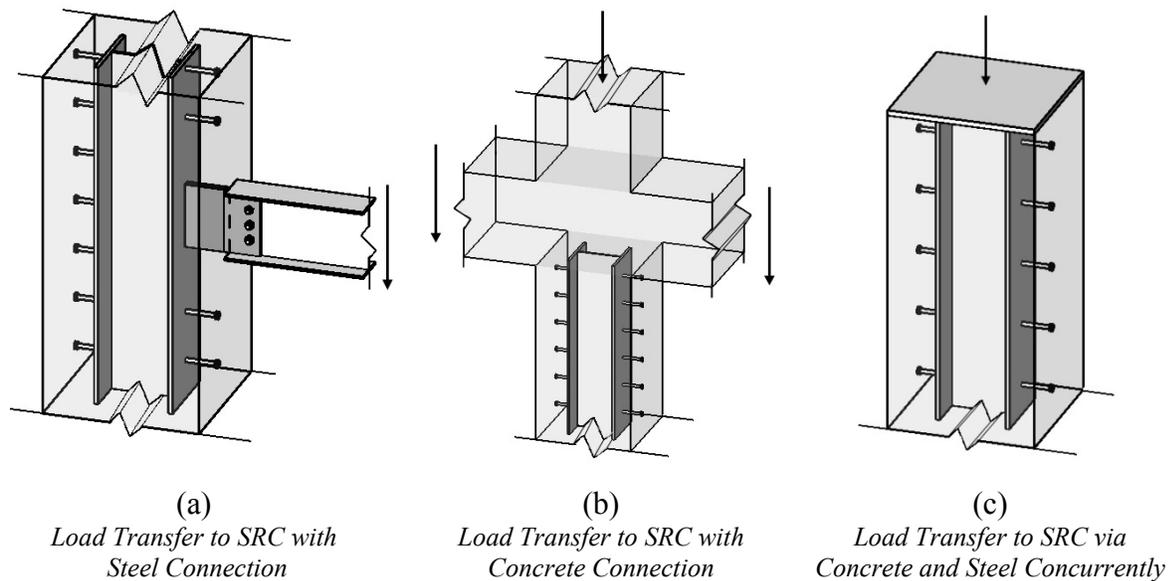


Figure 1. Examples of Force Introduction to SRC Columns

The design of these connections is not specific to composite design and should be performed using the relevant connection limit states provided in Chapters J and K of the AISC Specification or ACI 318 (ACI, 2008); however, the material to which the external force is imparted is key to determining the transfer of longitudinal shear required to engage composite action as discussed below.

The AISC Specification uses a plastic stress distribution model to determine the section strength of composite columns, meaning that both the steel section and the reinforced concrete section are assumed to reach their ultimate (yield and crushing) strengths. This model is represented by the composite member section strength P_{no} as follows:

$$\text{For SRC Columns: } P_{no} = A_s F_y + A_{sr} F_{ysr} + 0.85 A_c f'_c \quad (2010 \text{ AISC I2-4})$$

$$\text{For CFT Columns: } P_{no} = A_s F_y + C_2 f'_c \left(A_c + A_{sr} \frac{E_s}{E_c} \right) \quad (2010 \text{ AISC I2-9a/b})$$

where:

A_s	=	area of the steel section, in ² (mm ²)
A_c	=	area of concrete fill or encasement, in ² (mm ²)
A_{sr}	=	area of continuous reinforcing bars, in ² (mm ²)
C_2	=	0.85 for rectangular sections and 0.95 for round sections
E_c	=	modulus of elasticity of concrete, ksi (MPa)
E_s	=	modulus of elasticity of steel, ksi (MPa)
f'_c	=	specified compressive strength of concrete, ksi (MPa)
F_y	=	specified minimum yield stress of the steel section, ksi (MPa)
F_{ysr}	=	specified minimum yield stress of reinforcing bars, ksi (MPa)

In equations 2010 AISC I2-4 and I2-9a/b, the A_sF_y term represents the plastic strength of the steel section, and the remainder of the equation represents the reinforced concrete contribution. For force allocation purposes, the AISC Specification requires that the applied external forces be distributed within the composite section based on the same ratio of steel section strength to reinforced concrete section strength as represented by the plastic capacity model. For example, if the A_sF_y term of Equation 2010 AISC I2-4 represents 67% of the total plastic capacity of the composite section, an external force of 100 kips must be distributed with $(0.67)(100 \text{ kips}) = 67.0 \text{ kips}$ to the steel section, and the remainder (33.0 kips) to the concrete. If all of the external force is applied directly to the steel section as in Figure 1(a), it can be seen that 33.0 kips must be transferred internally as a longitudinal shear force to the concrete section to satisfy the plastic model ratio. Conversely, if all external force is applied directly to the concrete section, 67.0 kips must be transferred internally to the steel section to satisfy the plastic model ratio. This concept is presented in equation form in the AISC Specification as follows:

For entire external force applied to the steel section:

$$V'_r = P_r(1 - A_sF_y/P_{no}) \quad (2010 \text{ AISC I6-1})$$

For entire external force applied to the concrete section:

$$V'_r = P_r(A_sF_y/P_{no}) \quad (2010 \text{ AISC I6-2})$$

where:

V'_r	=	required longitudinal shear force to be transferred, kips (N)
P_r	=	required external force applied to the composite member, kips (N)
A_sF_y	=	plastic capacity of steel section, kips (N)
P_{no}	=	plastic capacity of composite section determined by 2010 AISC Equations I2-4 or I2-9a,b as appropriate for the member type

When external force is applied to both materials concurrently, the amount of force to be transferred is equal to the difference between the portion of force applied directly to the steel and that required by Equation I6-2 as follows:

$$V'_r = P_{rs} - P_r(A_sF_y/P_{no}) \quad (2)$$

where:

P_{rs}	=	portion of external force applied directly to the steel, kips (N)
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Some engineering judgment is required for determining the portion of external force applied directly to the steel, P_{rs} in Equation 2, in conditions of concurrent application (such as in Figure 1 (c)). One possible method of determining this force in a bearing plate condition is to assume the force is initially applied to each material in relation to their axial stiffness as determined by the ratio of area times the modulus of elasticity for each material. Note that it is generally conservative for load allocation purposes to simply assume all of the external force is applied directly to only one of the materials.

FORCE TRANSFER

Once the longitudinal shear force to be transferred, V'_r , is determined, a force transfer mechanism to convey this force between the steel and concrete must be selected. These force transfer mechanisms are provided in AISC Specification Section I6.3. For SRC columns, the AISC Specification allows the use of either direct bearing or shear connection. For CFT columns, the AISC Specification allows the use of direct bearing, shear connection, or direct bond interaction. The combination of force transfer mechanisms, though feasible in some conditions, is currently not allowed due to lack of research in this area.

Direct Bearing (AISC Specification I6.3a)

Direct bearing, in terms of a force transfer mechanism, refers to the use of bearing plates or other similar assemblies within the composite section to transfer the required longitudinal shear force between the steel and concrete as illustrated in Figure 2 for a CFT column with an internal bearing ring. Note that this is a separate, albeit related, concept to the application of external load to the composite member through bearing, such as illustrated in Figure 1(c), because in Figure 2 the external force is applied directly to the steel casing and the bearing ring is used only for the transfer of internal longitudinal shear.

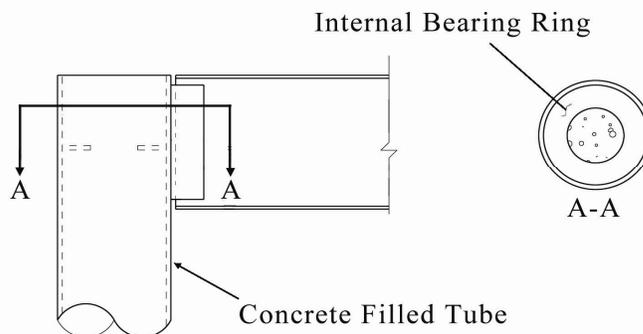


Figure 2. CFT with Internal Bearing Ring

The AISC Specification determines the available bearing strength as follows:

$$R_n = 1.7f'_c A_1 \quad \phi = 0.65 \text{ (LRFD)} \quad \Omega = 2.31 \text{ (ASD)} \quad (2010 \text{ AISC I6-3})$$

This equation was derived from the standard bearing equation provided in ACI 318 (2008) as follows:

$$\begin{aligned}
 R_n &= 0.85f'_c A_1 \sqrt{A_2/A_1} \quad \text{where} \quad \sqrt{A_2/A_1} \leq 2 \\
 &\rightarrow \text{Assume } \sqrt{A_2/A_1} = 2 \\
 &= 0.85f'_c A_1 \left(\sqrt{\frac{A_2}{A_1}} = 2 \right) \xrightarrow{\text{yields}} 1.7f'_c A_1
 \end{aligned} \tag{3}$$

where:

$$\begin{aligned}
 A_1 &= \text{loaded area of concrete, in}^2 \text{ (mm}^2\text{)} \\
 A_2 &= \text{maximum area of the portion of the supporting surface that is} \\
 &\quad \text{geometrically similar to and concentric with the loaded area,} \\
 &\quad \text{in}^2 \text{ (mm}^2\text{)}
 \end{aligned}$$

For composite construction, the confinement provided by the external steel encasement for CFTs or the adjacent steel section flanges in encased W-shapes was judged to be adequate to allow for the maximum value of two to be used for the $\sqrt{A_2/A_1}$ term, thus yielding AISC 2010 Equation I6-3 as indicated in Equation 3.

In addition to strength design considerations, there are several other practical limitations that relate to the use of bearing plates for longitudinal shear transfer. Foremost of these limitations is the physical space required to attach the bearing plate within the steel encasement. This is not a concern for larger built-up sections and encased columns; however, CFTs using standard HSS shapes will likely need to be cut at the bearing plate location to allow placement and welding of the plates. It is further recommended that bearing plates comprise no more than 50% of the width of the CFT section to allow for placement and consolidation of the concrete fill. Finally, if multiple internal stiffeners are required, they should be placed far enough apart to allow for the remaining compression stresses in the concrete to re-engage the perimeter of the section after engaging the first set of stiffeners. It is the author's opinion that a minimum spacing of twice the width of the bearing stiffener is adequate for this purpose, though additional research into this topic is warranted.

Shear Connection (AISC Specification I6.3b)

Though previous versions of the AISC Specification allowed the use of shear connectors (generally headed stud anchors commonly known as shear studs) as a force transfer mechanism, they failed to give the available strength values (ϕR_n or R_n/Ω) of the studs to be used for this purpose. Without additional guidance, it was recommended to use the nominal shear strength provided for flexural members in AISC 2005 Section I3.2d(3) (Leon et al., 2007). Note that the values for headed stud anchors in the 2005 AISC Specification were derived specifically for use in composite beams and did not include an explicit resistance or safety factor on the strength of the headed anchor itself. Explicit resistance or safety factors for the headed stud anchors are not needed in the design of typical composite beams, as a system resistance or safety factor is applied to the design of the bending strength of the composite beam as a whole. For use as a force transfer

mechanism in composite columns; however, appropriate values needed to be determined. The AISC Specification has added a new section, I8.3, specifically to cover the requirements for “steel anchors in composite components” for conditions such as load transfer where individual steel anchor strengths need to be determined.

One possible option for the determination of individual anchor strengths is to use the strength models provided in ACI 318 Appendix D (ACI, 2008) or PCI (PCI, 2004). The methods presented within these documents are applicable, but are general in nature and require consideration of several factors not typically found in composite column construction. It was decided that the requirement of either method would prove to be unnecessarily complicated for applications specific to composite construction and alternatives should be explored. A study of the available data was therefore performed at the University of Illinois at Urbana-Champaign (Pallarés and Hajjar, 2010) which serves as the basis for the AISC Specification values.

Pallarés and Hajjar (2010) determined, through a detailed review of the relevant data of headed stud anchors in shear, that headed stud anchors in normal weight concrete with a minimum h/d (total length over shaft diameter) ratio of five failed through steel strength failure (as opposed to concrete failure) in over 80% of tests. Their research also indicated the use of the steel strength equation still provided a safe assessment of capacity for the remaining failures that occurred within the concrete. Finally, their research indicated that a resistance factor, ϕ , of 0.65 (and corresponding safety factor Ω of 2.31) results in an acceptable reliability index (Ravindra and Galambos, 1978) of approximately 4. Based on this research, the AISC Specification provides the following equation for the determination of shear strength of isolated headed stud anchors:

$$R_n = A_{sc}F_u \quad \phi = 0.65 \text{ (LRFD)} \quad \Omega = 2.31 \text{ (ASD)} \quad \text{(From 2010 AISC I8-3)}$$

where:

$$\begin{aligned} R_n &= \text{nominal shear strength of single headed stud anchor} \\ A_{sc} &= \text{cross-sectional area of steel headed stud anchor, in}^2 \text{ (mm}^2\text{)} \\ F_u &= \text{specified minimum tensile strength of stud anchor, ksi (MPa)} \end{aligned}$$

Based on this equation and the required longitudinal shear force, V'_r , determined previously, the quantity of headed stud anchors required for force transfer may be determined by:

$$\begin{aligned} N_{anchors} &= \frac{V'_r}{\phi R_n} \quad \text{(LRFD)} \\ &= \frac{V'_r}{(R_n/\Omega)} \quad \text{(ASD)} \end{aligned} \quad (4)$$

where:

$$N_{anchors} = \text{required number of steel headed stud anchors for force transfer}$$

Though not as common for composite columns, the use of lightweight concrete was also investigated by Pallarés and Hajjar (2010), and similar results were found when the

minimum h/d ratio of the anchor in question was limited to seven. Table 1 provides the configurations and strengths of typically available “shear studs” that are approved for use in the AISC Specification as composite components for shear transfer based on the aforementioned h/d limitations and Equation 2010 AISC I8-3.

Table 1. Steel Headed Stud Anchor Limits and Shear Strengths for Composite Components

Steel Anchor Diameter in (mm)	Steel Anchor Area in ² (mm ²)	Normal Weight Concrete		Lightweight Concrete		Available Shear Strength ^{N3}	
		Minimum Length "h" ^{N1} in (mm)	Corresponding Standard Stock Shear Connector ^{N2}	Minimum Length "h" ^{N1} in (mm)	Corresponding Standard Stock Shear Connector ^{N2}	LRFD kips (kN)	ASD kips (kN)
3/4 (19)	0.44 (284)	3 3/4 (95)	3/4 x 4 3/16	5 1/4 (133)	3/4 x 5 7/8	18.7 (83)	12.4 (55)
7/8 (22)	0.60 (380)	4 3/8 (110)	7/8 x 5 3/16	6 1/8 (154)	7/8 x 7 3/16	25.4 (113)	16.9 (75)
1 (25)	0.79 (491)	5 (125)	1 x 6 1/4	7 (175)	N/A	33.2 (148)	22.1 (98)

^{N1} "h" refers to the installed height of the stud from the top of the stud head to the connected base.

^{N2} Standard stock shear connectors as determined from Nelson Stud Welding S3L Type (Nelson, 2010) taking burnoff into account.

^{N3} Available shear strength determined using Equation 2010 AISC I8-3 assuming $F_u = 65$ ksi (450 MPa).

It is important to note that although the use of Equation 2010 AISC I8-3 and the specified h/d ratios eliminates the need to check concrete failure in a pryout limit state as defined by ACI 318 (2008) Appendix D, it does not preclude the requirement to check concrete shear breakout. In general, the details associated with composite construction do not have free edges in the direction of the longitudinal shear, thus concrete breakout may safely be ignored and Equation 2010 AISC I8-3 may be used. For instance, for transfer of longitudinal shear within composite columns the shearing force is directed along the column length (hence the terminology longitudinal shear), which eventually terminates at a foundation element, and thus does not present a free edge.

If the circumstances arise where concrete breakout is a valid limit state, the AISC Specification requires that either reinforcing be placed across the breakout plane to resist this limit state as stipulated in ACI 318 Appendix D (ACI, 2008) Section D.5.2.9, or that concrete breakout is considered explicitly in determining the strength of the anchor using ACI 318 Appendix D. Furthermore, the designer is free to use headed stud anchors not meeting the height to depth limitations of the AISC Specification for composite components, provided that their strength is determined by ACI 318 Appendix D as opposed to Equation 2010 AISC I8-3.

Direct Bond Interaction (AISC Specification I6.3c)

Direct bond interaction makes use of the mechanical bond formed in CFT members between the concrete fill and steel encasement to transfer the required longitudinal shear for composite action. Though it is known that bond transfer also occurs in SRC members, the variability of possible configurations is more difficult to quantify, and bond has generally been ignored in practice in the United States in favor of shear connection.

Direct bond interaction was allowed in the 2005 Specification, but equations were not provided within the Specification itself for use in determining the strength of this force transfer mechanism. The 2010 AISC Specification allows the determination of bond strength as follows:

$$\text{For Rectangular CFT Columns: } R_n = B^2 C_{in} F_{in} \quad (2010 \text{ AISC I6-5})$$

$$\text{For Circular CFT Columns: } R_n = 0.25\pi D^2 C_{in} F_{in} \quad (2010 \text{ AISC I6-6})$$

$$\phi = 0.45 \text{ (LRFD)} \quad \Omega = 3.33 \text{ (ASD)}$$

where:

- R_n = nominal bond strength, kips (N)
- B = overall width of rectangular steel section at loaded face, in (mm)
- C_{in} = 2 if the CFT member extends to one side of the load transfer point
= 4 if the CFT member extends to both sides of the load transfer point
- D = outside diameter of round HSS
- F_{in} = nominal bond stress = 0.06 ksi (0.40 MPa)

In this context, the “load transfer point” is subject to engineering judgment. For bearing plate connections, this point coincides with the location of the bearing plate. For steel connections to the side of the member, it is recommended that the point of load transfer be taken as concurrent with the center of the steel connection.

AISC 2010 Equations I6-5 and I6-6 both assume that a single connection on one face of the steel encasement is serving as the means of external force introduction, and thus 25% of the steel encasement perimeter is active in transferring the longitudinal shear force. Where members frame into the composite column in multiple locations, direct bond interaction should be checked at each connection for the amount of force being introduced at each specific location. Where the force is introduced to the composite member in such a way as to engage the full perimeter of the section, the direct bond interaction strength provided by AISC 2010 Equations I6-5 and I6-6 may be increased by a factor of four to represent the entire perimeter strength.

Tests indicate that direct bond values have a wide range of scatter (Hajjar, 2000) thus the low resistance factor and high safety factor. Additionally, the recommended bond stress of 0.06 ksi (0.40 MPa) is based on tests in which some eccentricity was imposed on the composite member from the steel connections thus resulting in higher bond interlock due to increased friction against the sides of the steel encasement. Where little to no eccentricity is expected, such as in cap plate bearing connections, the designer should consider the use of a lower bond stress value (Leon et al., 2007).

As a final note on direct bond interaction, the provisions in the AISC Specification are intended primarily for load transfer of forces induced by axial compression. For applied bending moments, it has been shown in tests (Wheeler and Bridge, 2006) that the bond strength increase due to the large internal frictional forces induced by eccentricity associated with such moments is more than adequate to develop the required capacity without additional means of shear transfer.

Load Introduction Length (AISC Specification I6.4)

Once the load transfer mechanism is selected and designed to transfer the required longitudinal shear force, there are additional requirements within the AISC Specification for the load introduction length in which this transfer must take place. It is important for this shear transfer to take place as quickly as possible to facilitate composite action, thus the AISC Specification limits the load introduction length to two times the minimum transverse dimension (or diameter for circular filled tubes) both above and below the load transfer region. The load transfer region is not explicitly defined within the AISC Specification, but may be interpreted to equal the depth of the connection introducing the external force. These concepts are illustrated for an SRC Column in Figure 3.

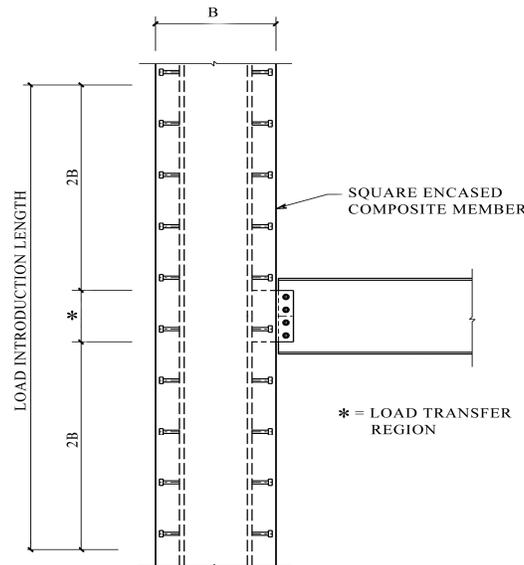


Figure 3. Load Introduction Length

The load introduction length provisions are primarily intended for the use of shear connection as a load transfer mechanism; however, they also apply to direct bearing in that the bearing plates should be located within this region. The force transfer mechanism of direct bond interaction generally satisfies the load introduction length by default as the bond strength is calculated based on similar requirements for introduction length with the assumption that the load transfer region length of the connection is equal to zero.

For composite columns in which a significant load must be transferred into the composite column (for example when composite columns are used in the lower levels of a high-rise building), it might not be possible to satisfy the requirements of the load introduction length at the top of the upper-most composite column lift. For a case such as this, it is recommended that the upper-most lift of composite columns be designed as non-composite, thus allowing the introduction length to be extended throughout this lift to allow the use of additional headed stud anchors for longitudinal shear transfer. Composite action can then be utilized for the remaining levels.

SUMMARY

The 2010 AISC Specification has been revised to clarify the requirements for load transfer in composite members through the addition of a new Section I6. This paper has presented these provisions and summarized their use in the design of composite filled tubes and encased columns. The concept of external load introduction to steel, concrete, or both materials concurrently, as well as the determination of longitudinal shear force required to be developed for equilibrium of the composite cross section in each of these cases, was reviewed. Three possible force transfer mechanisms were discussed with particular emphasis on the background of the new headed stud anchor component shear provisions. Finally, the concept of load introduction length was discussed. The composite provisions in the 2010 AISC Specification, including the load transfer provisions in Section I6, will continue to promote the implementation of composite construction by providing clear guidance to address component behavior, design techniques, and proper detailing considerations.

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APPENDIX A: LOAD TRANSFER PROCESS CHART

