REVIEW AND COMPARISON OF ENCASED COMPOSITE STEEL-CONCRETE COLUMN DETAILING REQUIREMENTS

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ABSTRACT

While there is a wealth of literature regarding strength models used to determine the capacities of encased composite columns, there is little information devoted to the equally important topic of detailing provisions with respect to these columns. The goal of this paper is to fill this gap by summarizing and comparing detailing provisions within three different model standards. Several areas where broad differences exist between the standards reviewed are highlighted, and recommendations for harmonizing these provisions are made.

INTRODUCTION

The purpose of this paper is to identify, present, and compare the encased composite steel-concrete column detailing provisions of ANSI/AISC 360-05 (AISC 2005) by the American Institute of Steel Construction, ACI 318-08 (ACI 2008) by the American Concrete Institute, and EN 1994-1-1:2004 (CEN 2004b), commonly known as Eurocode 4. Hereafter, these standards will be referred to as AISC, ACI, and EC4, respectively. The primary goal is to collect detailing provisions from these standards into a single reference for comparison and to provide comment and recommendations for the harmonization of these provisions.

Similarities exist when comparing the method of presentation for detailing provisions between the AISC and ACI standards with those of the Eurocodes. EC4 contains a majority of the detailing provisions required for composite design; however, it relies on EN 1992-1-1:2004 (CEN 2004a), commonly known as Eurocode 2, and hereafter referred to as EC2, for many of the concrete and mild reinforcement provisions. Similarly, AISC has traditionally relied on the provisions of ACI for detailing requirements pertaining to concrete and mild steel reinforcement while providing explicit provisions related to the steel core. The main discrepancies between the standards arise because the Eurocodes are developed by a single entity with the expressed intent of functioning as a unit, while AISC and ACI are developed by separate entities and often contain conflicting and overlapping provisions. It is, therefore, a secondary goal of this paper to examine the conflicts between AISC and ACI and to provide recommendations to aid in their resolution.

DETAILING CRITERIA - DISCUSSION

The detailing criteria reviewed in this paper are as follows: concrete material properties, steel core requirements, transverse reinforcement requirements, longitudinal reinforcement requirements, and shear transfer provisions. Detailed discussion on each topic is provided in this section followed by a section on recommendations for achieving consensus among the standards. An extensive table summarizing the provisions for each of these topics, including the applicable code references, is provided in the Appendix. It is important to note that the detailing criteria provided herein for EC4 and EC2 may be overridden by the National Annex of the country under consideration.

Concrete Material Properties

Minimum compressive concrete strength limits for normal weight concrete are similar among the three standards. AISC requires 3.0 ksi (21 MPa), ACI requires 2.5 ksi (17 MPa), and EC4 requires 2.9 ksi (20 MPa). Maximum compressive strength limits of 10 ksi (70 MPa) and 7.3 ksi (50 MPa) are provided by AISC and EC4 respectively, although AISC allows higher values to be used for stiffness calculations. According to the AISC Commentary, these limits provide a lower bound for good quality concrete and an upper bound based on available test data. Similar reasoning for the concrete limits in EC4 is given by Johnson and Anderson (2004), who state limited knowledge exists for “composite members with weak or very strong concrete.”

EC4 composite column provisions do not address lightweight concrete, while AISC imposes a limit of 6.0 ksi (42 MPa). In the United States, composite columns are typically constructed of normal weight concrete, and they are primarily used for increased flexural stiffness and axial load capacity for highly loaded members (Viest et al. 1997). It is doubtful that minimum limits on concrete strength or limits for lightweight concrete are restrictive in practice. The maximum concrete strength limitation for normal weight concrete could become a factor for high-rise construction. AISC addresses this limitation by explicitly allowing higher strengths where “justified by testing or analysis.”

Steel Core Requirements

AISC sets the lower limit for the cross-sectional area of the steel core to 1% of the gross cross-sectional area of the composite section. Since the typical range of steel core ratios for economic construction is considerably higher (Leon and Hajjar 2008), this limit is of minimal practical concern. ACI has no such limit, while EC4 is unique in that it provides a strength-based classification system that examines the contribution of the steel core to the plastic axial strength of the composite section. This system requires the steel core to provide between 20 and 90% of the section strength for the column to be considered composite. For core ratios below 20%, the member should be designed as a reinforced concrete column. For core ratios above 90%, the member should be designed as a steel column. This classification system is the most rational method among the three standards; however, it is cumbersome in that it requires strength calculations to be performed prior to determining core ratio acceptability.

The maximum specified yield stress of the structural steel core is similar between AISC and EC4, while ACI provides a more restrictive limit. AISC allows the use of 75 ksi steel (525 MPa) based on the upper limit of 72.7 ksi (500 MPa) represented within the test database for encased composite columns used to calibrate the column strength equations (Leon et al. 2007). EC4 provides an upper limit of 67 ksi (460 MPa) which is also based on test data limits. EC4 also imposes an additional limitation on strength calculations for composite columns that contain steel cores with yield stresses exceeding 61 ksi (420 MPa). This limit is in the form of an interaction check that must be performed under combined axial load and bending. The interaction ratio should typically be less than 0.9, but the use of high strength core steel decreases the maximum limit to 0.8. The reduced limit accounts for adverse effects due to increased strains within the concrete present at yielding of higher strength steel (Johnson and Anderson 2004). ACI attempts to justify a more conservative limit of 50 ksi (345 MPa) by stating that this stress corresponds to a maximum concrete strain of approximately 0.0018, below which concrete is unlikely to spall. This justification does not appear to take into account the confining effect provided by the transverse reinforcement present in these columns. The amount of transverse steel required to provide adequate confinement to prevent spalling of the core concrete is further addressed in the following section on transverse reinforcement. It is of interest that both ACI and EC4 address limitations on high strength steels in some manner (by disallowing them or setting further strength limits respectively), while AISC offers no additional provisions.

Although not a direct requirement for the actual core, a related consideration is the amount of concrete cover that must be provided to the steel core. Of the three standards, only EC4 provides explicit direction for determining this cover requirement. EC4 stipulates both a maximum (for calculations) and a minimum concrete cover requirement to the steel core. Traditionally, minimum cover requirements to mild reinforcement, such as those presented in ACI, are derived from environmental exposure and fire rating concerns. It is presumed that these same requirements would also apply to the steel core. The literature indicates two additional reasons for core cover requirements in EC4. First, the applicability of the simplified design procedure was validated within this range of steel core covers (Johnson 2004). Second, the concrete encasement provides restraint against local steel column buckling (ECCS 2000). Although they do not have explicit cover requirements for the steel core, ACI and AISC provide a minimum concrete cover limit of 1.5 in. (38 mm) to the transverse reinforcement. With a No. 4 tie, even in the unlikely condition that no space is provided between the core and tie, this provision would result in an absolute minimum of 2 in. (51 mm) of cover to the core. This amount is within the general range of EC4 provisions for the majority of core sizes.

Transverse Reinforcement Requirements

The primary purpose of transverse reinforcement in concrete-encased composite columns is to provide concrete confinement to prevent spalling around the structural steel core and to properly support longitudinal reinforcement to prevent buckling of the bars (Viest et al. 1997). Transverse reinforcement can also provide additional shear capacity. All three standards require some form of continuous transverse reinforcement (ties or spirals) within composite columns.

ACI limits the maximum tie spacing to 16 times the longitudinal bar diameter, 48 times the tie diameter, or one-half of the least column width. AISC specifies the same limits as ACI, with the notable exception of a minimum tie diameter limit which will be reviewed further in a following discussion. EC4 requires ties to be spaced at a maximum of 20 times the longitudinal bar diameter, the least column dimension, or 15.75 in. (400 mm).

The allowable transverse reinforcement limits have been plotted for the three standards over a range of square column widths and longitudinal bar sizes in Figures 1, 2, and 3. These figures indicate the maximum permissible spacing of transverse reinforcement when No. 3, No. 4, and No. 5 tie bars are utilized. The figures are plotted based on a range of standard reinforcing bar sizes found in typical column construction in the United States.

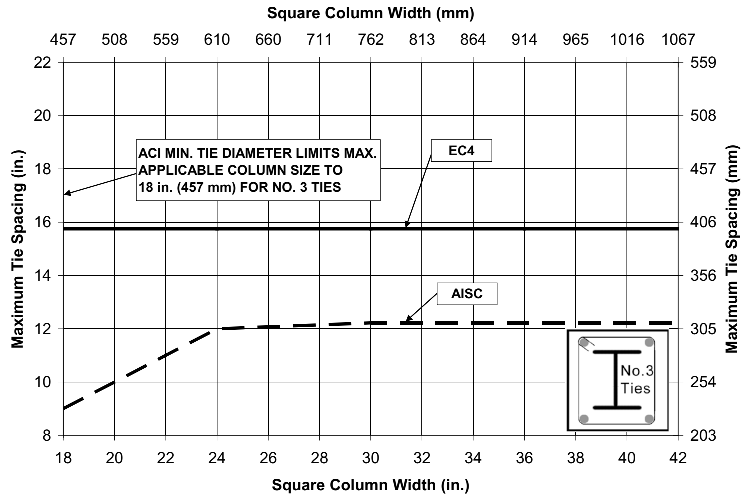

Figure 1 – Maximum transverse reinforcement spacing (No. 3 ties)

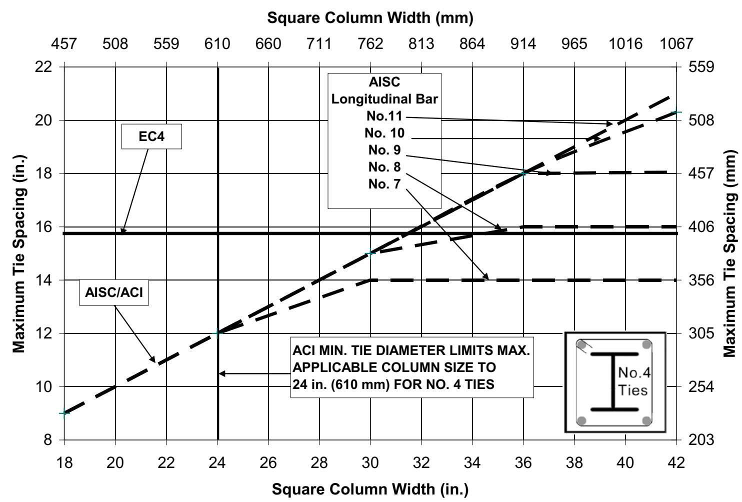

Figure 2 – Maximum transverse reinforcement spacing (No. 4 ties)

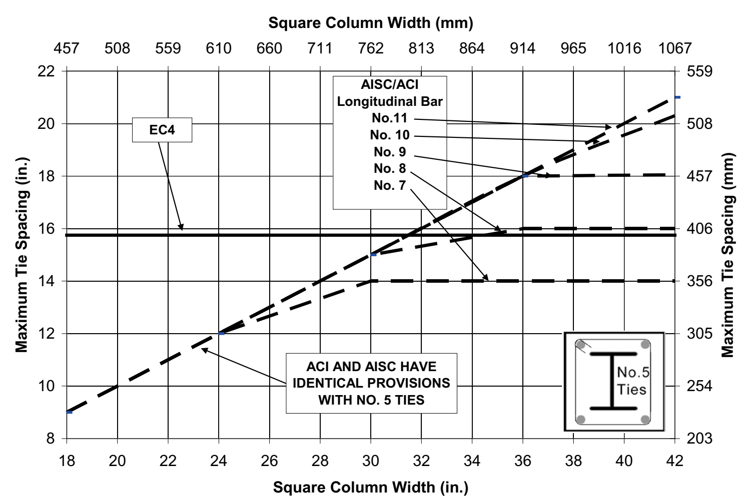

Figure 3 – Maximum transverse reinforcement spacing (No. 5 ties)

Several observations can be made through the examination of Figures 1, 2, and 3. First, the largest discrepancy between the three standards arises in the requirements for minimum tie diameters, where ACI is significantly more restrictive. ACI composite provisions result in the requirement of No. 4 ties for columns larger than 18 in. (457 mm) and No. 5 ties for columns larger than 24 in. (610 mm). Second, AISC does not have explicit provisions for tie diameters; however, it does limit the minimum area of the tie to 0.009 in.^{2} per in. (6 mm^2 per mm) of tie spacing. A similar limit can be traced back to the seminal composite column work by SSRC Task Group 20 (1979). If interpreted correctly, the limit has the effect of controlling vertical tie spacing to a maximum of approximately 12 in. (300 mm.) for No. 3 bars and 22 in. (560 mm.) for No. 4 bars. However, this limit is quite confusing to apply in its current form. Typically, concrete reinforcement limits are based on cross-sectional areas, not areas per unit of reinforcement spacing. Also, this limit leaves itself open to interpretation as to how many legs of the transverse reinforcement are to be used in its calculation. Third, for column sizes exceeding 36 in. (914 mm), AISC provisions yield significantly larger tie spacing for No. 4 ties when compared to the other two standards. Finally, the 15.75 in. (400 mm) limit of EC4 tends to control throughout the range of most composite column sizes including all configurations depicted in Figures 1, 2, and 3.

In addition to tie reinforcement provisions, ACI provides explicit provisions for spiral (helical) reinforcement. Both AISC and EC4 indicate that spiral reinforcement may be used, but neither provides specific provisions governing its use beyond those previously discussed for lateral ties.

A secondary topic in the discussion on transverse reinforcement is the requirement for intermediate ties for the support of longitudinal reinforcement located away from the column corners. EC4 provisions require longitudinal reinforcement in compression zones to be located within approximately 6 in. (150 mm) of a restrained bar. ACI has separate provisions for typical reinforced concrete columns and for composite columns. For reinforced concrete (non-composite) columns, ACI contains similar provisions in Section 7.10.5.3 that require every alternate longitudinal bar meeting certain limitations be laterally supported by intermediate ties. Additionally, no longitudinal bar can be located more than 6 in. (150 mm) away from a restrained bar. ACI is ambiguous as to whether the compression member provisions of Chapter 7 extend to composite members, although it seems reasonable to assume that they do. AISC does not provide specific intermediate tie requirements, although the general provisions provide a blanket statement referencing the building code and/or ACI for detailing of concrete and steel reinforcement. AISC Design Guide 6 provides further guidance on the detailing of intermediate ties including the use of “carry bars” adjacent to the steel core (Griffis 1992).

As mentioned in the preceding discussion on steel core requirements, the use of high strength steel (F_y > 50 ksi (345 MPa)) for the core raises the question of how much transverse reinforcement is required to prevent spalling at the high strain levels associated with core yielding. To the authors’ knowledge, there are no experimental studies that focus specifically on the effect of transverse reinforcement on composite column performance, regardless of the core yield strength. The current code requirements appear to be based on provisions for non-composite reinforced concrete columns. There are provisions in place for seismic design, such as those in ACI Section 21.6.4.4, which are known to provide adequate levels of concrete confinement for highly loaded columns. A history of the seismic provisions can be found in Saka and Shaikh (1989), and further discussion can be found in Paulay and Priestley (1992), Park and Paulay (1975), and Viest et al. (1997). Until experimental testing focusing on transverse reinforcement effects for encased composite beam-columns with high strength steel cores becomes available, the reader is cautioned to pay careful attention to tie detailing and to consider the use of seismic tie provisions for such columns.

Longitudinal Reinforcement Requirements

With respect to minimum longitudinal reinforcement requirements, ACI notably differs from EC4 and AISC by requiring the same percentage reinforcement for composite columns as that required for non-composite columns (1% of the concrete cross-sectional area). AISC and EC4 permit 0.4% of the gross column cross-sectional area and 0.3% of the net concrete cross-sectional area, respectively. According to the ACI Commentary, the 1% minimum limit for non-composite columns is based upon the phenomenon of stress transfer from the concrete to the reinforcement due to creep and shrinkage under service load levels. However, the inclusion of an encased structural steel section mitigates this effect and should consequently allow a smaller ratio of longitudinal reinforcement to concrete area.

Maximum longitudinal reinforcement percentages are generally based on construction considerations to limit congestion. ACI caps this overall percentage at 8%. Since this is the maximum limit within a splice region, typical reinforcing bar layouts yield considerably less reinforcement percentages through the remainder of the column length. An exception occurs where mechanical splices are used, thus permitting the full reinforcement percentage to be utilized throughout the column length. AISC does not provide a specific limit but defaults to ACI by general reference. EC4 allows up to 6% longitudinal reinforcement in non-lap regions to be used in calculations, which is more liberal than the 4% recommended by EC2 for non-composite concrete columns (Johnson and Anderson 2004). It is unlikely that steel reinforcement ratios exceeding 3% will be utilized, and these limits will, therefore, not be encountered in practice often.

Provisions for the required number of longitudinal reinforcing bars for composite columns are present within all three standards. EC4 states that longitudinal bars must be provided within each corner of the column. AISC is more specific and requires at least four continuous bars. AISC assumes that the bars are to be placed in column corners; however, this is not specifically stated, nor is the AISC provision applicable to irregular column geometries. ACI is unclear as to the minimum number of longitudinal bars required in a composite cross section. Section 10.13.8.6 states that "a longitudinal bar shall be located at every corner of a rectangular cross section, with other longitudinal bars spaced not farther apart that one-half the least side dimension of the composite column." This statement can be interpreted to require a minimum of eight longitudinal bars, although it is the authors' opinion that this is not the intent and that a minimum of four bars is sufficient. For circular columns, ACI and EC4 require a minimum of four longitudinal bars, with ACI requiring six bars for columns with spiral reinforcement.

Other considerations for longitudinal reinforcement are the minimum spacing allowed between reinforcing bars as well as between reinforcing bars and the steel core. ACI requires a minimum clear distance between longitudinal bars of 1.5 times the bar diameter or 1.5 in. (38 mm) whichever is greater. EC4 has a similar limit. AISC does not address this topic directly, and a general statement that steel reinforcement detailing shall be governed by ACI applies. EC4 is the only standard that directly addresses the clear distance required between longitudinal reinforcement and steel core. EC4 allows the reinforcement to be placed immediately adjacent to the core provided that the bond surface used to calculate development lengths is reduced. ACI provisions for increased development lengths for bundled bars are based on similar principles and could also be applied to this situation. Alternately, the same provisions used for minimum spacing between longitudinal bars could be used to the steel core.

Finally, it should be noted that development lengths, splice lengths, and anchorage provisions for longitudinal and other mild reinforcement are provided in Chapter 12 of ACI and by implicit reference to EC2 in EC4. AISC refers to ACI for general reinforcement detailing requirements within the general provisions of the composite member specification.

Shear Transfer (Load Introduction)

The method of load introduction is a significant topic for encased composite columns and one in which the three standards differ significantly. ACI is minimalistic, stating that "any axial load strength assigned to concrete of a composite member shall be transferred to the concrete by members or brackets in direct bearing on the composite member concrete." EC4, on the other hand, devotes four pages to the topic.

As an overview, EC4 splits composite columns into two regions: the introduction length, and the remainder of the column length. The introduction length is defined as the smaller of twice the minimum column width or one-third of the column length. Load introduced to the column must be transferred between the steel core and concrete encasement within the introduction length to attain force equilibrium of the cross section. The amount of longitudinal shear to be transferred is allowed to be determined by either elastic or plastic theory. EC4 is unique among the three standards in that it allows the use of bond for force transfer in encased columns. EC4 provides a design bond strength of 43.5 psi (0.30 MPa) for unpainted sections to be used for this purpose. If the bond strength is exceeded, mechanical connection (stud connectors) must be provided unless loads are introduced to both materials concurrently by endplates. Outside of the area of load introduction, no stud connectors are required unless additional longitudinal shears are created by transverse loads or end moments. EC4 does not provide a direct method for calculating the shear to be resisted due to these loads and simply states that elastic analysis considering creep and shrinkage of concrete may be used.

AISC requires the use of mechanical anchorage to transfer load. Although not specifically stated, the equations provided for the determination of the required shear force to be transferred are based on a plastic resistance model and are actually the same as those provided in ECCS (2000) for fulfillment of the more generic EC4 provisions. AISC provisions are somewhat confusing in that the differentiation between transfer mechanisms for load application to the column and load transfer within the column are not well defined. These provisions should be clarified to direct the designer to break the loading process down into two stages. First, force should be transferred to the composite column using direct connection to the steel (either through shear connection or direct bearing on the steel), direct bearing onto the concrete, or a combination of the two. Second, the amount of force required within the steel core and concrete encasement for cross-sectional equilibrium should be calculated using the plastic resistance equations provided in the standard. The difference in forces between what is applied and what is required for cross-sectional equilibrium is the longitudinal shear that must be transferred between the two materials using shear connectors or internal bearing plates.

AISC contains what is believed by the authors to be an error in the detailing requirements for load introduction. For composite construction, it is generally advisable to achieve composite action expeditiously to ensure that the full capacity of the composite section may be used for force resistance. AISC requires that "shear connectors shall be distributed along the length of the member at least a distance of 2.5 times the depth of the encased composite column above and below the load transfer region." This provision requires a *minimum* load transfer length. It is the authors' belief that the intent was to require that the shear connectors be distributed *within* a distance of 2.5 times the depth of the encased composite column. This revision would result in a *maximum* introduction length similar to that specified in EC4, which would allow the steel core to become composite with the concrete encasement within a compact distance.

AISC sets a limit on maximum spacing between shear connectors of 16 in. (406 mm), and provides no guidance for resisting longitudinal shear due to flexure.

DETAILING CRITERIA – HARMONIZATION

Through comparison of the provisions within AISC, ACI, and EC4, it is apparent that further work is needed to move toward a more complete and consistent set of composite detailing provisions. The discordance between ACI and AISC when compared to the tight integration of EC2 and EC4 is of particular importance. The overlapping and often conflicting provisions between ACI and AISC serve to create confusion within the design community. Also, although it is recognized that EC4 is based on alternate sets of test data and is sometimes aimed towards construction techniques that might not be common within the United States, there are several areas in which the American and European standards can benefit from the careful consideration of each other's provisions.

The following list is a summary of recommendations aimed at both improving the harmonization of detailing provisions among the three standards and filling perceived gaps within the standards themselves.

- *General Coordination Between ACI and AISC:* In order to improve integration between the steel (AISC) and concrete (ACI) standards in use within the United States, it is recommended that one of two options be explored.

  The first option is a revision of ACI composite column provisions to include only concrete and mild reinforcement detailing criteria and to reference AISC for strength design and other steel core related criteria. As current ACI composite provisions have not undergone a significant update in many years, the detailing provisions would also need to be revised to incorporate more recent research. Additional revision would be necessary to eliminate ambiguities regarding the required number of longitudinal reinforcing bars and intermediate tie requirements. AISC could then remove concrete and mild reinforcement detailing information and incorporate ACI's provisions for these items by reference. This option would eliminate overlapping and conflicting provisions while maintaining the traditional symbiotic relationship between ACI for concrete design and AISC for structural steel design.

  The second, and perhaps more practical short-term option, is for AISC to explicitly exclude the composite-column-specific provisions of ACI and refer to the remainder of the non-composite provisions within ACI for the majority of mild reinforcement detailing needs. Additional limits and detailing provisions could then be provided within AISC for criteria specific to composite columns. Option 2 is not as clean as option 1; however, given the time and coordination effort that option 1 would require, option 2 is a viable one to provide designers with a comprehensive set of composite column design criteria that minimizes contradictory provisions.

- *Material Strengths:* It is recommended that EC4 allow the use of higher strength concretes where justified by testing or analysis as permitted by AISC.

- *Steel Core Requirements:* Although the process of determining the minimum steel core ratio is more rational in EC4, the requirement of strength calculations to determine this ratio is cumbersome for practical designs compared to the 1% limit of AISC.

- *Transverse Reinforcement Requirements:* ACI tie diameter provisions need to be re-evaluated due to their conservatism when compared to the other two standards. It is recommended that AISC rewrite their tie provisions to make them clearer. Requiring the use of a No. 3 bar at 12 in. (305 mm) and a No. 4 or greater bar at 16 in. (406 mm) would meet AISC's intent for No. 3 bars and impose a more conservative upper spacing limit for larger tie bars consistent with EC4. The proposed maximum spacing would also coincide with the maximum shear stud spacing currently allowed in AISC.

Both AISC and EC4 need to provide more explicit treatment of spiral (helical) ties.

AISC and ACI need to clarify that additional intermediate ties are required for the support of longitudinal bars not placed at the corners of the cross section.

Determining the amount of transverse reinforcement required to prevent concrete spalling and promote structural integrity when high strength (F_y > 50 ksi (345 MPa)) steel is used in the core is a topic that warrants further research. Until such research can be performed, it is recommended that highly loaded encased columns that make use of high strength steel cores utilize transverse reinforcement based on the seismic design provisions of ACI Section 21.6.4.4.

- *Longitudinal Reinforcement Requirements:* For practical designs, the maximum and minimum limits for longitudinal reinforcement are generally not of concern. The ACI minimum limit is extremely conservative compared to the other standards, and consideration should be given to its revision.

  ACI and AISC provisions for the required minimum number of longitudinal bars need to be clarified. ACI's provisions can be interpreted as requiring eight bars, and AISC's provisions are too specific to apply to general non-rectangular sections.

  ACI and AISC should address minimum spacing requirements between longitudinal steel and the steel core. It is recommended that a minimum spacing similar to that used in ACI between longitudinal bars be imposed. Alternately, a development length extension factor similar to that used for bundled bars could be utilized.

- *Shear Transfer (Load Introduction):* ACI's provisions for load introduction are inadequate and need to be revisited. Alternately, reference to another document should be made.

  EC4's axial load introduction provisions are extensive and provide detailing requirements and provisions beyond the level of information typical of American standards. Shear transfer due to flexure is one topic where guidance is lacking.

  AISC's shear transfer provisions are incomplete and, at times, confusing. It is recommended that they be re-written to clarify the distinction between load application to the column and load transfer for equilibrium within the column. It is the authors' opinion that an error exists within the load transfer length provisions that needs to be revised to allow for composite action to be attained more quickly. The use of bond and the allowance of alternate methods for the determination of transfer forces should be investigated as is allowed by EC4. Finally, as recommended for EC4, provisions for shear transfer due to flexure should be provided.

APPENDIX: TABULAR SUMMARY OF DETAILING REQUIREMENTS

The following table contains the provisions for each topic covered within the preceding discussion. The first column contains an overall subject, the second "requirement" column indicates a specific topic, and the following three columns provide related provisions from the three standards. A reference to the standard section from which this information is taken is provided in italics at the bottom of each provision. For EC4 provisions, references are provided to EC4 unless specifically denoted as being from EC2.

	REQUIREMENT	AISC	ACI	EC4
Material Properties	Concrete compressive strength (normal weight)	Min. f'_c = 3.0 ksi (21 MPa) Max. f'_c = 10.0 ksi (70 MPa) *[I1.2(1)]*	Min. f'_c = 2.5 ksi (17 MPa) *[1.1.1]*	Min. f_{ck} = 2.9 ksi (20 MPa) Max. f_{ck} = 7.3 ksi (50 MPa) *[3.1(2), 6.7.1(2)]*
	Concrete compressive strength (lightweight)	Min. f'_c = 3.0 ksi (21 MPa) Max. f'_c = 6.0 ksi (42 MPa) *[I1.2(1)]*	Min. f'_c = 2.5 ksi (17 MPa) *[1.1.1]*	Not permitted. *[6.7.1(2)]*
Steel Core	Steel core limitations	The cross-sectional area of the steel core shall comprise at least 1% of the total composite section. *[I2.1a(1)]*	No requirement.	Limitations are based upon a minimum and maximum "steel contribution ratio" which measures the portion of plastic bending resistance of the composite section provided by the steel core. To be considered composite, this ratio can not be less than 20%, or more than 90%. *[6.7.1(4), 6.7.3.3(1)]*
	Concrete cover for encased steel member	No requirement.	No requirement.	Min. of 1.6 in. (40 mm) or one-sixth times steel core flange width, whichever is greater. *[6.7.5.1(2)]* A max. of 0.4 times the composite column width in the strong direction or 0.3 times the composite column depth in the weak direction may be used for calculations. *[6.7.3.1(2)]*
	Steel core yield strength	Max. F_y = 75 ksi (525 MPa) *[I1.2(2)]*	Max. F_y = 50 ksi (345 MPa) *[10.13.7.1, 10.13.8.1]*	Max. F_y = 67 ksi (460 MPa) with more restrictive strength limits for $F_y \geq 61$ ksi (420 MPa) *[3.3(2), 6.7.3.6(1)]*
Transverse Reinforcement	General transverse reinforcement requirements	Concrete encasement of the steel core shall be reinforced with continuous longitudinal bars and lateral ties or spirals. *[I2.1a(2)]*	Lateral ties shall extend completely around the steel core. *[10.13.8.2]*	Every longitudinal bar or bundle of bars placed in a corner should be held by transverse reinforcement. *[6.7.5.2(2), EC2 9.5.3(6)]*
	Transverse reinforcement area/diameter	Min. tie area shall be at least 0.009 in^2 per in. (6 mm^2 per mm) of tie spacing. *[I2.1a(2)]*	Min. tie diameter = 0.02 times greatest column dimension. Bars must not be less than a No. 3, or more than a No. 5 bar. *[10.13.8.3]*	Min. tie diameter shall be no less than 0.25 times the longitudinal bar diameter or 0.24 in. (6 mm), whichever is greater. *[6.7.5.2(2), EC2 9.5.3(1)]*

	REQUIREMENT	AISC	ACI	EC4
Transverse Reinforcement Cont.	Intermediate transverse reinforcement requirements	General reference made to ACI. *[I1]*	No specific requirement for composite members. General rules for compression members require that every corner and alternate longitudinal bar shall have lateral support. Additionally, no longitudinal bar shall be farther than 6 in. (150 mm) clear from a laterally supported bar. *[7.10.5.3]*	No bar within a compression zone shall be located further than 6.0 in. (150 mm) from a restrained bar. *[6.7.5.2(2), EC2 9.5.3(6)]*
	Transverse reinforcement spacing	Max. spacing of lateral ties is the least of $16d_b$, $48d_{stirrup}$, or 0.5 times the least column dimension. *[I2.1f]*	Max. spacing of lateral ties is the least of $16d_b$, $48d_{stirrup}$, or 0.5 times the least column dimension. *[10.13.8.4]*	Max. spacing of lateral ties is the least of $20d_b$, the least column dimension, or 15.75 in. (400 mm). At beam-column intersections and lapped joints, spacing is limited to 60% of the above requirement. *[6.7.5.2(2), EC2 9.5.3(3,4)]*
	Spiral transverse reinforcement requirements	General reference made to ACI. *[I1]*	Volumetric spiral reinforcement ratio (ρ_s) shall not be less than: $\rho_s = 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_c}{f_{yt}}$ *[10.13.7.2, 10.9.3]*	No specific requirement.
Longitudinal Reinforcement	Longitudinal reinforcement ratio	$0.004A_g \leq A_{sr}$ *[I2.1a(3)]*	$0.01A_c \leq A_{sr} \leq 0.08A_c$ *[10.13.7.3, 13.13.8.5]*	$0.003A_c \leq A_{sr} \leq 0.06A_c$ *[6.7.5.2(1),6.7.3.1(3)]*
	Concrete cover for longitudinal reinforcement	Min. reinforcement clear cover = 1.5 in. (38 mm) *[I2.1f]*	Min. reinforcement clear cover = 1.5 in. (38 mm), or more for special conditions. *[7.7.1]*	Min. reinforcement cover ranges from 0.4 in. (10 mm) to 2.2 in. (55 mm). with a minimum of one bar diameter based on exposure condition, bond, and fire resistance. *[6.7.5.1(1), EC2 4.4.1]*
	Min. diameter of longitudinal reinforcement	No requirement.	No requirement.	Min. dia. =0.3 in. (8 mm) *[6.7.5.2(2), EC2 9.5.2(1)]*
	Location and number of longitudinal reinforcement bars	At least four continuous bars shall be used in encased composite columns (presumably at corners, although not specifically stated). *[I2.1f]*	Vertical bars must be located at each member corner, with other longitudinal bars spaced not farther apart than one-half the least side dimension of the composite member. Four bar min. for circular ties, six bar min. for spirals. *[10.13.8.6, 10.9.2]*	Min. of one bar per corner for any column shape, and four bars for a circular shape. *[6.7.5.2(2), EC2 9.5.2(4)]*

	REQUIREMENT	AISC	ACI	EC4
Longitudinal Reinforcement Cont.	Longitudinal reinforcement spacing	General reference made to ACI. *[I1]*	Min. clear distance is $1.5d_b$, or 1.5 in. (38 mm), whichever is greater. *[7.6.3]*	Min. spacing is the longitudinal bar diameter, the diameter of aggregate + 0.2 in (5 mm), or 0.8 in. (20 mm), whichever is greater. However, rebar may be directly attached to the steel shape provided the bond surface is reduced by one-half or three quarters, depending upon the location of the reinforcement with respect to the embedded steel shape. *[EC2 8.2(2), 6.7.5.2(3)]*
Shear Transfer (Load Introduction)	Load transfer between concrete encasement and steel core	Shear connectors must be placed symmetrically on at least two sides of the steel core. Shear connectors must be distributed above and below the load transfer region for a distance equal to at least 2.5 times the column depth. Max. connector spacing may not exceed 16 in. (406 mm). *[I2.1f]*	Any axial load strength assigned to concrete of a composite member shall be transferred to the concrete by members or brackets in direct bearing on the composite member concrete. *[10.13.3]*	Need not be used if the design bond/friction strength is sufficient. If required, must be distributed in the region equal to 2.0 times the minimum transverse column dimension (or diameter for circular columns) or one-third of the column length, whichever is greater. Concrete confinement effects may be considered in computation of shear resistance for members with studs connected to the web. *[6.7.4.2]*
General Reinforcement	Development length	General reference made to ACI. *[I1]*	Various requirements are contained in ACI Chapter 12. *[12.2-12.13]*	No specific requirement in EC4; implicit reference made to EC2 which contains various requirements in Clause 8. *[1.2.2, EC2 8.4,8.8,8.9]*
	Lap splices	General reference made to ACI. *[I1]*	Requirements for tension lap splices, compression lap splices, and general provisions are contained in ACI Chapter 12. *[12.14-12.17]*	No specific requirement in EC4; implicit reference made to EC2 which contains various requirements in Clause 8. *[1.2.2, EC2 8.7-8.9]*
Miscellaneous	Connection of multiple encased shapes	When two or more steel shapes are encased, they must be interconnected with lacing, tie plates, batten plates, or otherwise, to avoid individual shape buckling prior to concrete hardening. [*I2.1f]*	No requirement.	No requirement.

NOTATION

A_c = cross-sectional area of concrete, in.^{2} (mm^2)
A_{ch} = cross-sectional area of a column measured to the outside edges of transverse reinforcement, in.^{2} (mm^2)
A_g = gross cross-sectional area of the column section, in.^{2} (mm^2)
A_{sr} = area of continuous longitudinal reinforcing bars, in.^{2} (mm^2)
d_b = diameter of longitudinal reinforcement, in. (mm)
$d_{stirrup}$ = diameter of transverse reinforcement, in. (mm)
f'_c = specified minimum concrete compressive strength, ksi (AISC/ACI)
f_{ck} = characteristic compressive cylinder strength of concrete at 28 days, MPa (EC2/EC4)
F_y = specified minimum steel yield stress, ksi (MPa)
f_{yt} = specified minimum yield stress of transverse reinforcement, ksi (MPa)
ρ_s = ratio of volume of spiral reinforcement to volume of core confined by the spiral (measured out-to-out of spirals)

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