Progressive Collapse Requirements

Cold-Formed Steel Load Bearing Construction

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Figure 1: Cold formed steel load bearing mid-rise construction.

In 2001, the Department of Defense (DoD) published its design guidelines to resist the progressive collapse of structures resulting from an extreme loading event in the Unified Facilities Criteria UFC 4-023-03 *Design of Buildings to Resist Progressive Collapse*. This document provides the design requirements necessary to reduce the potential of progressive collapse for new and existing DoD facilities.

The use of UFC 4-023-03 is controlled by the applicability requirements of UFC 4-10-01 document *DoD Minimum Antiterrorism Standards for Buildings*. UFC 4-023-03 covers the design strategies and requirements for buildings made of reinforced concrete, structural steel, masonry, wood, and cold-formed steel (CFS). The criteria includes design examples and design details for all the above materials except cold-formed steel. It is the objective of this article to discuss the progressive collapse requirements in UFC 4-010-01 and UFC 4-023-03 as it relates to mid-rise construction using cold-formed steel load bearing walls.

CFS Load Bearing Construction

In the opinion of the authors, the use of CFS load bearing framing in typical mid-rise construction (*Figure 1*) brings the value of reducing associated construction cost in comparison to other structural framing systems such as reinforced masonry, structural steel and wood. A key component of the cost savings is the lighter mass of the structure relative to the design of the lateral force resisting system and the foundation. It is important to note that several types of floor systems can be integrated with CFS load bearing walls. Among these types are composite steel deck-concrete slabs, CFS joists or open bar joists with a concrete or wood floor diaphragm, and pre-cast hollowcore concrete planks. The structural system combining CFS load bearing walls and hollowcore planks is ideal for low and mid-rise construction of three to eight stories in height. Because precast hollowcore concrete planks provide the advantages of high stiffness-to-weight ratio and rapid field installation, this allows for a wide range of building usage including apartment buildings, office buildings, health care facilities, hotels, schools, and dormitories.

Progressive Collapse Requirements

UFC 4-010-01 requires that all new and existing buildings of three stories or higher be designed to avoid progressive collapse. UFC 4-023-03 offers two levels of design procedures to resist progressive collapse:

- The first level of progressive collapse design employs the "Tie Forces" method, which is based on the catenary (membrane tension) response of the structure. This design level may be used for buildings assigned Very Low and Low Levels of Protection (VLLOP and LLOP). Horizontal ties only are required for buildings assigned VLLOP, while horizontal and vertical ties are required for buildings assigned LLOP.
- The second level of progressive collapse design employs the "Alternate Path" method, which is based on flexural performance of the floor system, as the building must bridge across removed vertical supporting elements. This design level must be used for building assigned Medium and High Levels of Protection (MLOP and HLOP).

Tie Forces requirements and additional ductility requirements must be also satisfied for MLOP and HLOP. In the case that an adequate Tie Force cannot be developed in a vertical structural element, then the Alternate Path method is allowed to be used to verify that the building can bridge over the deficient element.

DoD mid-rise building projects include, but are not limited to, housing facilities (barracks) in addition to dining, gathering, operations centers, administrative buildings, and health care facilities. These types of facilities are typically assigned VLLOP or LLOP (UFC 4-010-01, Table B-1). As a result, the Tie Forces method can be used by the designer to satisfy the progressive collapse resistance part of the design. The Tie Forces method is a simple, indirect design approach that enhances the continuity, ductility and structural redundancy of the building by requiring horizontal and vertical "ties" to mechanically keep the building together in the event of an extreme loading that causes local damage. *Figure 2* (*see page 10*)

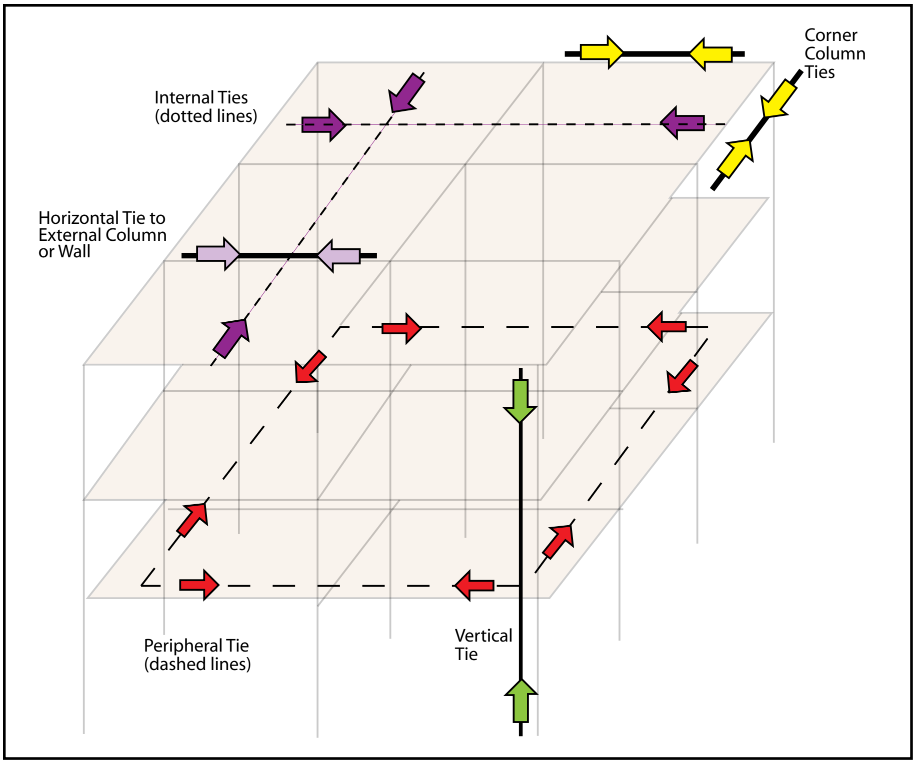

Figure 2: Tie forces in a frame structure (Reference UFC 4-023-03).

shows the different types of ties that must be provided in the building design. There are two main groups of ties; horizontal and vertical. Horizontal ties include internal ties within the floor system, ties to edge columns or walls, ties to corner columns, and peripheral ties around the perimeter of the building. While horizontal ties must provide a straight continuous load path from one building edge to the other, vertical ties must provide a straight continuous load path in columns and load bearing walls. Along a particular horizontal or vertical load path, different structural elements may be used to provide the required tie strength. Adequate manufactured connections must be provided between these structural elements to ensure the continuity of the load path.

Other additional design requirements that apply to all levels of protection (VLLOP through HLOP) are:

a) Multistory vertical load bearing elements must be capable of supporting the vertical load after the loss of lateral support at any floor level with an unsupported length (L_u) of:

$L_u = 2\, l_s$ *Eq. 1*

where l_s is the floor height in (ft). This should be analyzed with the following factored load combination:

$(0.9 \text{ or } 1.2)D + (0.5L \text{ or } 0.2S) + 0.2W$ *Eq. 2*

where D is Dead Load, L is Live Load, S is Snow Load and W is Wind Load.

b) In each bay (one at a time) and at all floors and the roof, the slab/floor system must be able to withstand a net upward factored load of:

$1.0D + 0.5L$ *Eq. 3*

Floor/Roof Tie Force Requirements

Internal Ties

The requirements for floor and roof internal ties vary based on the construction material used. As a general rule: internal ties must be provided at each floor and roof level in two directions; they must be effectively continuous; and they must be anchored to peripheral ties at each end. Additionally, they may be spread evenly or grouped. In walls, these ties must be within 1.6 ft. of the top or bottom surface of the floor diaphragm.

For reinforced concrete and CFS floor and roof systems, internal ties must have a required tensile strength (in kips/ft width) equal to the greater of:

$$\frac{(1.0D+1.0L)l_r}{8475.2}F_t \text{ or } \frac{1.0}{3.3}F_t \qquad Eq. 4$$

Table 1: Unfactored Design Loads

	Dead Load	**Live Load**	**Wind Load**
Roof	20 psf	20 psf	±15 psf
Ceiling	15 psf	–	–
Typical Floor (other than Corridor)	80 psf	40 psf	–
Corridor	80 psf	100 psf	–
Exterior Walls	48 psf	–	25 psf
Interior Walls	12 psf	–	5 psf

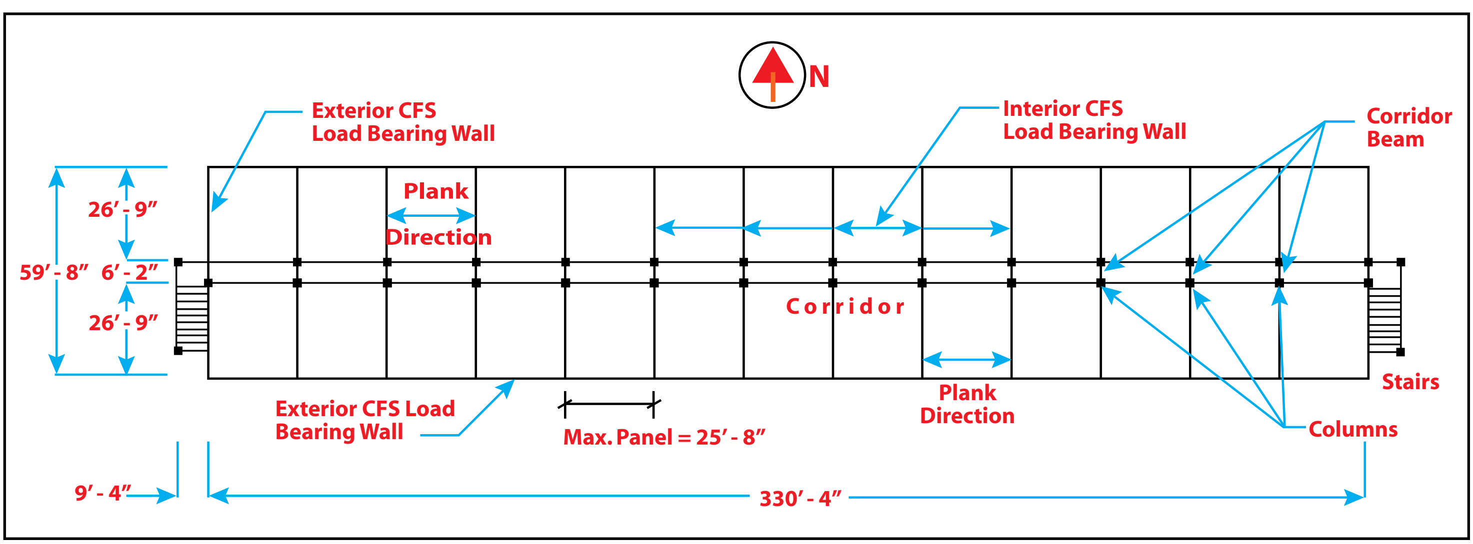

Figure 3: Typical floor plan.

where D and L are in pounds-per-square-foot (psf) and l_r is in feet. F_t is the "Basic Strength" which is the lesser of $(4.5 + 0.9\ n_o)$ or 13.5 for reinforced concrete floor/roof systems and the lesser of $(1.62 + 0.33\ n_o)$ or 4.92 for CFS floor/roof systems. The variable n_o is the number of stories.

Cold-Formed Steel Walls Tie Force Requirements

Peripheral Ties

At each floor level and roof level, provide an effectively continuous peripheral tie capable of sustaining a required tensile strength equal to:

$1.0\ F_t$ (kips) *Eq. 5*

This tie must be located within 3.9 ft. of building edges or within the perimeter wall.

Horizontal Ties to External Walls

Every 3.3 ft. length of external load bearing wall must be tied horizontally into the structure at each floor and roof level with a tie having a required tensile strength equal to the greater of:

a) Lesser of $2.0\ F_t$ or $\frac{l_s}{8.2} F_t$ *Eq. 6*

or b) 3% of the total ultimate vertical load carried by the wall at that level where l_s is in (ft). Where the peripheral tie is located within the wall, provide horizontal ties adequate to anchor the internal ties to the peripheral ties.

Vertical Ties

Tie each column and load-bearing wall continuously from the lowest to the highest level. The tie must be capable of resisting a sile force equal to the maximum design

Table 2: Required Tie Forces

Tie Force	Basic Strength	Reference Equation	Parameters	Required Force
Horizontal Internal, TF_i (Floor)	F_t = lesser of $(4.5 + 0.9\ n_o)$ or 13.5 $n_o = 4$ $F_t = 8.1$	Equation (4)	D = 80 psf L = 40 psf $l_{r\ (E\text{-}W)}$ = 25' 8" $l_{r\ (N\text{-}S)}$ = 26' 9"	$TF_{i\ (E\text{-}W)}$ = 2.94 kips/ft $TF_{i\ (N\text{-}S)}$ = 3.07 kips/ft
Horizontal Internal, TF_i (Corridor)		Equation (4)	D = 80 psf L = 100 psf $l_{r\ (E\text{-}W)}$ = 25' 8" $l_{r\ (N\text{-}S)}$ = 6' 2"	$TF_{i\ (E\text{-}W)}$ = 4.41 kips/ft $TF_{i\ (N\text{-}S)}$ = 2.45 kips/ft
Horizontal Peripheral TF_p	F_t = lesser of $(1.62 + 0.33\ n_o)$ or 4.92 $n_o = 4$ $F_t = 2.94$	Equation (5)	–	TF_p = 2.94 kips
Horizontal to External Walls TF_e		Equation (6)	l_s = 11' 4" Max. 3.3-ft. wall load (E-W) = 27.2 kips Max. 3.3-ft. wall load (N-S) = 15.4 kips	$TF_{e\ (E\text{-}W)}$ = 1.23 kips/ft $TF_{e\ (N\text{-}S)}$ = 1.23 kips/ft
Vertical TF_v (Walls)	N/A	Equation (7), one story	–	$TF_{v\ (Interior)}$ = 4.3 kips/ft $TF_{v\ (Exterior\text{-}Sides)}$ = 2.7 kips/ft $TF_{v\ (Exterior\text{-}Long)}$ = 2.3 kips/ft
Vertical TF_v (Columns)		Equation (7), one story	–	$TF_{v\ (Columns)}$ = 20.3 kips

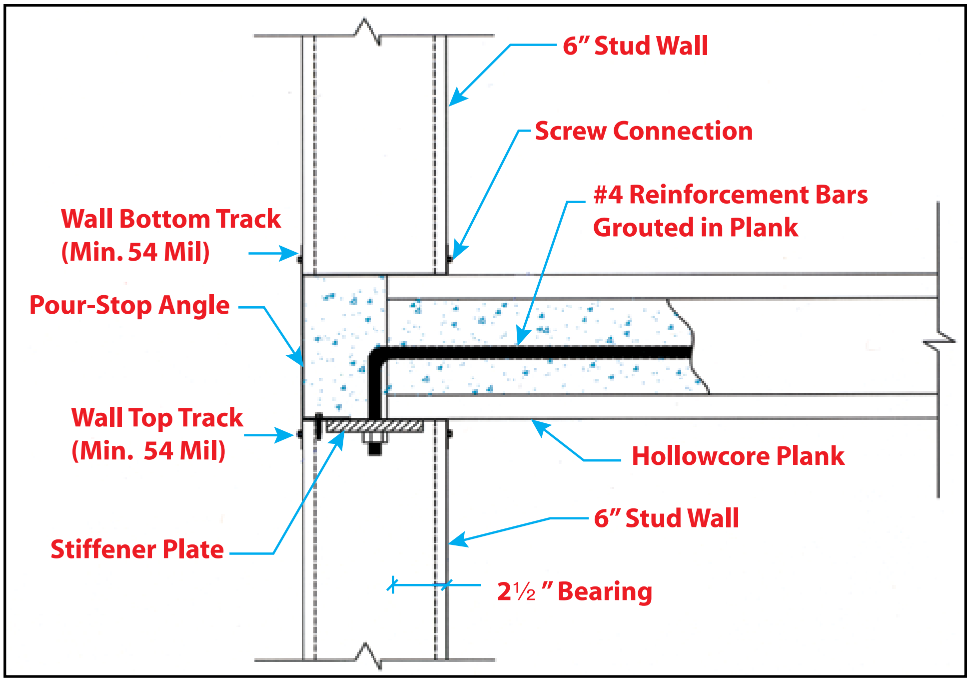

Figure 4: Peripheral tie and horizontal tie connection to external wall.

ultimate dead and live load received by the wall or column from any one story:

$1.2D + 1.6L$ (kips) *Equation 7*

This is the 2003 IBC factored load combination.

Worked Design Example

Building Description

A four-story barracks building designed with CFS load bearing walls and hollowcore precast concrete planks for the floor slabs is considered in this example. The barracks building is assigned LLOP and is approximately 330 feet long and 60 feet wide, with an 11-foot, 4-inch floor to floor height and a CFS truss roof system. The building incorporates a normal weight brick veneer finish on the exterior walls. The typical structural system consists of interior and exterior load bearing walls in the N-S direction that have variable spacing between the bearing walls with a maximum span of 25 feet, 8 inches (*Figure 3, see page 10*). Exterior walls in the E-W direction are also load bearing walls, but only support the truss roof loads in addition to their self weight and the lateral wind pressure. The interior corridor is supported by corridor beams resting on individual CFS columns at the inside edges of the load bearing walls.

Hollowcore planks are selected to be 8 inches thick to accommodate the maximum span of 25 feet, 8 inches between the N-S load bearing walls. The planks require a seating/bearing width of 2 to 2.5 inches on top of the stud walls as recommended by the 1998 Design Manual of the Precast/Prestressed Concrete Institute. A minimum of 6-inch width wall framing can accommodate the required plank seating width, but 8-inch walls are typically recommended for interior walls to allow enough gap between planks to insert diaphragm connectors. The unfactored design loads for this building are summarized in *Table 1 (page 10)*.

Required Tie Forces

This barracks building is considered a composite construction since it has CFS walls and columns with hollowcore concrete slabs and CFS roof trusses. Hence, the floor system is required to meet the internal tie requirements for reinforced concrete design while the roof system is required to meet the internal tie requirements for CFS design. The walls and columns are required to meet the peripheral, external and vertical tie requirements for CFS design, as applicable. Appropriate over-strength factors (Ω) and strength reduction factors (Φ) must be used for different materials as given in UFC 4-023-03. The required horizontal and vertical tie forces for the typical floor and interior and exterior walls and columns for this building are calculated as given in *Table 2 (see page 11)* to generate tie schemes and mechanical connections.

Tie Forces Schemes

a) Internal Ties

The required internal tie forces between hollowcore planks can be achieved using various connection details offered by the Precast/Prestressed Concrete Institute to satisfy their structural integrity and diaphragm action requirements. Reinforcement steel

continued on page 14

bar ties may be run inside the core of the planks in their longitudinal direction and in the connection joint between the planks in their perpendicular direction. Grouting is used to provide the bond between the steel bars and the planks. Reinforcement steel bars can also be used in the concrete topping in the longitudinal direction of the planks, in addition to shorter anchored bars to tie adjacent planks in the perpendicular direction. Using #4 Grade 60 rebar (60 ksi yield strength) spaced 2 feet on center satisfies all the internal tie force requirements (Maximum required strength = 4.41 kips/ft).

b) Peripheral Ties

The required peripheral ties around the perimeter of the building can be achieved through the steel runner tracks bounding the exterior load bearing CFS stud walls. 6-inch exterior stud walls are recommended along with a minimum of 54 mil (0.0566-inch design thickness) runner tracks (*Figure 4, see page 12*). A single 33 ksi yield strength standard track (1.25-inch flange) provides an ultimate tensile strength of 14 kips, which exceeds the required strength of 2.94 kips. Care must be taken at splice locations of runner tracks in order to provide a splice connection capable of resisting the required tensile strength. Another method to provide the required peripheral ties is to use longitudinal steel bars embedded in the end grout. Two #4 Grade 60 rebar provide an ultimate tensile strength that exceeds the required tie strength.

c) Horizontal Ties to External Walls

The required horizontal ties to external walls can be achieved by using reinforcement steel bars grouted into the hollowcore planks from one side and anchored to the runner tracks of the CFS stud walls from the other side. *Figure 4* (*see page 12*) shows these ties where the planks are supported by the stud wall and transferring vertical loads (E-W direction of the barracks building). Similar ties should be provided where the planks are only resting on the stud wall but not transferring any vertical loads (N-S direction of the barracks building). Anchorage of the horizontal ties to the runner tracks ensures the continuity between internal ties and peripheral ties as required by UFC 4-023-03. Number 4 Grade 60 rebar can be used at spacing 2 feet on center, which provides a tensile strength that exceeds the required strength of 1.23 kips/foot. If steel bars are used as peripheral ties, the horizontal ties must extend to overlap with the peripheral ties to provide the required anchorage between the two sets of ties.

d) Vertical Ties

The specifications for vertical ties are the most critical requirements in this building's structural system due to the relatively heavy weight of the floor slab. For interior load bearing walls, mechanical connectors are T-shape steel sections made of ⅜-inch thick plates welded together with stiffeners and attached to both the bottom and top studs of the wall with ½ inch bolts (*Figure 5*). The T-shape connectors are tied together using two ½-inch through bolts that run through the separation gap between the planks. A tested T-shape connector with the same dimensions provides a tensile strength of about 21.8 kips. Use of this connector to tie every third stud (every 4 feet) in interior walls would satisfy the required tensile strength of 4.3 kips/foot (4.3 kips/ft x 4 ft = 17.2 kips < 21 kips). The tensile capacity of two ½-inch through bolts exceeds the required tensile strength. The number of ½-inch bolts required to connect the T-shape to the studs (acting in shear) is dependant on the thickness of the stud. For example, a stud that is 54 mils thick and 50 ksi yield strength requires eight ½-inch bolts to develop connection shear strength of 17.8 kips. The stud itself must also be checked to resist the same strength in tension. Similar or lighter mechanical connectors can be used for exterior load bearing walls in the N-S and E-W directions of the barracks building since the required tensile strength is significantly less.

Corridor beams are typically designed as structural steel W-or WT-shape resting on top of the corridor columns. The columns are built-up CFS studs attached together with weld or screws, and capped from each end with a welded closure plate (*Figure 6*). The hollowcore planks rest on top of the structural steel beam. The required vertical ties for the columns can be achieved, as shown in *Figure 6*, first by welding the closure plate of the bottom CFS column to the W-shape steel beam. Then, four ½-inch through bolts (two on each side of the column) run through the hollowcore planks and are fastened at one end to the top flange of the W-shape beam and at the other end to the closure plate of the top CFS column. Stiffener plates for the W-shape steel beam are provided to connect the beam flanges together at the vertical tie location. The tensile capacity of four ½-inch through bolts exceeds the required tensile strength of 20.3 kips for the vertical tie.

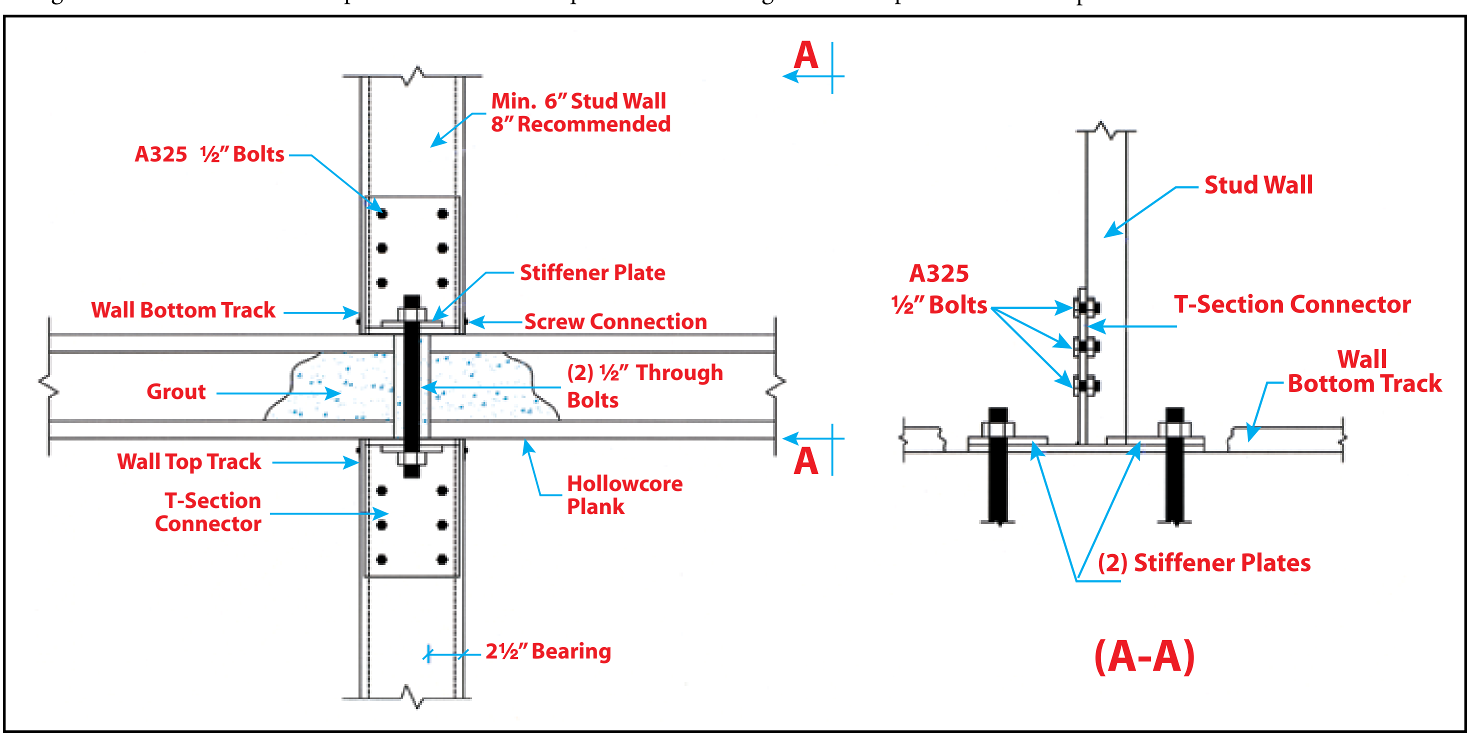

Figure 5: Vertical tie connection in internal wall.

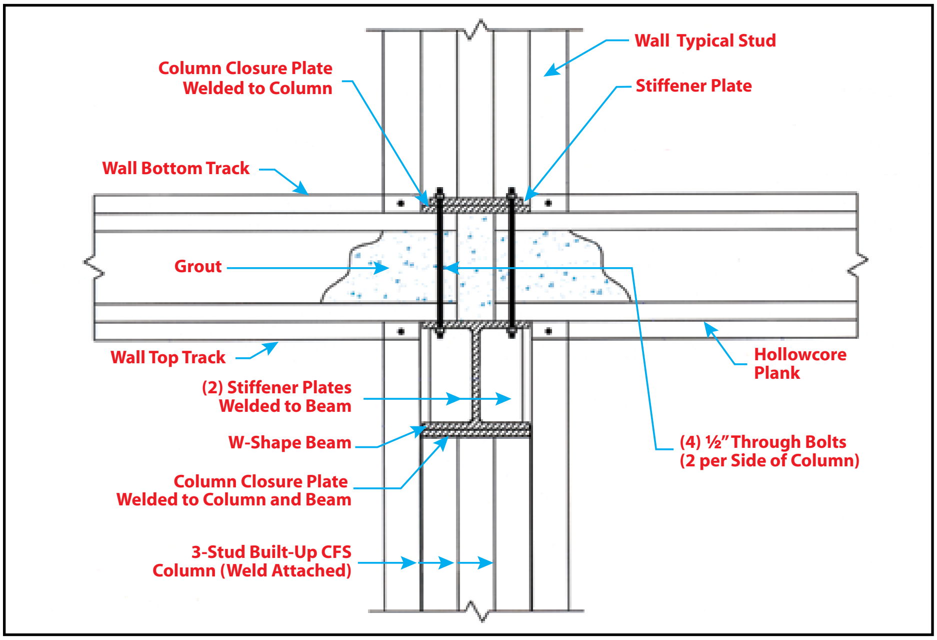

Figure 6: Vertical tie connection in corridor column.

Design for Loss of Lateral Support

Loss of lateral support for load bearing walls and columns necessitates that these load bearing elements be designed at any floor level with an un-supported length (L_u) that is twice the floor height (*Equation 1*). For CFS walls, the lateral direction of the wall is the strong-axis direction of the studs. Therefore, only the strong-axis unsupported length of the studs should be doubled when design is performed to satisfy this requirement.

In addition, the loss of the lateral support in exterior walls subjected to lateral wind pressure requires that the connection between wall sections must be capable of resisting the resulting bending moment; otherwise the wall system becomes unstable under lateral wind loads. The governing factored load combination to design this condition is given in *Equation 2* and the factored design load would be (0.2W). For the barracks building under consideration, if this connection detail is used every third stud (every 4 feet), the maximum factored moment to be resisted for a continuous 22 feet, 8 inches beam is 15.4 in-kips.

Conclusions

This article summarizes the progressive collapse requirements in UFC 4-010-01 and UFC 4-023-03 as it relates to mid-rise construction using CFS load bearing walls. A worked design example for a four-story barracks building with CFS load bearing walls and hollowcore precast concrete slabs assigned LLOP has been used to demonstrate that all the tie forces requirements can be achieved through existing structural elements of the building or added mechanical connections. Special requirements such as loss of lateral support in exterior walls have also been discussed. Design details have been proposed for all the tie forces requirements and special requirements. If CFS load bearing walls are used with other floor systems (such as composite steel deck or CFS joists), some of the presented design details will need to be adjusted accordingly; however, the same method of achieving the tie forces requirements would still apply.▪

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