Structural integrity of precast concrete modular construction

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- This paper explores the structural integrity provisions currently available for precast concrete panel construction and how they can be applied to precast concrete modular construction.
- Typical modular construction configurations were analyzed for multiple scenarios using alternate path analysis and structural integrity provisions to determine appropriate strategies to avoid or mitigate disproportionate collapse.
- Recommended updates to design guidelines and connection details to preserve structural integrity in precast concrete modular construction are presented.

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The American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*[1] contains structural integrity provisions for precast concrete panel buildings but does not address the structural integrity of precast concrete modules. ACI 318 requires spaced steel ties in all directions to tie the precast concrete panel elements together. These criteria are impractical for precast concrete modules due to the construction methods and the overall rigidity of each module. Precast concrete modules are inherently stable, even when subjected to General Services Administration (GSA) criteria[2] for partial removal of structural walls or corners, which require that if a portion of a wall or an entire module is removed, the remaining portions must have sufficient capacity to carry the resulting gravity loads. This paper examines the stress increases due to partial wall removal and the possibility of total module removal. It discusses strength reserves, provides recommendations for future editions of ACI 318 and the *PCI Design Handbook: Precast and Prestressed Concrete*, and presents conceptual connections that provide the continuity and ductility needed to maintain structural integrity following total module removal.

Background

Progressive or disproportionate collapse occurs when a local failure cannot be contained within a prescribed area and the failure moves either vertically or horizontally through the structure.[3] This condition results in a series of failures,

ending in partial or total collapse of a building. Structural integrity is the design and detailing effort needed to preclude or mitigate disproportionate collapse. Structural integrity is addressed in conventional reinforced concrete buildings through prescriptive continuity and ductility detailing specified in the member provisions of ACI 318-19.[1]

The ACI 318 provisions for precast concrete buildings and joints were developed following the May 1968 partial collapse of the Ronan Point apartment building in London, England. The Ronan Point incident occurred when an explosion caused a precast concrete panel to blow out. This created an interruption in the structural system and, due to the lack of continuity, large portions of the building collapsed.[4] Following this collapse, Fintel and Schultz[3] addressed progressive collapse in precast concrete panel buildings. In their paper, they determined that the weak link in precast concrete panel construction was the lack of panel continuity and proposed design guidance to create continuity and ductility. Continuity is essential in transferring and redistributing loads. Ductility is important for abnormal loads because it gives the building the ability to absorb some of the energy and allows redistribution of loads resulting from the failure of a single connection. Fintel and Schultz proposed adding distributed ties in the longitudinal, transverse, and vertical directions. This approach is adopted in ACI 318 and in PCI documents,[5] and it is the established standard for structural integrity of panel construction. Although distributed reinforcement is a logical solution for panel systems, precast concrete modules with integral floors and walls are not readily suited to a distributed-reinforcement connection solution.

GSA alternate path analysis

In the GSA guidelines for progressive collapse resistance,[2] alternate path analysis is the preferred design approach. The GSA requires this design approach for all new construction and major renovation of existing construction. Although this guidance is not directly applicable to modular construction, it is useful for establishing a design methodology for modular construction's structural integrity.

The GSA guidelines begin with the concept of facility security level (FSL). FSL I and FSL II apply to buildings less than four stories tall and in noncritical use. Buildings in these categories require no progressive collapse design effort. FSL III and FSL IV apply to buildings with four or more stories, as well as all other GSA-defined "important" buildings regardless of story height. Designs for these buildings require an alternate path analysis. The alternate path analysis requires removal of a vertical-load-carrying element, such as a column or portion of a wall. The structure is then assessed by either a force- or deformation-controlled analysis to ensure adequate strength.

Section 3.2.9 of the GSA document specifies that the load-bearing column element be removed. For a frame structure, this involves removing a single column. Multiple analyses, each removing a single interior, perimeter, or corner column, are required to determine critical conditions. An important aspect of the GSA guidelines is that the column is removed without disturbing the beams framing into the column. Thus, beams are assumed to remain continuous. Interpretation of the column removal provision for modular construction is complicated by the fact that walls, not columns, carry the vertical load.

The GSA guidelines require removal of portions of the bearing walls. **Figure 1** illustrates the portion of the wall to be removed. For modular construction, the requirements are ambiguous. The value *H* is the wall height and is projected to be the corresponding wall removal length. For example, the guidelines do not specify what is required if the load-bearing wall corner also contains an internal column (Fig. 1). Such a requirement would be more stringent than those applied to frame or shear wall structures. Modular construction may have independent, not common, walls (that is, two walls immediately adjacent to each other). This implies that conditions for exterior walls also address conditions for interior walls in Fig. 1. Removal of a complete module is not explicitly required in the GSA guidelines but could be considered as a worst-case scenario.

GSA acceptance criteria for concrete structures are provided for beams, two-way slabs, and slab-column structures. A pushover analysis is suggested in the American Society of Civil Engineers/Structural Engineering Institute (ASCE/SEI) national consensus standard *Seismic Rehabilitation of Existing Buildings* (ASCE/SEI 41).[6] Load factors, resistance factors, and overload/overstrength provisions in the GSA guidelines are the same as ASCE/SEI 41. These provisions are appropriate for structures subjected to seismic loadings, which would usually exceed the structural integrity provisions for gravity loads.

The pushover analysis is appropriate for buildings limited by flexural behavior. Modules tend to move as rigid bodies due to the inherent diaphragms. Thus, a pushover analysis could result in rigid body movement but not a flexural failure.

Design conditions for structural integrity of modules

This paper addresses two design considerations for modular construction. First, the stress in a module was examined to determine the stress increase resulting from a partial wall removal. This condition directly addresses GSA requirements. Second, a multibay, multistory modular structure was examined to assess the consequences of the loss of a complete module. A full module removal allows comparison with a partial wall removal in panel construction. In both cases, the basis for assessment was a gravity load scenario. A modular structure subjected to earthquake loads would require an individually detailed design approach due to the unique combination of seismic loading and structural system.

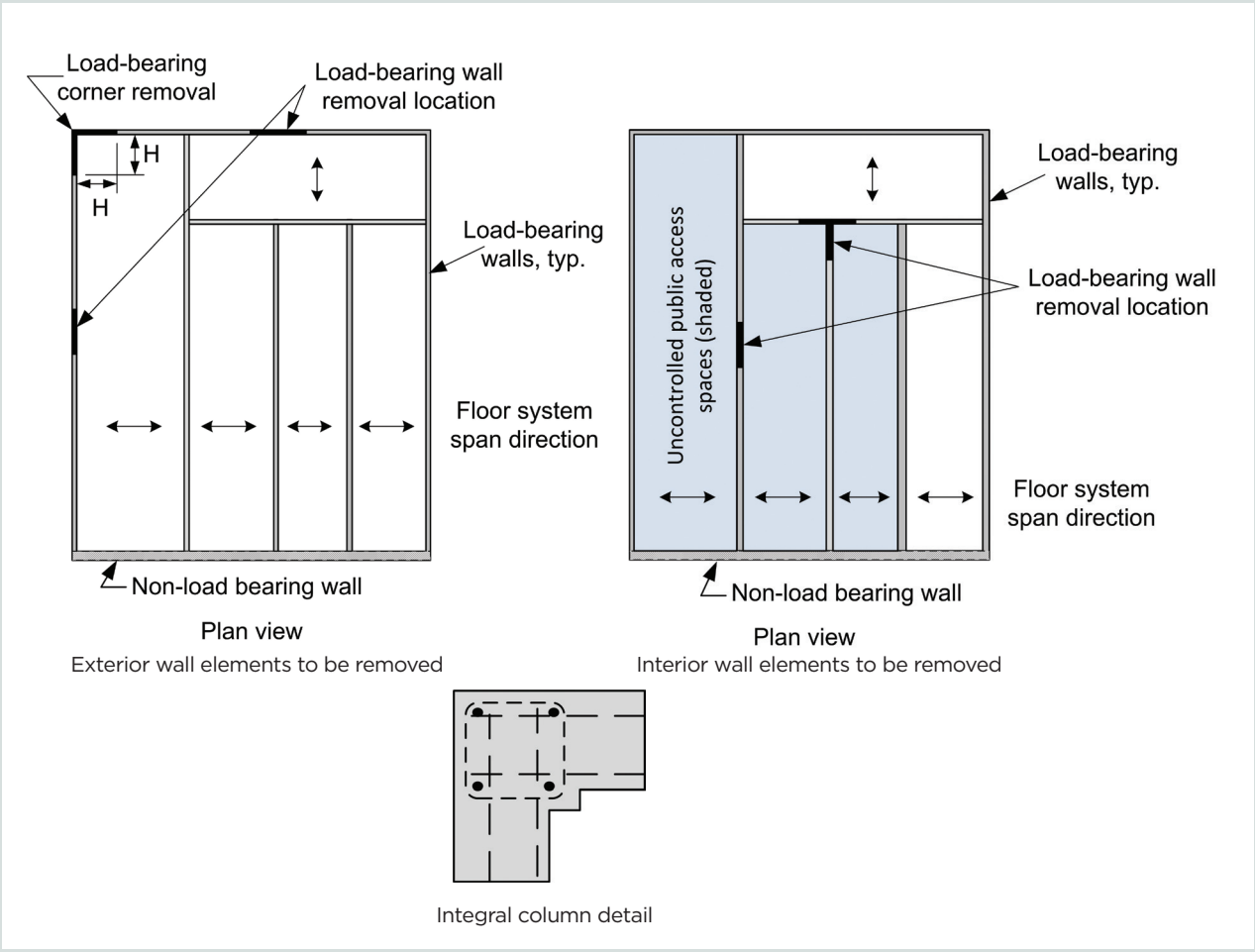

Figure 1. General Services Administration (GSA) guidance for removal of wall elements.
Source: Adapted from GSA's *Alternate Path Analysis and Design Guidelines for Progressive Collapse Resistance* (2013).

Single module behavior

A single module subjected to gravity load exhibits a stress increase in the walls when a portion of the wall is removed. The stress increase is a function of the module size and the length of wall removed. Assessment is complicated by the variable size and layout of the module, the location of design openings, and any additional opening from a GSA alternate path analysis. A simplistic analysis approach was adopted using a rectangular module. One side of the module length was fixed, and the orthogonal side length was varied. An alternate path wall removal was used, and portions of either the long or short side wall were removed. The approach is simplistic because few modules are truly rectangular. Interior partitions for utility chases, nonrectangular layouts, and other geometric variations complicate any such assessment. Nonetheless, a simple rectangular layout provides considerable insight into module behavior as wall area is lost.

The basic premise is that as part of a wall is removed, the centroid of the module resistance moves away from the opening. The center of the gravity load remains essentially constant due to modules above, thus increasing the gravity load eccentricity. The resulting moment on the module increases the stress in the remaining wall near the opening and decreases the stress on the back wall. **Figure 2** illustrates this behavior and the corresponding geometric, sectional properties and equations for a fixed wall length a and a variable wall length b of αa, where α is the ratio of the length of the long side to the length of the short side of the module. The door opening c was assumed to be the same whether in the long or short wall. Both openings are indicated in Fig. 2; however, a shift in the module centroid with respect to the loads above and the resulting eccentricities to the farthest corner were calculated for each direction assuming only one opening was present.

The stress increase at the corner or edge farthest from the new centroid was found by assuming that the axial load on each module is a constant load P. The axial load may be considered as combinations of dead plus live loads, factored or unfactored, and may be for one module or a stack of modules. For the basic module, the stress factor around the floor perimeter, ignoring door openings, is

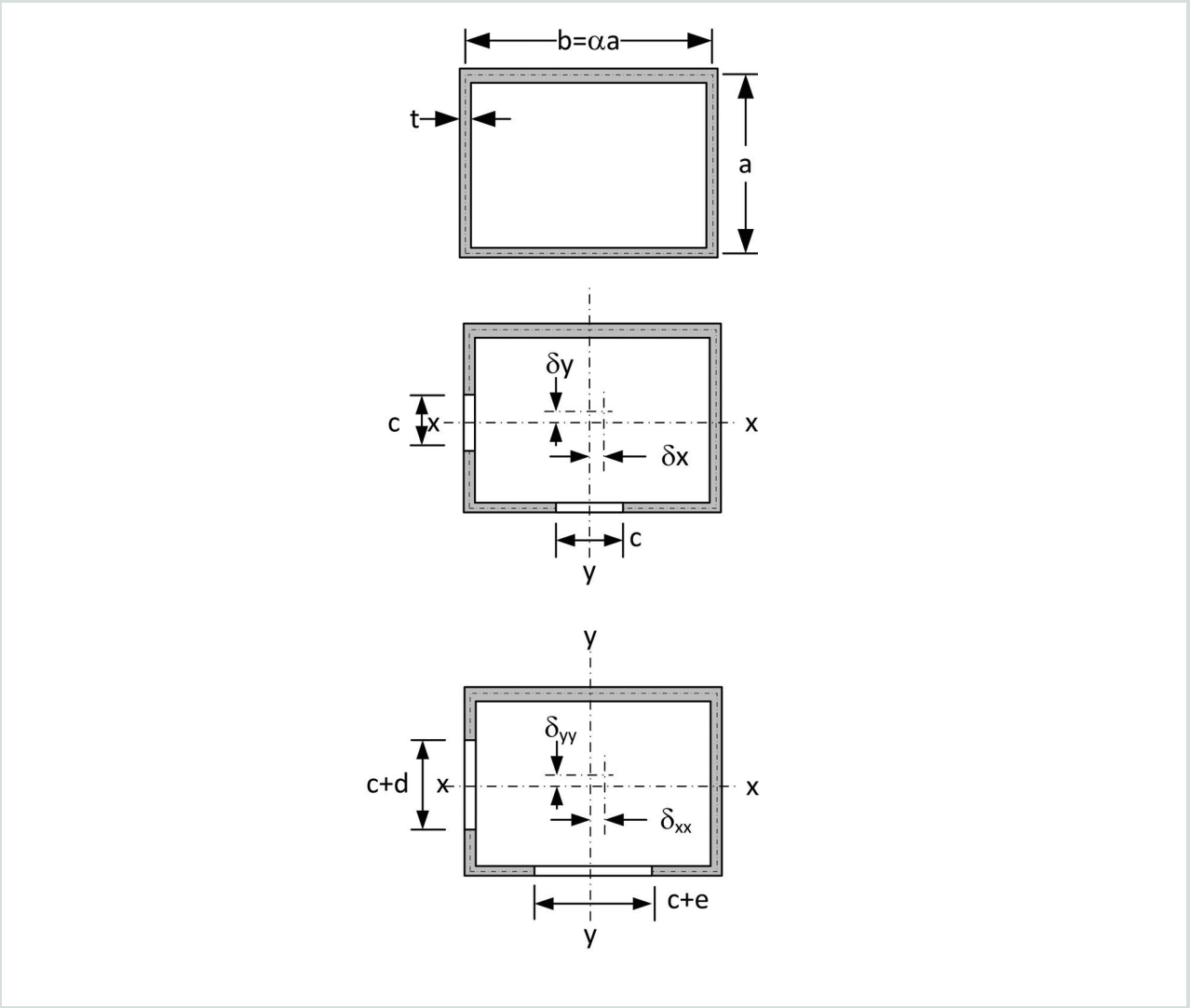

Figure 2. Calculations and geometry for the behavior of a module with a door and partial wall removal. Note: a = fixed wall length of short side of module; A_o = area of the base of the wall; A_{ox} = revised area of the module base due to the door opening in the short wall; A_{oy} = revised area of the module base due to the door opening in the long wall; A_{xx} = revised base area due to the door and additional wall removal openings in the short wall; A_{yy} = revised base area due to the door and additional wall removal openings in the long wall; b = variable wall length of long side of module; c = length of door opening in wall; c_x = distance from the new centroid due to the door opening to the farthest edge in the long direction; c_{xx} = distance from the new centroid due to the door and wall removal openings to the farthest edge in the long direction; c_y = distance from the new centroid due to the door opening to the farthest edge in the short direction; c_{yy} = distance from the new centroid due to the door and wall removal openings to the farthest edge in the short direction; d = length of additional opening in the short side of the module; e = length of additional opening in the long side of the module; I_{ox} = moment of inertia about the x-x axis of the module with door opening in the short wall; I_{oy} = moment of inertia about the y-y axis of the module with door opening in the long wall; I_x = moment of inertia about the x-x axis of the module; I_{xx} = moment of inertia about the x-x axis of the module with the door and wall removal openings in the short wall; I_y = moment of inertia about the y-y axis of the module; I_{yy} = moment of inertia about the y-y axis of the module with the door and wall removal openings in the long wall; t = wall thickness; α = ratio of length of long side to length of short side of module; δ_x = shift in centroid due to the door opening in the long wall; δ_{xx} = shift in centroid due to the door and wall removal openings in the long wall; δ_y = shift in centroid due to the door opening in the short wall; δ_{yy} = shift in centroid due to the door and wall removal openings in the short wall.

$$f_o = P/A_o$$

where

f_o = average stress under the module wall

A_o = area of the base of the wall

For the module with a door opening c, revised base area due to the door opening in the shorter wall A_{ox} and longer wall A_{oy} are the revised area of the module base due to the door opening in the short and long walls, respectively. As the module centroid moves away from the axial load, the stress on the wall with the door opening increases, so the stress factor becomes

$$f_{ox} = \left[\frac{P}{A_{ox}} + \frac{P\delta_y c_y}{I_{ox}} \right]$$

$$f_{oy} = \left[\frac{P}{A_{oy}} + \frac{P\delta_x c_x}{I_{oy}} \right]$$

where

f_{ox} = increased stress about the x-x axis due to the door opening

δ_y = shift in centroid due to the door opening in the short wall

c_y = distance from the new centroid due to the door opening to the farthest edge in the short direction

I_{ox} = moment of inertia about the x-x axis of the module with door opening in the short wall

f_{oy} = increased stress about the y-y axis due to the door opening

δ_x = shift in centroid due to the door opening in the long wall

c_x = distance from the new centroid due to the door opening to the farthest edge in the long direction

I_{oy} = moment of inertia about the y-y axis of the module with door opening in the long wall

Finally, for a module with the door opening plus an opening in the module due to wall removal, the stresses are:

$f_{xx} = \left[\frac{P}{A_{xx}} + \frac{P\delta_{yy} c_{yy}}{I_{xx}} \right]$ and $f_{yy} = \left[\frac{P}{A_{yy}} + \frac{P\delta_{xx} c_{xx}}{I_{yy}} \right]$ on the compression face

$$f_{xx} = \left[\frac{P}{A_{xx}} + \frac{P\delta_{yy}\left(\frac{a}{2} + c_{yy}\right)}{I_{xx}} \right] \text{ and } f_{yy} = \left[\frac{P}{A_{yy}} + \frac{P\delta_{xx}\left(\frac{a}{2} + \delta_{xx}\right)}{I_{yy}} \right]$$

on the tension face

where

f_{xx} = increased stress about the x-x axis due to the door opening and wall removal opening in the short wall

A_{xx} = revised base area due to the door and additional wall removal opening in the short wall

δ_{yy} = shift in centroid due to the door and wall removal openings in the short wall

c_{yy} = distance from the new centroid due to the door and wall removal openings to the farthest edge in the short direction

I_{xx} = moment of inertia about the x-x axis of the module with the door and wall removal opening in the short wall

f_{yy} = increased stress about the y-y axis due to the door opening and wall removal opening in the long wall

δ_{xx} = shift in centroid due to the door and wall removal openings in the long wall

c_{xx} = distance from the new centroid due to the door and the wall removal openings to the farthest edge in the long direction

A_{yy} = revised base area due to the door and additional wall removal opening in the long wall

I_{yy} = moment of inertia about the y-y axis of the module with the door and wall removal opening in the long wall

The resulting percentage stress increase about the x-x axis Δf_x and the y-y axis Δf_y due to the wall removal opening are then a function of f_{xx}/f_{ox}, or

$$\Delta f_x = 100\left[1 + \frac{f_{xx}}{f_{ox}}\right]$$

and

$$\Delta f_y = 100\left[1 + \frac{f_{yy}}{f_{oy}}\right]$$

Thus, the stress increase was estimated independently of the load P, the load combination, and the wall thickness t. For comparison purposes, the wall thickness was assumed to be uniform, the long direction of the module was a ratio α of the short side, and the short side was set at 12 ft (3.7 m). The ratio α varied between 1 and 4, giving modules ranging from square to 48 ft (14.6 m) long. These values were judged to be reasonable limits for shipping a module on the highway. **Figure 3** summarizes the stress increase if a 3 ft (0.9 m) wall loss is considered in addition to the door opening. **Figure 4** indicates the stress increase due to a 6 ft (1.8 m) wall loss. The loss is in addition to the 3 ft wide door opening. Wall removal on the side opposite the door is less critical. A 3 ft wide additional opening is 25% of the short wall length. The 6 ft wide opening plus the door is approximately 22% of the long side length. These lengths of 6 to 9 ft (1.8 to 2.7 m) address the wall length H indicated in Fig. 1. The choice allows extrapolation for intermediate H values. A loss of wall on each side of a corner is approximately equal to the product of the two independent stress increases.

Multibay, multistory behavior

The GSA uses ASCE/SEI 41 for its design criteria, which

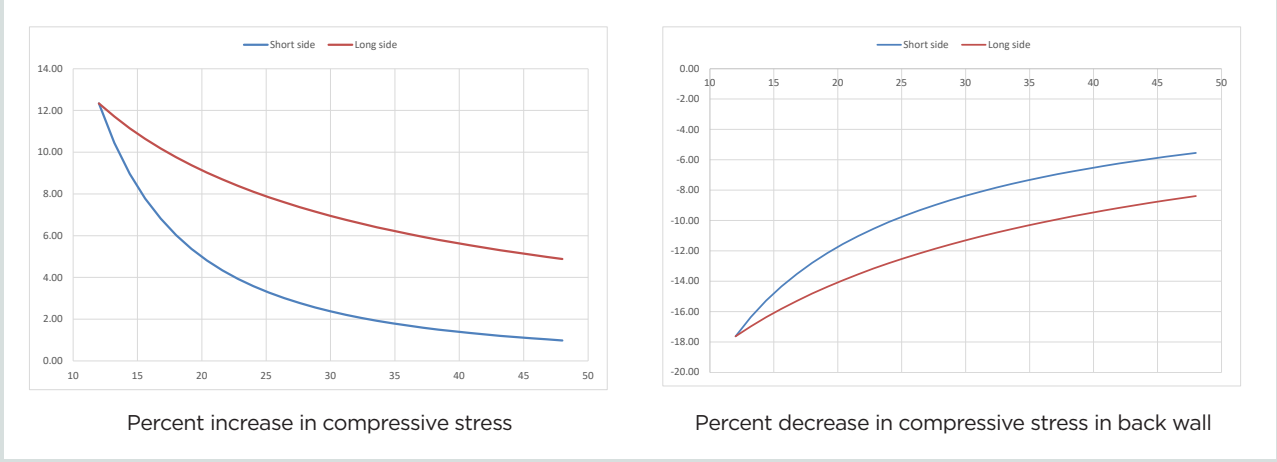

Figure 3. Stress variations due to a 3 ft wall loss in addition to a 3 ft door opening. Note: The short side is 12 ft. 1 ft = 0.305 m.

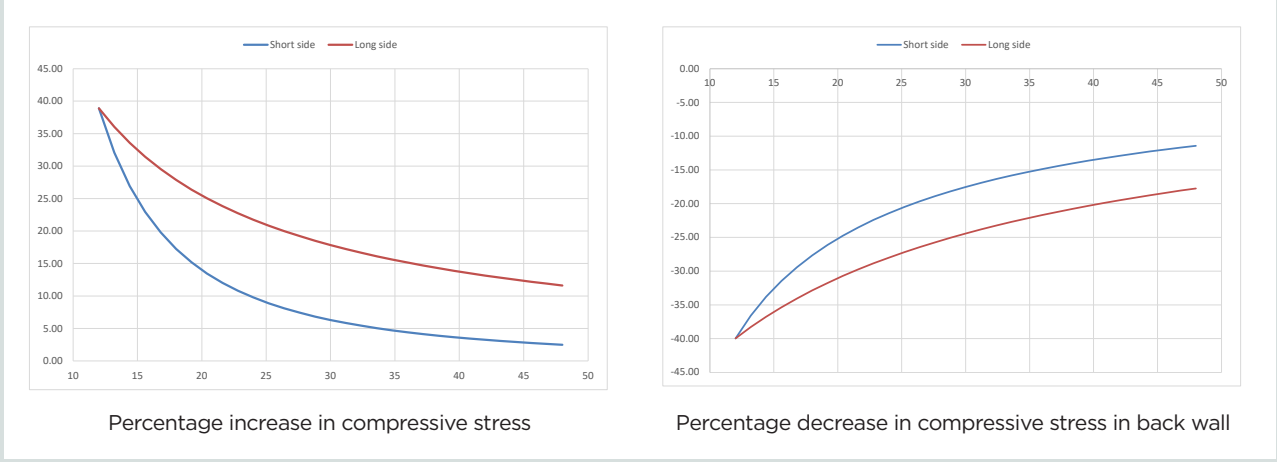

Figure 4. Stress variations due to a 6 ft wall loss in addition to a 3 ft door opening. Note: The short side is 12 ft. 1 ft = 0.305 m.

is concerned with seismic loading, and the development of ACI 318 structural integrity provisions are for nonseismic gravity load conditions. For gravity loadings, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7-16)[7] was used as a reference to define loads required by the connections in the corners of the precast concrete modules. To determine the loads in each corner, the dead load of a single module plus 30% of the live load and wind load was used, consistent with Fintel and Schultz's approach for panel construction.[3] The live load was based on the expected live loads in a given module and a concurrent wind event.[8] The rationale for reduced live load was an assumption that not all modules have maximum loading simultaneously at the time of abnormal loading.

As modules become more complex, selection of wall segments, corners, elements, or implied columns becomes equally complex. The most severe condition would be the failure of a complete module. By examining behavior if one module is completely lost, all possible subelement failures are addressed. An alternative condition occurs when a common wall (that is, two adjacent interior walls) is lost. These are worst-case scenarios because in most cases, the entire module or two adjacent walls would not be removed simultaneously even under an abnormal loading situation. The effect of any partially damaged module that helps distribute overall loads was not considered.[3]

Structural integrity conditions In the modular construction analysis for this study, three critical conditions were examined to ensure that structural integrity was achieved (**Fig. 5**). The first critical condition removed a complete ground-level interior precast concrete module (Fig. 5). The second critical condition removed an outside corner precast concrete module, thus creating cantilevers in the modules above and creating tension and shear loads at the corners of the remaining modules (Fig. 5). A third critical condition removed one set of common walls. Based on these conditions, a design approach that restrains the module at each corner was examined. Consistent with the

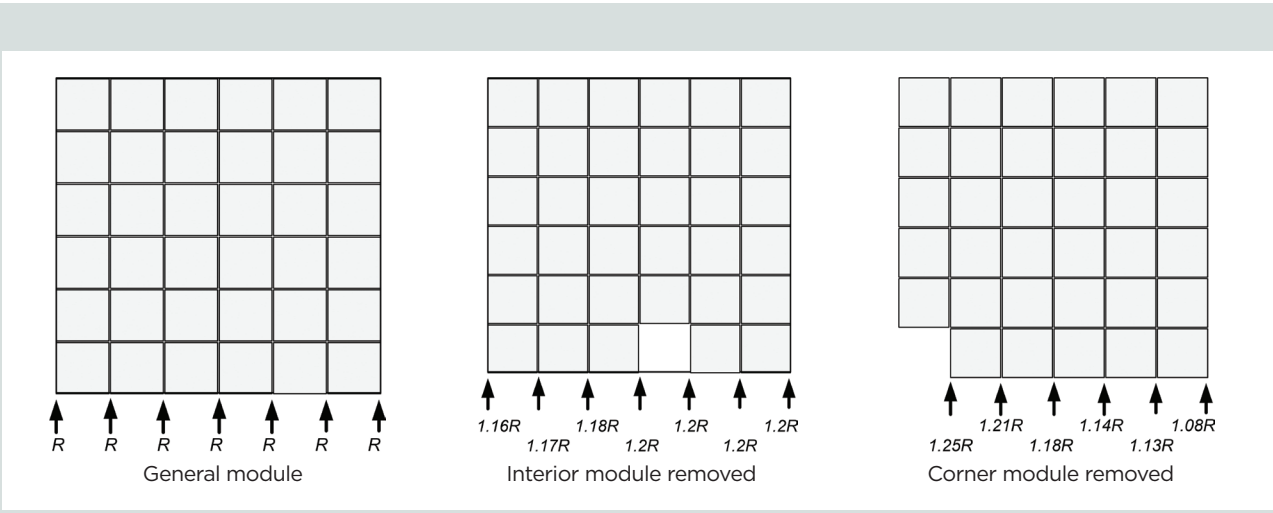

Figure 5. Reaction effect factors caused by removing critical elements. Note: *R* = calculated reaction force in general module.

approach in ACI 318,[1] the analysis addressed only the structural elements above the foundation.

Modeling a modular building and resulting loads The modular building for this analysis was modeled as six stories high and six bays wide. The stack height is typical of precast concrete modules found in industry practice, though some modular construction is more than 12 stories high. The module for this analysis was 12 ft (3.7 m) wide, 12 ft high, and 33 ft (10.1 m) long, with walls that were 4 in. (100 mm) thick. This is representative of one of the larger sizes found in practice.[9,10] Each module consists of walls and a ceiling, not unlike an inverted shoebox (**Fig. 6**). As the modules are stacked, the ceiling becomes the floor of the next unit. Doors, windows, and other openings were ignored to create the largest loads on each connection. The factored loads for each condition were determined for the load combination

$$1.2D + 0.3L + 0.3W$$

where

D = dead weight of the module

L = prescribed live load

W = wind load

This same load combination was used in the Fintel and Shultz paper for determining loads in the connections.[3]

A two-dimensional (2-D) frame model was selected for this building, and SAP 2000 version 14 was used for the initial analysis. A frame model was selected to model the rigid corners in the module. Walls and floors create a diaphragm system that transfers forces from the front to the back of the module, allowing the building to be modeled as a 2-D structure. The 2-D model incorporated shell elements for the walls and ceiling/floor of the module to reflect the module stiffness. Corner connections between each module were 1 in. (25 mm) in length and pinned to each adjacent module, allowing the movement needed to develop shear-friction reactions between modules. The loads were placed in each shell element based on self-weight and live load contribution. The analysis was repeated for each critical condition to determine the building load transfers. In each situation, the analysis model indicated that loads transfer across and down the building, resulting in a structure that has small deformations but no collapse. These connections meet global requirements for structural integrity. Reactions adjacent to the removed module were greater than those due to gravity loading after removing the module, and maximum load effect factors are summarized in Fig. 5.

The module was assumed to be a box with an open bottom (**Fig. 7**). Although doors and windows reduce the end stiffness, their effect was not included in the analysis. It was assumed that such openings would be locally reinforced for the applied loads and bearing under each wall is nominally uniform. Each

Figure 6. Precast concrete module being placed. Courtesy of Doug Buhrens.

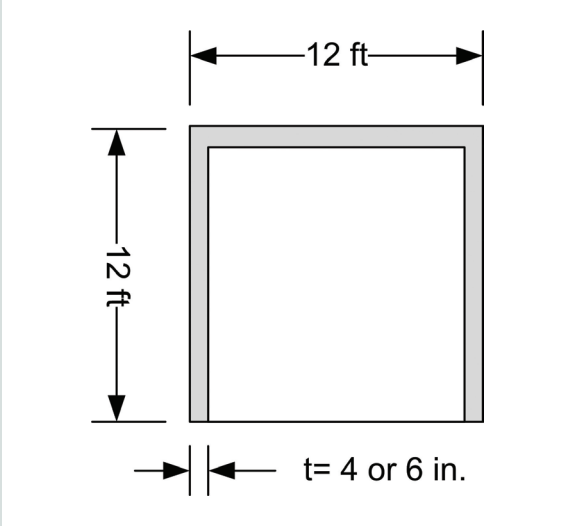

Figure 7. Module dimensions for analysis. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

module was placed on the foundation slab or the module below. The wall element acts as a fixed-pinned cantilever, being pinned to the section below and fixed to the top slab.

Wall loads

Begin with a module 12 ft (3.7 m) high, 12 ft wide, and 33 ft (10.1 m) long with walls 4 in. (100 mm) thick (Fig. 7). Conservatively assuming solid ends, no floor, and a unit weight of concrete of 150 lb/ft^3 (23.6 kN/m^3), the weight of the module is 71.5 kip (318 kN).

If the wall thickness is increased to 6 in. (150 mm) and the concrete unit weight increased to 160 lb/ft^3 (25.2 kN/m^3), the weight of the module is 114.5 kip (509 kN).

Assuming a live load of 40 lb/ft^2 (1.9 kN/m^2) with 30% of the live load present at the time of a disproportionate collapse, the live load is 14.9 kip (66.3 kN).

Using a load combination of $U_4 = 1.2D + 1.6L$, the maximum load on a complete module with walls 4 in. (100 mm) thick is

$U_4 = 1.2D + 1.6L = 1.2 \times 71.5$ kip $+ 1.6 \times 14.9$ kip $= 109.6$ kip

For a module with walls 6 in. (150 mm) thick U_6, the same load combination is

$U_6 = 1.2 \times 114.5$ kip $+ 1.6 \times 14.9$ kip $= 161.2$ kip

Neglecting any bearing in the end panels, the stress f_{c4} along the base of a wall 4 in. (101 mm) thick is

$f_{c4} = U_4/(33 \text{ ft} \times 12 \text{ in./ft} \times 4 \text{ in.} \times 2 \text{ walls}) = 34.6$ psi

For a wall 6 in. (150 mm) thick f_{c6}, the stress is

$f_{c6} = U_6/(33 \text{ ft} \times 12 \text{ in./ft} \times 6 \text{ in.} \times 2 \text{ walls}) = 33.9$ psi

For a six-story building with walls 4 in. (100 mm) thick, the factored stress f_{cu} at the base of the wall with the corner module missing is

$f_{cu} = 5$ stories $\times$ 2 module walls $\times$ 1.25 effect factor $\times$ 34.6 psi + bottom module wall = 450 psi

where the 1.25 effect factor comes from the analysis results indicated in Fig. 5.

For a 6 in. (150 mm) thick wall

$f_{cu} = 5$ stories $\times$ 2 module walls $\times$ 1.25 effect factor $\times$ 33.9 psi + bottom module wall = 440 psi

Wall capacity

From ACI 318 section 11.5.3.1, the wall capacity for a wall with thickness t of 4 in. (100 mm), an unsupported height l_e of 11.33 ft or 136 in. (3.45 m), a concrete strength of at least f'_c of 4000 psi (27.6 MPa), and an effective height factor k of 0.7 for a propped cantilever, the nominal capacity of a 1 ft (0.3 m) section of wall f_n is

$$f_n = 0.55 f'_c \left[1 + \frac{kl_e}{32t}\right] = 0.55(4000)\left[1 - \frac{0.7 \times 136}{32 \times 4}\right] = 564 \text{ psi}$$

Applying a strength reduction factor ϕ of 0.65 means the factored load that can be applied to the wall f_u is

$f_u = \phi f_n = 0.65 \times 564 = 366$ psi (2.5 MPa)

For a 6 in. (150 mm) thick wall, the unsupported height l_e reduces to 134 in.

Figure 8. Simple gravity dowel connections on grout pad. Courtesy of Zebra Constructors, Australia.

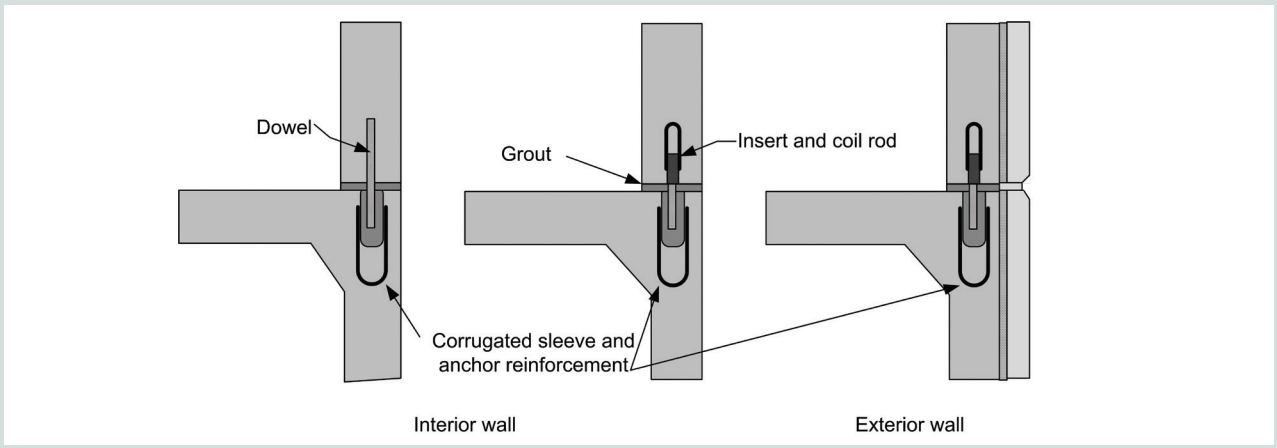

Figure 9. Schematic interior and exterior wall connections for use in precast concrete modules.

$$f_n = 0.55 f'_c \left[1 + \frac{kl_e}{32t}\right] = 0.55(4000)\left[1 - \frac{0.7 \times 134}{32 \times 6}\right] = 1109 \text{ psi}$$

Applying a strength reduction factor ϕ of 0.65 means the factored load that can be applied to the wall is

$$f_u = \phi f_n = 0.65 \times 1109 = 721 \text{ psi}$$

For the six-story building in Fig. 5, the 4 in. (100 mm) thick wall is not adequate. The nominal capacity of a 6 in. (150 mm) thick wall is about 1109 psi (7.7 MPa) based on ACI 318 section 11.5.3.1. The corresponding factored load is 731 psi (5.0 MPa), or approximately 60% of the wall capacity, indicating that the wall is adequate.

Connection requirements

Modular construction connections for gravity-only construction vary from only grout between modules to dowels or ties vertically between modules (**Fig. 8** and **9**). Modular construction in the United Kingdom uses blockouts and through bolts to provide some continuity (**Fig. 10**).

Gravity connections alone do not allow lateral force transfer and may be inadequate because the loss of a complete module could lead to the progressive collapse of the modules above. Thus, the 2-D analysis indicates that modules must be tied laterally to adjacent modules to distribute the loads. The critical structural integrity condition occurs when a bottom corner module is removed, creating a cantilever situation for the modules above. The connections along the upper modules must be able to develop shear and tension forces such that the modules above the failed unit are restrained, just as the Fintel and Schultz paper[3] proposed for panel construction. These connections are designed not to yield but will deform under load. The connection deformation creates the effective ductility in the event of a localized failure. Each module is then designed so connections carry a single unit by shear friction. Small slippage allows each module above to engage the shear

Figure 10. Blockouts for through bolt connections are seen along module edges. Courtesy of PCE Ltd.

friction force, and each module is carried individually. The resulting shear friction between modules allows the loads to be distributed laterally and vertically.

Structural integrity design approach

Structural integrity design requires two features. First, the wall capacity must be sufficient to resist the increased load resulting from the loss of critical members. Based on the individual module assessment and the 2-D analysis, a wall capacity reserve of 40% is adequate to meet this criterion. Second, lateral connections must develop shear-friction-resisting forces between the remaining modules. Selecting a 45 kip (200 kN) reaction for each module corner provides a resistance comparable to the loads in the Fintel and Schultz recommendations[3] for panel construction. The strength reduction factor ϕ used for shear friction is 0.75, and the strength reduction factor ϕ for tension is 0.90. Each connection is designed such that loading exceeds yield; hence a lower-bound

solution exists. The shear friction connection at the corners of the modules should be capable of carrying at least one-half of the factored load corresponding to the load combination $1.2D + 0.3D + 1.3W$. This connection ensures distribution of the loads both horizontally and vertically in the event of the loss of a complete module.

Conceptual connections Current practice uses gravity connections between modular elements. Such gravity connections do not provide the redundant load path needed for structural integrity. We therefore offer a series of conceptual connections that provide the redundancy and load path needed for development of shear friction and structural integrity.

The first connection concept uses a through bolt to join two adjacent modules to develop a shear friction restraint (**Fig. 11**). The connection uses bearing plates to prevent pullout and dry pack to conceal the connection. Anchor reinforcement needed to meet the anchoring to concrete provisions of ACI 318 chapter 17 is not detailed. A similar connection at the top of the wall resists cantilever actions. The top detail may require architectural treatment for the topping and finish requirements.

An A325 bolt with a yield strength of 92 ksi (634 MPa) and a friction coefficient of 1.0 requires a minimum ⅝ in. (15.9 mm) diameter to develop a 45 kip (200 kN) factored load reaction. The final selection is dependent on the bolt type and bolt strength. For example, a net area of approximately 1⅝ in.^{2} (1048 mm^2) of A36 steel is required for the same connection. The bolt size would increase for the end modules to include the tension force from the cantilever action. Many modules have thicker corners for embedded column elements, making this type of connection easier to integrate.

The second connection concept examines the use of a plate to connect adjacent module walls (**Fig. 12**). This connection mobilizes the inserts already employed in the basic gravity connections. A corrugated sleeve and anchor reinforcement need to be sufficient to prevent concrete breakout of the bolt in the event of a module failing below this connection. The exterior corner module requires reinforcement engaged in both horizontal directions. This reinforcement additionally resists forces caused by an edge module failing and provides a cantilever restraint at the top of the module.

ACI 318 and *PCI Design Handbook* recommendations

When structural integrity provisions for a precast concrete panel structural system are considered, a single panel is removed, remaining panel loads are analyzed, and connections are designed to maintain structural continuity. In a precast concrete module system, a similar design approach is used by either providing reserve wall capacity, removing an entire precast concrete module, or removing a set of common walls.

The ACI 318 philosophy for structural integrity relies on prescriptive conditions such as specified continuous reinforcement. Reducing the strength reduction factor ϕ from 0.65 to 0.60 for the walls and vertical-load-carrying elements of a precast concrete module provides the 40% strength reserve indicated in the parametric studies. Historically, the strength reduction factor is not used for structural integrity, so this would be a divergence from past practice. While the strength reduction factor ϕ for compression members addresses more than just strength, this approach is consistent with the ACI 318 philosophy of providing strength reserve and addresses basic structural integrity for modular buildings. This reduction in the strength reduction factor ϕ results in a minimal impact in the wall design and is applicable to all buildings in the GSA's FSL I and FSL II.

For buildings in the GSA's FSL III and FSL IV, or all "important" buildings, reduction in the strength reduction factor ϕ alone may not be sufficient to prevent progressive collapse. Based on these analyses, load-carrying connections

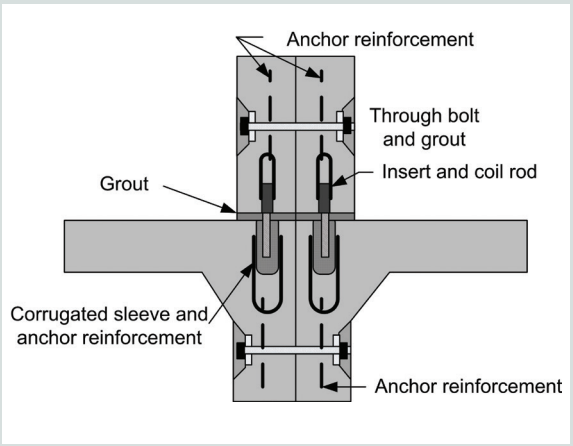

Figure 11. Shear friction connection using a through bolt.

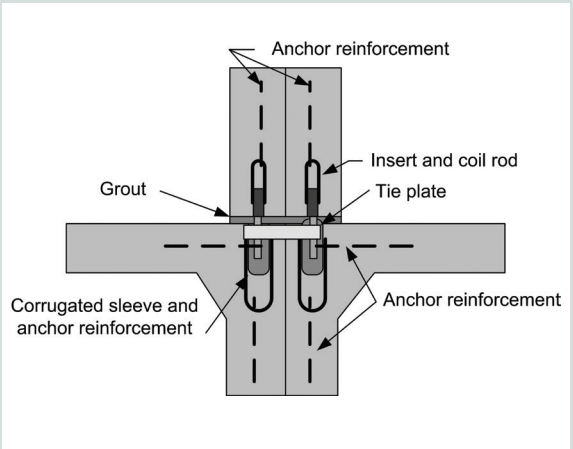

Figure 12. Embedded steel plate integrity connection.

are required to ensure structural integrity. Connections with a tensile capacity of at least 45 kip (200 kN) per corner are sufficient to develop shear-friction-resisting forces to support each upper module in the event of a total module failure. The 45 kip criterion plus any tensile reaction for cantilevered modules may be considered for inclusion in ACI 318 or the *PCI Design Handbook*. Detailed connections are beyond the scope of the building codes. The *PCI Design Handbook* provides a logical location for a discussion of these connections and the associated anchorage to concrete provisions.

Conclusion

The loss of a partial wall, a complete module, or a common wall in a modular building system that is designed for gravity and wind has been presented. Modular units are inherently stable and require little supplemental reinforcement to ensure structural integrity. The suggested provisions built into the basic design requirements of structural integrity account for abnormal loading. Findings from past research conducted on the structural integrity of precast concrete panels and the results of the structural analysis and rigid body reaction models indicate that the same principles can be used for precast concrete modules. Corner connections join modules and create structural integrity, ensuring that in the event of an abnormal failure, the building will absorb the energy and transfer the load throughout the remaining structure. The intention of this design approach is to create redundant ductile load paths to prevent the progressive collapse of precast concrete modules. Strength reduction criteria, loads, and example connections are suggested to be prescriptive and easily incorporated. This in turn creates a condition in which the modular construction behaves like a traditional cast-in-place concrete building or precast concrete panel construction for structural integrity.

Acknowledgments

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Notation

a = fixed wall length of short side of module

A_o = area of the base of the wall

A_{ox} = revised area of the module base due to the door opening in the short wall

A_{oy} = revised area of the module base due to the door opening in the long wall

A_{xx} = revised base area due to the door and additional wall removal openings in the short wall

A_{yy} = revised base area due to the door and additional wall removal openings in the long wall

b = variable wall length of long side of module

c = length of door opening in wall

c_x = distance from the new centroid due to the door opening to the farthest edge in the long direction

c_{xx} = distance from the new centroid due to the door and wall removal openings to the farthest edge in the long direction

c_y = distance from the new centroid due to the door opening to the farthest edge in the short direction

c_{yy} = distance from the new centroid due to the door and wall removal openings to the farthest edge in the short direction

d = length of additional opening in the short side of the module

D = dead weight of the module

e = length of additional opening in the long side of the module

f_c' = compressive strength of concrete

f_{c4} = stress along the base of the 4 in. thick wall

f_{c6} = stress along the base of the 6 in. thick wall

f_{cu} = factored stress at the base of the wall with the corner module missing

f_n = nominal capacity of a 1 ft wall section

f_o = average stress under the module wall

f_{ox} = increased stress about the x-x axis due to the door opening

f_{oy} = increased stress about the y-y axis due to the door opening

f_u = ultimate (factored) capacity of a 1 ft wall section

f_{xx} = increased stress about the x-x axis due to the door opening and wall removal openings

f_{yy} = increased stress about the y-y axis due to the door opening and wall removal openings

H = wall height and corresponding length of eliminated wall

I_{ox} = moment of inertia about the x-x axis of the module with door opening in the short wall

I_{oy} = moment of inertia about the y-y axis of the module with door opening in the long wall

I_x = moment of inertia about the x-x axis of the module

I_{xx} = moment of inertia about the x-x axis of the module with the door and wall removal openings in the short wall

I_y = moment of inertia about the y-y axis of the module

I_{yy} = moment of inertia about the y-y axis of the module with the door and wall removal openings in the long wall

k = effective height factor

l_e = unsupported height

L = prescribed live load

P = axial load

R = calculated reaction force in general module

t = wall thickness

U_4 = load combination for a 4 in. thick wall

U_6 = load combination for a 6 in. thick wall

W = wind load

α = ratio of length of long side to length of short side of module

δ_x = shift in centroid due to the door opening in the long wall

δ_{xx} = shift in centroid due to the door and wall removal openings in the long wall

δ_y = shift in centroid due to the door opening in the short wall

δ_{yy} = shift in centroid due to the door and wall removal openings in the short wall

Δf_x = percentage stress increase about the x-x axis due to the wall removal opening

Δf_y = percentage stress increase about the y-y axis due to the wall removal opening

ϕ = strength reduction factor

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Abstract

The American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)* contains structural integrity provisions for precast concrete panel buildings but does not address the structural integrity of precast concrete modules. ACI 318 requires spaced steel ties in all directions to tie the precast concrete panel elements together. These criteria are impractical for precast concrete modules due to the construction methods and the overall rigidity of each module. Precast concrete modules are inherently stable, even when subjected to General Services Administration criteria for partial removal of structural walls or corners, which require that if a portion of a wall or an entire module is removed, the remaining portions must have sufficient capacity to carry the resulting gravity loads. This paper examines the stress increases due to partial wall removal and the possibility of total module removal. It discusses strength reserves, provides recommendations for future editions of ACI 318 and the *PCI Design Handbook: Precast and Prestressed Concrete*, and presents conceptual connections that provide the continuity and ductility needed to maintain structural integrity following total module removal.

Keywords

Connection, modular construction, structural integrity.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

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