An Approach to Analytically Modeling Modular Vertical Expansions

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Abstract: Multi-story modular construction methods may offer advantages over site-intensive construction methods for some vertical expansion projects. Vertical expansions can be design-intensive depending on the condition of the existing building and the availability of design documentation. Feasibility of a modular vertical expansion is highly dependent on a variety of factors such as local ordinance and code, the building construction type and use, as well as the site and existing building conditions.

Identifying those factors that can adversely affect feasibility on complex projects, such as vertical expansion, can often be difficult in the preliminary design stages. Front-end planning tools can be used to help identify those factors early on in the preliminary design stages to help eliminate costly design errors. In modular projects, design errors could have an amplified effect due to the inability to make design changes after module production has begun.

In this paper, some of the factors that can affect the feasibility of a modular vertical expansion are explored, and the benefits of using a coarse finite-element modeling approach to help identify those factors are discussed. A case study is used to demonstrate this approach and provide project-specific factors, some of which can be generalized to other modular applications. The results of the case study show the important planning information that can be obtained by studying generalized structure behavior in the front-end portion of the design.

1. Introduction

Prefabrication and modular construction methods have been identified by the National Institute of Standards and Technology (NIST) as a potential way to improve productivity in the U.S. construction industry (MBI, 2010). Multi-story modular construction is a subset of modular construction.

Multi-story modular construction methods, as shown in Figure 1, are currently being utilized by the construction industry for the purposes of quickly constructing cost-effective, multi-family housing. In the U.S., the merits, effectiveness and applicability of these methods are currently topics of interest and debate within the construction community, and research shows that projects currently employing multi-story modular construction methods are experiencing varying degrees of success (Jellen, 2015).

Figure 1. SoMa Studios, a 23-unit apartment building in San Francisco's trendy South Market district (image by Modular Building Institute (MBI)).

To capitalize on the construction methods' available productivity benefits, it is important to understand how to best implement this prefabricated method and recognize the factors that can adversely affect feasibility. The research discussed here was initiated to study how to optimally maximize the benefits of multi-story modular methods in construction projects. It was discovered early on in the research that the pairing of the method to a suitable application and the proper execution of the front-end design process can increase feasibility for complex projects involving higher levels of prefabricated components.

To develop a deeper understanding of the design process and study feasibility factors, a multi-story modular construction application was selected and the design process was mapped. A case study was then used to verify the mapped design process and to identify factors that could potentially affect feasibility (Jellen 2015). The case study helped to identify additional factors that were more easily recognized during the engineering design process.

The scope of the research was limited to studying the construction of multi-family residential facilities. Multi-family residential structures such as apartments, student housing and social housing units were identified in the research as good candidates for modular construction methods because of their often simple, repetitious floor plan and geometry. These aspects make the module templating process for production more efficient.

2. Modular Construction Study and Application Selection

Initially, an in-depth state-of-the-art review was conducted to determine specific benefits available to users of multi-story modular construction methods, barriers to implementation, appropriate applications for the construction method, and opportunities for expanded use of the construction method. The review pointed to two primary advantages over the competing site-intensive construction methods: 1) the significant construction schedule reductions available through off-site production and 2) the reductions in community/business disturbance associated with just-in-time delivery of the modules.

Notable barriers identified include the social stigmas that exist regarding prefabricated housing and the term "modular", the geometric limitations (transportation and production) of the method, redundancy of assemblies that exist due to the six-sided nature of a module, varying break-even points associated with the economical production of the modules, the significant amount of pre-planning necessary to successfully implement a prefabricated component into a construction project, and the difficult nature of making design modifications once production of the modules has begun.

The review highlighted vertical expansion as an appropriate use for multi-story modular construction methods and one that might be used more frequently in the United States (U.S.). A vertical expansion project can benefit, in some situations, from both the time saving aspects and the reduced community disturbance available to users of this construction method. However, in order to determine whether modular construction methods are appropriate for any particular project, preliminary planning and feasibility analysis should be conducted.

2. The importance of Pre-planning effort

Users of prefabrication and modular construction techniques can be rewarded with productivity improvements in their construction projects, but misapplication and poor planning or implementation can produce just the opposite effect. Fully modular projects require a significant amount of pre-planning effort, and design changes are difficult to implement once the production of the modules has begun. Because of these aspects, it is necessary for designers to ensure that all factors that affect project feasibility are investigated in the front-end of the design. Any missed items in the planning stages could result in project inefficiencies. A vertical expansion would be considered a fully modular project. Mostly complete modules would be delivered to the construction project and installed. Once the modules are set, the majority of the construction effort is complete.

To elaborate on the importance of the planning stage of projects involving higher levels of pre-fabrication, the design process for the conceptual modular vertical expansion case-study building, shown in Figure 2a, will be discussed. The decision to modularize a project does not necessarily have bearing on all aspects of the design process, but there are particular parts of the process that can be impacted by the decision and will be further discussed.

3. Vertical Expansion Design Process

Vertical expansion of an existing building can be daunting engineering task. There are processes, decisions and inputs within the design process, many of which are not directly related to modular construction, that require detailed consideration. The engineering problem involves mating a new structure to an in-service structure. Among other considerations, the design team must ensure that 1) the existing structure is adequate to accept the new loading, 2) the aesthetics and enclosure integrity are maintained on the exterior, and 3) access/egress routes to and from the new expansions are provided.

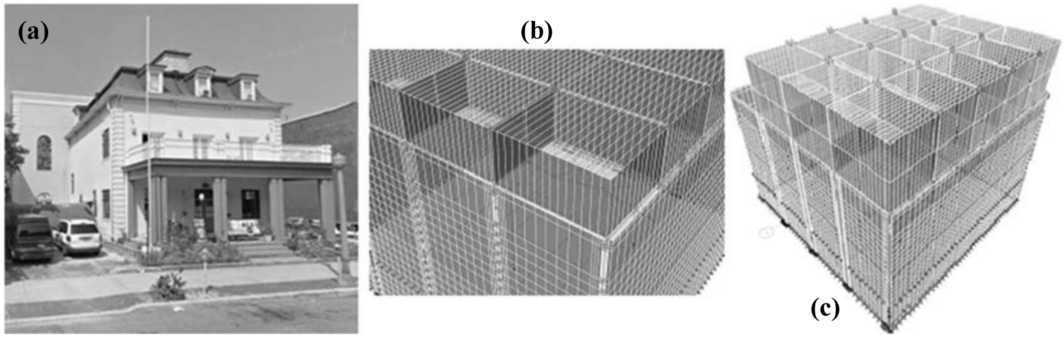

Figure 2. (a) Case study building used to conceptualize and investigate feasibility factors. (b) Analytical model of the expanded case study building shown in Figure 2a. (c) Two-story expansion.

In the research, the design process for a modular vertical expansion was studied to evaluate factors related to modular construction that could have an effect on project feasibility. The case study building, shown in Figure 2a, was identified in the research as a good candidate for vertical expansion. The design process was mapped for the expansion of this building, and the analytical model, shown in both Figure 2b and 2c, was used to validate the process and extract factors more easily recognizable during engineering design.

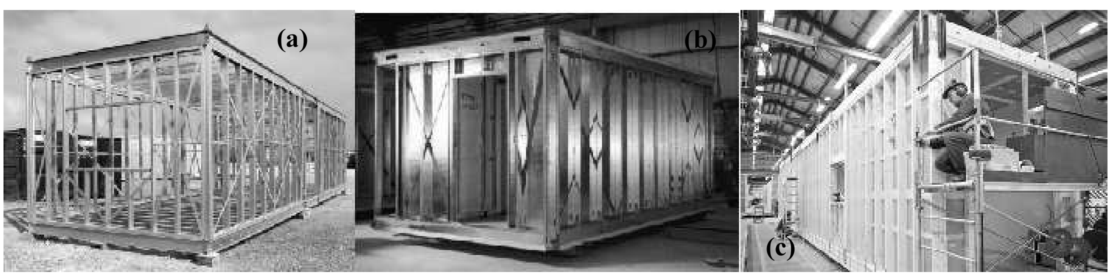

Figure 3. (a) Corner-post bearing module (image by Lawson and Ogden, 2008), (b) CFS wall-bearing module (image by Lawson and Ogden, 2008) (c) Wood wall-bearing module (image by MBI)

During the course of the research, typical structural modules used in modern modular construction were identified. The two dominant structural module types discovered were wall-bearing types and Corner-post bearing types. An example of each is shown in Figure 3. A simplified computer model of the existing building was created, and one- and two-story expansions were successively added to the model to explore the effects of each. Wood-framed wall bearing and cold-formed steel wall bearing modules had similar structural systems and weights (Table 1), so a generic wall-bearing expansion was explored rather than creating individual representations of each.

Table 1. Estimated weights of modules in comparison with steel framing. The module weights include framing and gypsum coverings

Construction Type	Weight (lb/ft^2)
Corner-Post Bearing	57.5
CFS Wall-Bearing	36.8
Wood Wall-Bearing	37.7
Structural Steel Framing	61.2

In order to document the design process and identify factors influenced by the decision to use modular construction, a series of seven process maps were created to describe in general terms the engineering design process. The majority of the focus was placed on the structural engineering and building codes assessment aspects. The engineering design process for the modular expansion was divided into four pre-construction phases; the pre-planning phase, structural evaluation of existing building phase, expansion conception phase, and expansion analysis phase.

In the pre-planning phase, the existing building was evaluated for candidacy. The candidacy evaluation process had two sub-processes, which were the project conceptual evaluation and the modular application evaluation. During the conceptual evaluation process, the validity of the concept is explored. Client motivations, constructability-related considerations, interfaces, and safety and access questions are all inputs to the process. During the modular application evaluation portion of this phase, the design/client must evaluate initially whether modular construction would benefit the project. If it is not appropriate, the owner can choose at this point, early on in the design process, to evaluate site-intensive construction methods or terminate the process. There are many decisions that occur during this phase that can have an effect on feasibility.

The structural evaluation of the existing building would occur shortly after or concurrent with the pre-planning phase. In this stage, the design team must assemble all available documentation and make a decision on the extent of investigation required to assess the condition of the building, the likelihood of expansion, regulatory environment, excess structural capacity of the building, strong connection points for the new expansion, and determine load reduction opportunities to increase feasibility of expansion. There is little in this phase that is influenced by the decision to modularize, although it is critical to project success and safety that this step is diligently executed.

After the existing building has been evaluated and the decision has been made to move ahead, the expansion conception phase can begin. The decision to modularize a project can have significant impact on project feasibility during this phase. It is in this stage where the appropriate module/manufacturer are selected for the project as well as the expansion height. This phase involves an iterative loop where different module types are investigated for use in the expansion. The method of load transfer and connection methodology should be defined after this stage. Building code evaluation as well as preliminary structural analysis is conducted to estimate expansion height and the effect of the expansion on surrounding elements.

Following the conception phase is the analysis phase. A sound concept should be delivered from the expansion conception phase. During the analysis phase the concept is proofed with further structural analysis and regulatory review. If necessary, changes can be made here to improve feasibility. If significant changes are involved it may be necessary to re-evaluate the concept. If no significant changes are needed and the design looks feasible, the analytical model will be ready to be delivered for final detailed design upon completion of this phase. At this point the model/concept can most likely be released for use in bid documents.

4. Lessons Learned From Design Process Validation

As mentioned previously, the case study was used to validate the design process map. While the state-of-the-art review and creation of the design process map were helpful in identifying the more obvious factors that could affect project feasibility, the case study was helpful in revealing the more subtle factors. In this part of the research, the mapped process was used to implement four expansions on the case study building. During the design of these conceptual expansions, factors that could affect project feasibility for this particular expansion were observed and documented.

An initial lesson learned was the importance of selecting an appropriate modeling technique to efficiently obtain the information required for the task. In this instance the information required for the research was primarily front-end planning related, similar to the information that would be required for an actual project. It was decided that a coarser model, in this case, was better suited to the needs of the research.

4.1 Modeling Lessons Learned

Initially, it was attempted to model the modules in their entirety with individual beam elements for the framing components and finite-element shells used for the gypsum wall sheathing and floor sheathing (Figure 4a). Modules modeled in this manner were overly complicated for the intended use. The many elements necessary to construct one module slowed computation time down and the modules became overly rigid without the use of multi-dimensional springs attaching the wall- and floor-sheathing to the structural framing.

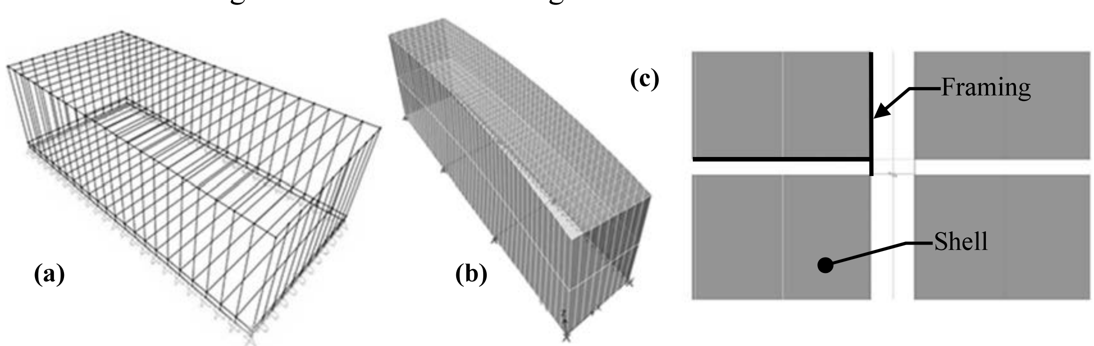

Figure 4. (a) Initial detailed version of a single wall-bearing module (b) Simplified shell version of stacked wall-bearing modules, shown in deflected form (wind load) (c) Intersection of four corner-post bearing modules.

The interaction of wall- and floor-sheathing with the structural framing (studs and joists) is complicated and difficult to model properly. Attachment of sheathing to stud or joist is typically accomplished with nails or screws and sometimes involves the use of an adhesives to strengthen the connection. Deformation of sheathed light-framed assemblies occurs due to rotation caused by nail slip, lateral translation due to bearing of fastener failure, and direct shear deflection of the sheathing. The summation of these three actions produces the total lateral translation of the sheathed wall assembly (Vieira and Shafer 2012). In order to model the three translation actions accurately, Vieira and Shafer (2012) used springs to represent the stiffness in each of these directions. Their method was not appropriate for this research.

The initial detailed finite element model of a wall-bearing module, shown in Figure 4a, was overly complicated for the goals of the project and it was decided to pursue an alternative approach. In the revised finite element model, the walls and floor system in their entirety were represented by the thin-shell finite-elements shown in Figure 4b. A 5/8 in. thick shell wall and a 23/32 in. thick shell floor system were defined in SAP2000 for use in the final ETABS model. Empirical formulas and test data from Intertek and HUD ("5/8" Dense-Glass Gold" 2003), (NAHB Research Center 1999) were used to calculate the mechanical properties necessary to represent the stud-wall assembly and framed floor system of the wall bearing module using isotropic finite elements.

The Modulus of Elasticity (E) developed for the wall system and floor system are shown in Table 2. The Modulus of Elasticity was defined as behaving linearly for the wall and floor system. In actuality, the behavior of both the sheathed wall- and floor-system was non-linear in both the Intertek and HUD tests. The linear modulus for both assemblies was estimated using a secant modulus in the expected stress range.

For the purposes of the research, it was only necessary to develop the mechanical properties for one wall and one floor system. Wall Type A, listed in Table 2, was used to resist/transfer both gravity and lateral loads for the wall-bearing modules and lateral loads only for the corner-post bearing modules. The test-coupon for the Intertek tests on Wall A was constructed from wood framing. It was assumed that the stiffness of a similar wall constructed from cold-formed steel elements would behave comparably to the wood-constructed coupon. Figure 4c shows how the area elements were utilized as infill for the corner-post bearing modules. A gap was left between top and bottom modules to ensure gravity load was transferred through corner posts only. The floor system for the corner-post bearing modules consisted of structural steel framing and a composite concrete floor slab, which were easily modeled using predefined properties in the software packages.

Table 2. Module wall and floor assembly mechanical properties

Assembly	**Description of tested assembly**	**E (KSI)**	**Wt. (PSF)**
Wall A	2x4 studs @ 16" O.C. , 5/8" Dense-Glass Gold gypsum sheathing nailed @ 4" on the perimeter and 8" in the field (1 ¾" Galvanized Roofing Nails).	31,300	7
Floor A	2x8x43 mil CFS joists @ 24" O.C. ; 23/32 OSB Sheathing attached with #8 Tek screws spaced @ 6" at the perimeter and @ joints and 12" in the field.; panels staggered.	60,000	10

4.2 Lessons Learned During the Design Process Validation

To determine the factors that could potentially affect the feasibility of a modular vertical expansion, the developed modules were added to the existing building finite-element model. The study suggested that feasibility was most affected by the quality of execution of the front-end design effort.

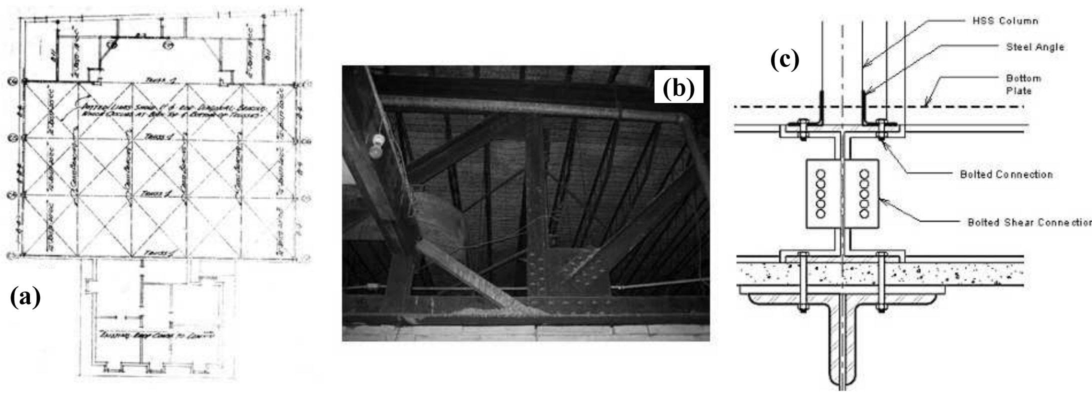

Figure 5. (a) Existing building roof plan; load bearing trusses are orientated left-to-right (b) Photo of load bearing truss (c) Intersection of four corner-post bearing modules.

In this vertical expansion study, both corner-post bearing modular expansions and wall-bearing expansion were modeled to explore advantages of each. It was found that each can have an advantage for different expansion projects. However, for the one- and two-story expansions, modeled in the research, the wall-bearing modules appeared to be more appropriate if combustible material is acceptable for the project. It was also discovered that modular construction may not be the right choice for some vertical expansion projects. Below is short list of some of the feasibility affecting factors discovered during the validation process:

1. Existing building geometry and existing structural connection points are important considerations. In this case study, the existing roof structure had convenient tie-in locations. The 60 ft. long trusses, shown in Figure 5a and b, were arranged at 15 ft.-6 in. spacing's, which are feasible modular dimensions. The simple structural steel grid, shown in Figure 6c was used to transfer the loads from the conceptual floor plan shown in Figure 6a and b.
2. In this case, it appears that it would be possible to detail the transfer grid, such that is acts compositely with the existing roof trusses. The connection is shown in Figure 5c. The study showed that by engaging composite action and removing of the existing roof-top cinder fill, the effects of the single-story modular expansions on the existing roof trusses were minimal. Internal load-effects and mid-span deflections were comparable to those of the original structure.
3. Considering point 3, a single-story expansion may have minimal effect on the existing structure. If this is so, then the extent of required structural strengthening measures could potentially also be minimized, which could improve project feasibility. A vertical expansion would most likely be categorized as an addition per IBC 2009. Per Section 3403.3, if the gravity-

load on the existing building is not increased by more than 5%, then it is possible that no strengthening measures would be required for the gravity-load carrying members within the existing building. Per the IBC Section 3403.4 exception, if any of the lateral-load carrying elements demand/capacity ratio increases by less than 10% then it is possible to leave those elements unaltered.

4. The redundant structural wall, ceiling/floor assemblies due to the six-sided nature of the modules could be limiting where floor space and story-height is valuable. Preliminary IBC review, for this building, showed that it may be difficult to consider wall-bearing modules, containing any combustible structural components, for a two-story expansion with ceiling heights greater than 7 ft-11 in. Modular construction may not be an option if structural steel corner-post bearing modules are required, due to the high break-even points.
5. The study shows that a two-story corner-post bearing modular expansion increases the demand-capacity ratio to 0.903 in some truss members and increases bearing pressure to greater than 4 KSF under some footings; both results may not be acceptable to the design team. The use of lighter wall-bearing modules, if possible, could increase feasibility.
6. Corner-post bearing modules only require support/connection @ corners, whereas wall bearing modules require support along the entire longitudinal wall. In this case half of the beams in the transfer grid were able to be eliminated when corner-post bearing modules were considered.
7. Story-drift was not a concern with the one- and two-story modular expansions modeled in this study.

Figure 6. (a) Rendering of the wall-bearing single-story expansion used in the study (b) Conceptual maintenance module envisioned to house roof-top mechanical equipment servicing the existing building (c) The finite element model of the steel beam transfer grid.

In this research, finite-element module models were used as tools to help quickly model modular expansions such that the effects of different expansions on the existing building could be studied. Using detailed analytical models, in this case, was not an efficient way of identifying those factors affecting expansion feasibility. By using the coarser finite-element models, design alternatives were able to be evaluated more efficiently. A few examples of some of the beneficial planning information able to be obtained through the use of this approach follows:

1. In this project, the differences in the effects of wall-bearing and corner-post bearing expansions of both one- and two-story were able to be studied effectively.
2. Different variations of the transfer structure were able to be studied as well as strategies for addressing the parapet and the benefits of composite action of the transfer structure.
3. The connection points were able to be identified and basic floorplan geometry was able to be established.
4. In some projects, this method could be used to evaluate whether the expansions effects on the existing building meets the IBC section 3403 exceptions for gravity and lateral loading.
5. One could potentially coarsely define several different wall-assemblies to quickly explore the structural benefits of each in a project. Serviceability criteria such as drift can be generally explored to eliminate, up front, those assemblies that might be too flexible/stiff or light/heavy.

The primitive finite element tool functioned as expected and although detailed module structural design information was not able to be extracted, the model did reasonably represent the effects of each expansion on the existing building and all the important items discussed earlier were able to be identified for use by a design team.

6. Closing Statements

The research discussed in this paper studied one type of prefabricated construction methods which is modular construction. Vertical expansion was identified in the research as an appropriate application for multi-story modular construction. Finite-element models were used to explore feasibility affecting factors. A diligent study of the vertical expansion design process revealed the modular construction specific factors, while case study verification was able to identify those additional considerations.

Modular construction was found to be appropriate for vertical expansions in some cases, but not all. For one- and two-story expansions, wood-framed wall-bearing modules were thought to be the most feasible if combustible construction is allowed on a project. Heavier non-combustible steel corner-post bearing modules were found to have higher break-even production thresholds thus potentially eliminating them from lower square-footage projects. However, considering the 2 ½ - story case study building used in the research, it was difficult to meet the IBC combustible construction requirements, while maintaining reasonable ceiling heights. This situation presented an issue that might eliminate modular construction from consideration on this particular project. In this instance a custom steel module fabricator may have an advantage.

There are improvement that could be made to the finite-element definitions that could improve functionality and broaden the applicability of this approach. The finite-elements were defined as having isotropic mechanical properties, where in reality the performance of the wall and floor assemblies would be anisotropic. It was not necessary for this research to define these finite-elements as anisotropic. The information required from the models did not warrant the increased effort; however, if this technique was applied to other modular design scenarios, it might be advantageous to have the mechanical properties in all directions defined more accurately. Refining the design would allow for more detailed study of out-of-plane behavior of the elements and stresses at connection points.

7. References

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