Residential Vertical Expansion of Existing Commercial Buildings Using Modular Construction Methods

Anthony C. Jellen P.E. [1] and Ali M. Memari PhD, P.E. [2]

[1] Department of Civil Engineering, 105 Engineering Unit B, University Park, PA 16802

[2] The Pennsylvania Housing Research Center (PHRC), Department of Architectural Engineering and Department of Civil and Environmental Engineering, 219 Sackett Building, University Park, PA 16802

Abstract: Off-site construction methods may offer advantages over site-intensive construction methods for certain types of vertical expansions, such as those that could add valuable residential units to an existing commercial building. Evaluating the feasibility of a vertical expansion is, in itself, involved. When considering the use of modular construction there are additional items to be reviewed during the conception stage. Vertical expansions can be design intensive depending on the condition of the existing building and the availability of design documentation. Feasibility 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.

1. Introduction

Modular Construction is ideal for the construction of buildings with repetitive floor plan elements. Residential structures such as apartment buildings, student housing and workforce housing tend to be ideal candidates for modularization. The projects that are highly compatible with modular construction methods tend to be those that would significantly benefit from off-site construction, construction schedule time-savings, and reductions in community disturbance or business operations.

Renovation projects, particularly those planned for congested urban areas, can potentially take full advantage of these benefits. Initially, by choosing to renovate a building versus constructing a new one, owners can preserve the historic nature of their building and its relationship with the surrounding community, as well as take advantage of the existing embodied energy, avoid expensive foundation and site activities, and eliminate the need to purchase new land.

Renovation through vertical expansion is an approach that can be used to add roof-top apartments to buildings that are able to accept expansion. Vertical expansion, if feasible for a given existing building, can provide the financial benefits gained from rental or sale of the new units as well as be a part of a more comprehensive roof renovation plan that would not only add more square footage to the building but can simultaneously replace aging roof components and improve the energy performance of the roof system.

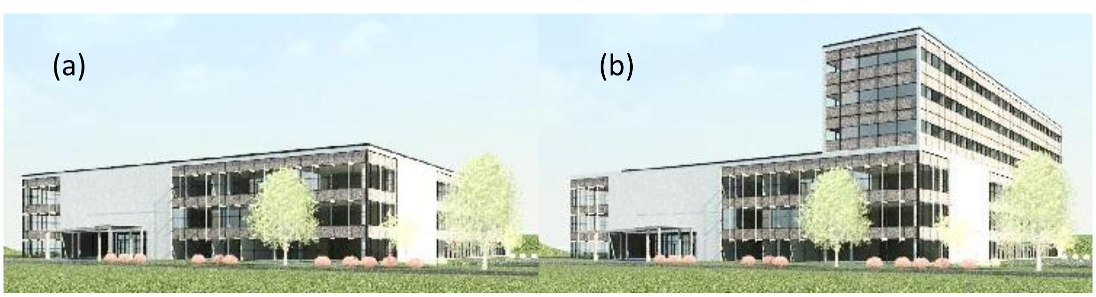

Figure 1. (a) Rendering of an existing commercial building (b) Vertically expanded building.

The modularization of an expansion can introduce the benefits of off-site construction, such as lower wages, high quality components and just-in-time delivery schemes. The benefits of modular construction can have value to a building owner who desires to accomplish renovations quickly, while maintaining the operation of an existing business. The Steel Construction Institute (SCI) suggests the following advantages modular construction may have if applied to an expansion project (Lawson 2008):

- New facilities are added cost-effectively
- Construction is rapid, which minimizes costs and disruption
- High-quality can be achieved by off-site manufacturing
- Delivery of modules can be timed to suit local conditions
- Light-steel constructed modules may not over-load an existing building
- In some projects it is not necessary for the occupants to move out during renovation

1.1 Objective

The objective of this paper is to explain the relevant typical design considerations pertinent to a modular vertical expansion in the U.S. The paper begins with a brief description of how members of the European Union have been using roof-top expansions to add space to the top of existing buildings. Following is a summarization and discussion of important items that should be considered when evaluating the feasibility of a modular vertical expansion. The considerations are broken into non-structural and structural categories.

1.2 Roof-top Extensions

Modular construction, along with light-steel framing and panel construction, is used by members of the European Union (EU) to add roof-top extensions to existing buildings, in particular, older masonry and concrete apartment buildings that were constructed between 1950 and 1970 (W/E Consultants 11/07). Figure 2 shows an example of a concrete building, in Denmark, extended with CFS modules to create communal space.

Figure 2. Communal space added to the roof of a concrete building in Denmark (SCI 2001)

Lawson points out (Lawson 2008) that many buildings, of this construction type, were initially built to house the post-world war II homecoming. A large stockpile of these buildings exist in the EU. Lawson goes on to say that many of the buildings are aging and are currently due for either renovation or demolition. He also points out that modular construction, when used for renovations to this type of building is generally used to accomplish the following:

- Expand building horizontally or vertically

- Add bathroom, balcony or stair modules
- Upgrade façade to improve aesthetics or building energy performance

1.1.1 Renovation of Buildings Using Steel Technologies (ROBUST)

In order to address the problem of the aging buildings research was conducted to determine renovation alternatives. Two notable research projects that, in part, investigated the benefits and challenges of using modular construction for roof-top extensions were reviewed for this paper.

ROBUST, one of the research projects, was conducted between 2007-2010 by a consortium of representatives from the European steel industry ("ROBUST - Renovation of Buildings Using Steel Technologies" 2013). The project focus was on the use of Cold-Formed Steel (CFS) construction methods in renovations. CFS Modules were reviewed, as an option, and information regarding their use in renovation is presented in the resulting third work package (WP3), which investigates the use of steel-intensive technologies for building extensions and conversions.

In WP3 roof-top extension design considerations are reviewed. WP3 also contains research regarding the use of portal moment frames to stabilize rooftop extensions. Although this is more relevant to framed light-steel extensions, there is still important information contained in the document pertaining to roof-top extension connections to existing masonry and concrete that could be relevant to modular extension connections as well. Two publications, which were part of WP3, point out some important design issues. The first publication points out constructability, safety and technical issues with general roof-top extensions (Lawson et al. 2013) and the second points out some specific issue with using modular construction for roof-top extensions (Lawson 2008). Below are a few important points identified by the authors of the reports:

1) *Motivations for extending buildings*

    a. Create more space
    b. Change of use
    c. Energy efficiency improvements
    d. Upgrades to new regulations
    e. New lift, stairs or balcony required
    f. Conservation of historic property
    g. Deterioration of existing building

2) *Constructability*

    a. Will the project be economical?
    b. What are the township and zoning regulations and what are the aesthetics and visual integration requirements?
    c. What are the characteristics of the building. Is it suitable for extension?
    d. What are the technical issues in regards to structure, thermal insulation and fire safety?
    e. Will the extension infringe on the neighbors natural light access?
    f. Are there historic building restrictions?
    g. Will modular construction methods be able to be successfully used?
    h. Can strong points be identified in the existing structure, for module attachment, to ensure stability?
    i. Is the cladding of new structure compatible with that of the existing structure?
    j. Does light-weight façade materials need to be attached by sub-frames to the modular units or to the existing building?

k. Will the modular units have adequate bearing?
l. Will the foundation system have adequate excess capacity, if needed?

3) *Interfaces that require special attention*

a. New structure/old structure interface
b. New cladding/old cladding interface
c. Expansion joints

4) *Safety and access issues*

a. New egress routes, additional occupant load to existing egress routes
b. Change of fire resistance ratings of building elements such as doors or roof due to the addition of the roof-top extension
c. Fire load characteristics of the new envelope must reduce the risk of fire propagation
d. New requirements for fire-fighting access brought on by increase in building height.
e. Addition of elevator with only one additional level

2. Non-Structural Considerations Associated with Modular Vertical Expansions

2.1 Economic Considerations

Projects that involve a high level of off-site manufacturing (OSM) are generally more cost-effective with larger projects. Fixed overhead factory costs and transportation costs are large in comparison to the overall budget in smaller projects, but conversely, smaller projects can be economical if they are repeated several times. The economics of OSM in smaller project may be improved in the future by the integration of numerically controlled machinery and integrated CAD/CAM software (Lawson and Ogden 2008).

Modularization of a project usually involves a break-even point. This is the point (usually measured in square footage or units produced) where it becomes economical to choose modular construction over a competing site-intensive construction method. One New York City modular manufacturer of corner-post structural steel modules estimates their break-even point around 20,000 ft^2 (O'Hara 2013). In other words, the manufacturers experience shows that in order to achieve economy, the project size should be larger than 20,000 ft^2. Manufacturers of all wood or CFS modules may have a lower break-even point. ASCE points out that typically corner post bearing modules are more costly to manufacture than an all light-steel product (Lawson et al. 2012).

The primary benefit of using modular construction is time savings. The time savings can provide the benefits of reduced interest charges from outstanding loan balances, early rental income and also less disruption to the existing business (Lawson et al. 2012). When assessing the economics of a modular projects, these benefits as well as others are often weighed against the production costs of the modules. Other less tangible benefits can include fewer call backs due to higher quality product and gains from material efficiency.

Local labor rates can affect the economy of a modular project. The Building Industry Association of Philadelphia shows that considerable cost savings can be achieved through modularization in locales where the labor rate is high (Black 2010). Labor rates in Philadelphia, for example, are 39% higher than the national average and construction costs are 18% higher than the national average. The report shows that, due to reductions in labor costs achieved by using off-site construction, a modular single-family row home (one example only) constructed in the city can cost 20% less than an identical home constructed by on-site wood-framed construction.

2.2 Regulatory Considerations

Local zoning code and building code regulations have significant effect on the feasibility and cost-effectiveness of a vertical expansion. According to the ROBUST report (Lawson et al. 2013), the following zoning issues can have influence on the design.

- Local regulations may impose limitations on aesthetics, height, shape of roofs, as well as type of use.
- Height is also connected to the natural lighting issue. The geometrical arrangement of the new building has to preserve natural light for the neighbors.
- The building can be registered as a historical site. In this case, the project has to take into account the constraints on the appearance of the façades and the roof.

In addition to the zoning regulations, the building code has a large influence on a design. The International Building Code (IBC) is the governing document adopted by a large percentage of municipalities across the U.S. The 2009 IBC (International Code Council 2009) has many regulations that could significantly affect the feasibility or heavily influence the choice of building materials for a specific project.

Most vertical expansions would be categorized as an addition per the IBC definition. They would follow the regulations either in IBC Chapter 34 Existing Structures, or the most recently adopted version of the International Existing Buildings Code (IEBC). Chapter 34 requires that any addition causing greater than a 5% stress increase to elements within the gravity load system or 10% increase to elements part of the lateral force resisting system be altered to resist the increased load. Another relevant point in chapter 34 is section 3409, which states that the provisions of the IBC are not mandatory for historic buildings judged by the building official to not constitute a distinct life safety hazard.

Allowable building heights and areas prescribed in chapter 5 affect the choice of materials used for the expansion. Structural steel and CFS modules can be used in non-combustible construction applications, whereas wood framed modules are combustible and are restricted to the requirements for Type V and Type III construction.

Apartments are semi-permanent dwellings and are categorized as an R-2 use group according to section 310. Table 503 allows for a maximum building height of 50’ (max. three stories) with Type 5A construction and 40’ (max. two stories). Type III construction allows for a maximum height of 65’ (max. four stories) and 55’ (max. four stories), respectively, for Type A and B construction with the provision of a two-hour rated exterior wall according to table 601. Section 504.2 allows for an increase of one story and 20’ if an automatic sprinkler system is installed, but at the same time restricts the total increase to 60’ and four stories.

The IBC allows combustible construction to be set on a non-combustible Type 1A podium, maximum one story, with a 3-hour fire resistive barrier between the two (with special restriction on podium occupancy and other prescriptive requirements). In this manner, the amount of allowable stories and building height for wood construction can be increased by the podium height.

The IBC maximum building height restrictions will typically limit the use of wood-framed modules to vertical expansion no greater than four stories and 60’ unless special provisions are followed or local exceptions pertain. According to Cheung (Cheung 2010), some locales such as Portland, Tacoma and Seattle allow for the construction of 5 and 6 story wood framed buildings (with some restriction). The 2006 Seattle building code has allowed, in the past, for two-story non-combustible podiums beneath five stories of combustible wood framing (Cheung 2010). In general, building height regulations with podium construction consideration can affect material selection for modules and also will determine whether the construction type of the existing building is adequate for expansion.

Fire protection requirements of the IBC should be considered early on in the design process or feasibility analysis. Initially, the addition of even one story of residential occupancy brings a requirement for an automatic sprinkler system in accordance to NFPA 13 or 13R if under four stories (Section 903). In addition, according to Section 905, Class I or III standpipes are required for buildings that have any floor level greater than 30' above fire department vehicle access height. Lastly, buildings having an occupied floor greater than 75' are considered high-rise according the IBC and are subject to the requirements of section 403. Increasing the height or changing the construction type of the building can require a higher degree of fire-protection for the whole building. This can greatly affect the feasibility or cost-effectiveness of a vertical expansion.

Separation of occupancies and dwelling units is another component of fire protection that must be considered. Both non-separated and separated occupancy classifications can be considered for an expansion if the occupancies in the expanded building differ. Depending on the particular project, one classification may offer advantages over the other. If the building is evaluated as non-separated, then the whole building is subject to the most restrictive occupancy related to height and area according to table 503. If the building is considered separated, then a horizontal assembly would be required between the proposed expansion and the existing building according to table 508.4. Each occupancy will then follow the height and area restrictions pertaining to their individual use groups and the construction type of the building. The exception being that a particular use group cannot be located on a story higher than its allowable amount of stories or height according to table 503 unless section 509 special provisions is followed and a podium design is constructed as discussed earlier. This may allow for more overall stories to be constructed but may not be relevant if the developer is considering wood-framed units on the top stories.

In addition to the building separation requirements, the separation of the residential units should be considered. This can be a deciding factor in module selection. Depending on the IBC requirements, a structural steel module, may end up costing less because the fire resistive detailing is easier to implement than other module types. Group R-2 occupancies are required by section 420 to have fire partitions, per section 709, separating the units on a floor, and horizontal assemblies, per section 712, providing the story to story separation.

Accessibility and egress should be given consideration during feasibility analysis. Initially, access must be provided to the new floors, by either stair or elevator. In addition to access, the egress must be provided per chapter 10. Additions must meet the IBC requirements for new construction and therefore must have accessible egress according to section 1007. If the accessible floor is above four stories, then an elevator is automatically required, with some exceptions.

Section 1107 has requirements for accessible dwellings. When residential units are added to the top of a building, it is likely that section 1107 will require that at least the bottom floor of the expansion have Type A or Type B accessible dwelling units unless the building being expanded already has adequate accessible units on lower floors. In this case, some of the general exception in section 1107.7 may apply. In any regards, consideration should be given to the IBC accessibility and egress requirement because it may turn out that adding just one floor of residential units to the existing building can require the installation of an elevator or lift, which can be cost prohibitive to smaller projects.

2.3 Consideration of Air Rights

The high cost and scarcity of land in dense cities along with the existence of sprawling low-height transportation systems and short buildings in urban areas make vertical development in dense cities a reasonable alternative for developers to consider. Air-rights provide incentive and a framework to develop vertically. Air rights describe the vertical property rights of a landowner. According to Goldschmidt (Goldschmidt 1964) the landowner owns as much of the space above the ground as he can occupy or use in connection with the land. This of course has limitations set by aviation regulations. The first air rights construction project was in New York over the New York Central Terminal where a street, apartment buildings and an office building were constructed over the railroad track.

Air rights can be transferrable rights in which the land owner can sell the rights to a another party to develop the space above their property. The space usually involves a set horizontal division at some agreed upon elevation. New York City has provisions in the zoning code to define air rights within the city. From the definition of development rights, the air rights are associated with the maximum allowable building area set by zoning. If the building is smaller than the maximum allowable, by zoning code, then the unused portion of this amount can be considered developable and transferable ("NYC Zoning - Glossary" 2014). Additional Air rights can also be obtained through lot mergers or transfers of development rights from neighbors.

3. Structural Considerations Associated with Modular Vertical Expansions

3.1 General Concerns

The primary objective for the structural engineer employed to design or evaluate the potential of a vertical expansion is to assess the structural capacity of the existing building system and determine how many stories can be added to the existing structure and what, if any, modifications are required to the existing system.

In general, the structural engineer will accomplish this by conducting an investigation and developing an assessment of the condition of the existing structure. The engineer will conduct structural analysis to determine the capacity and reserve capacity of the structural system and use the analysis to make prudent recommendation regarding the maximum amount of stories that might be added and the appropriate structural systems that might be used for the addition. Vertical expansion can be grouped in three categories:

- *Category I* - This type of expansion was previously planned for when the existing building was first designed. The original plan set is readily available and foundation and structural systems have been designed to support a designated amount of additional stories. Minimal structural analysis and investigation is necessary in order to proceed with design.
- *Category II* – In this case, the structure has not been originally designed with the intent of future vertical expansion. The original plan-set or as-built drawings are available and reliable. Only minor investigation of existing structural elements is necessary to verify accuracy of drawings and condition of the structure. Structural analysis is required to assess the feasibility of the addition.
- *Category III*– In this case, the structure has not been originally designed with the intent of future vertical expansion. No drawings are available and significant structural investigation and analysis is necessary to assess the condition and capacity of the existing structural system.

The level of difficulty, in evaluating a vertical expansion will often increase, respectively, from a "Category I" to a "Category III" expansion. The availability and trustworthiness of the original design documents can greatly affect the amount of initial structural investigation that is required for analysis, thereby affecting the cost of evaluation. If a building has already been designed for a future vertical expansion, very little investigation and analysis may be required unless building codes have significantly changed between original design and newly proposed addition. If no design documents are available a full building structural investigation is often necessary, which most likely will be costly and time consuming.

Many of the buildings being considered for vertical expansion are historic and should be reviewed carefully because the building codes, material strengths, occupancy and building construction methods are likely to be different than todays standards. Thornton (Thornton et al. 1991a) lists the areas below that should be researched when evaluating the feasibility of the vertical expansion of a building:

- Review as-built drawings, compare drawings to field observations and measurements of the existing structure
- Comparison of the analysis and design methods in use at the original time of design to present practice
- Comparison of the requirements of the prevailing codes and standards in effect at the time of the original design to the present requirements
- Comparison of code provisions for live load reduction at the time of the original design to the present requirements
- Review of the changes in functional use within the building

In general, Gustafson suggests (Gustafson 2007) that the building materials of the period be considered. He points out that, in particular, steel design and composition has had many changes over the years and that AISC Iron and Steel Beams, Design Guide 15 and Appendix 5 of the AISC Specifications for Structural Steel Buildings have good reference information for evaluating existing structural steel framing.

Schwinger mentions (Schwinger 2007) that the building should be carefully evaluated for any damage and emphasizes the importance of a thorough building examination. He points out the following items to look for:

- Framing damage
- Corrosion
- Signs of modification to structure or the addition of heavy mechanical equipment that may have been conducted or installed without engineering review
- Unusual deflection
- Foundation settlement
- Cracks in slabs

Structural design methods have matured over recent decades and have led to more efficient use of structural building materials. A better understanding of live loads and lateral loads have led to more accurate and often times smaller design loading over the years. Often older building were designed much more conservatively and have significant structural capacity (Thornton et al. 1991a).

Thornton points out (Thornton et al. 1991b) some ways that the changes in building code and design methodology have made it possible to design a cost-effective vertical expansion for the B. Altman building in New York city. The building was constructed in the early 1900's and the following changes in methodology and code were taken advantage of:

- Allowable steel stress at the time was 16 ksi, and in 1991 the allowable stress was 0.66fy=0.6*33ksi=22ksi, which gained the designers 35% more steel strength.
- 22 kips per floor structural capacity was gained through changes in occupancy loads.
- The application of live load reduction reduced design live loads for columns and foundations up to 60% in some location.
- Heavy roof cinder was removed and a lighter concrete floor deck was used. This provide extra structural reserve capacity.

In addition to the techniques used for the B. Altman building expansion, engineers will strive to use the lightest possible structural elements in their designs to reduce stress on the existing structural system. An eight-story vertical additions was added to an existing office building in Philadelphia, PA. The structural engineer specified an innovative light-weight composite joist floor system and a bearing steel wall panel assemble to increase the amount of level able to be added to the building (Squitiere and Vacca 2013).

3.2 Weight of the Modules

Modular construction can offer a light-weight alternative to structural steel framing in some settings. The three most common modules used for multi-story modular construction are show in Figure 3. Figure 3a shows a corner post bearing module or open sided module. Corner post bearing modules are typically constructed with HSS corner and intermediate columns, CFS non-bearing in-fill walls, structural steel perimeter framing and either light steel or concrete floor systems. Loads are transferred primarily through the HSS columns. These modules are typically used in applications where wider spaces (Lawson 2007) are required or situations that require higher strength structural steel components (Lawson and Richards 2010). Corner-post bearing modules are typically stable for no more than 2-stories and require additional bracing from diaphragm action or braced core.

Figures 3b and 3c show wall bearing modules constructed from all CFS or all wood, respectively. These modules are used for cellular structures up to eight stories. Wall bearing modules are traditionally stand-alone and typically transfer both vertical and horizontal loading through continuous wall bearing and diaphragm action within the wall system (Lawson and Richards 2010).

The weights of each of the modules are shown below in Table 1. The weights reflect typical module construction considering only the framing components and gypsum board. Structural steel construction is listed in the table as a point of comparison to site intensive construction methods.

Table 1. Weight of typical modules used in multi-story modular construction.

Construction Type	Weight (lb/ft2)
Corner-Post Bearing	57.5
CFS Wall Bearing	36.8
Wood Wall Bearing	37.7
Structural Steel Framing	61.2

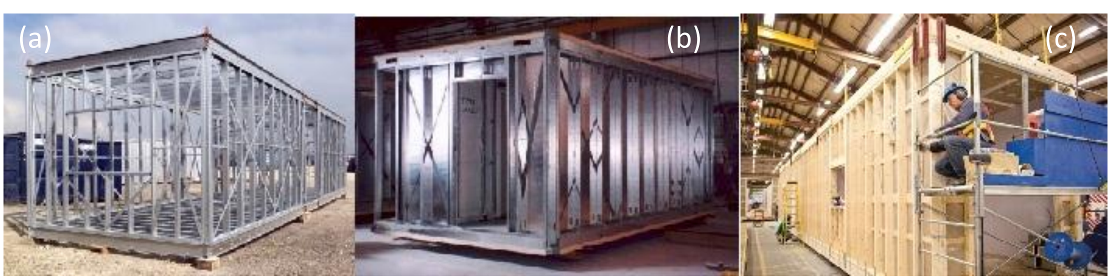

Figure 3. (a) Corner-post bearing module (image by Lawson and Ogden, 2008), (b) CFS wall bearing module (image by Lawson and Ogden, 2008) (c) Wood wall bearing module (image by Modular Building Institute)

3.3 Transfer Mechanisms and Structural Remediation

Both gravity and lateral loads must be transferred from the proposed expansion to the existing building and the existing structural components strengthened if they do not possess adequate capacity. Often the structural system proposed for a new expansion is not the same as that of the original building. Often large transfer beams or trusses can be required to transfer loads. In the case of the Philadelphia office building renovation, mentioned earlier, the engineer specified custom trusses constructed from HSS steel members to transfer the loads to a concrete column grid spaced at 27', below the expansion. Large steel tie-downs constructed of plate steel and rod were fastened to the existing columns to resist the large uplift forces imposed by the new expansion.

The university of Plymouth used modular construction to add 28 roof-top bedrooms to an existing four-story steel-framed building (SCI 2001). The extended building is shown in Figure 5. The engineer specified a grillage of structural steel to transfer the loading from the proposed expansion to the existing structure.

Figure 4. Modular residential expansion of existing university building

If the structural system or component within the structural system does not have adequate capacity, then remediation is required to resist the new loads. Schwinger points out (Schwinger 2007) that there are generally two options for the remediation of a floor system. Either new framing could be added to distribute the increased loading or the existing framing could be strengthened. He suggests, that often it is more economical and easier to strengthen the existing construction. Schwinger also discusses that column strength is typically dictated by the slenderness of the column and if added capacity is required, he recommends stiffening the column weak axis with plate steel in an efficient manner. Lastly, he recommends welding new steel to existing steel if possible, because it is easier and requires less precision than field drilling bolt holes.

3.4 Structural Design of Modules

Structural design of modules is typically accomplished by the modular manufacturer and reviewed by a third party structural engineer or designed by a structural engineer and review by the manufacturer. The external loads to a modular building are derived in the same manner as any other site-constructed building. Loads can be determined from provisions in ASCE/SEI 7 or prescribed by local building code and zoning regulation.

Chapter 16 of the IBC regulates the structural design criteria for most construction projects in the U.S. Some criteria, such as load combinations, are specified directly in the text but most are referenced from reliable design codes and sometimes modified partly by language within the IBC. Table 3-2 lists design codes referenced by the 2009 IBC that are applicable to modular design.

Table 2. IBC referenced codes applicable to modular design.

Structural Material	Referenced Standard
Structural Steel	AISC 360-05
Cold-Formed Steel	
Composite Slabs:	ASCE 3
Non-Composite Floors:	ANSI/SDI-NC1.0
Framing Members:	AISI 100,200,210,211,212,214-07
Lateral Design:	AISI 213-07
Wood	
Framing Members:	AF&PA NDS-05
Lateral Design:	AF&PA SDPWS-08
Concrete	ACI 318-08

Modules must be structurally designed for different stages of construction. Smith points out (Smith 2010) that a module must be hoisted onto a truck for shipping, transported to a building site, hoisted off a truck, maneuvered around the site, and finally placed into service. Smith goes on to say that often times dynamic loads placed on the prefabricated element are often the largest that the element will experience in its lifetime and that at times the overdesign of the structural elements for this stage can be a deterrent to using modular construction for a project. The following is a list of items that require design by an architect or structural engineer:

- Structural design of the gravity system
- Structural design of the lateral force resisting system
- Stability of structure under lateral loading
- Connections
- Cladding
- Interface with other modules or building elements
- Robustness in taller buildings
- Fire-safety
- Acoustic Performance
- Durability
- Airtightness and thermal performance

The module is the basic element of a modular building and consists of beams, columns, braces and stressed skin structural elements. Modules are typically categorized as either a wall bearing module in which loads are transferred through the side walls, a corner-post bearing module in which loads are distributed horizontally through edge beams and transmitted vertically through corner or intermediate columns and lastly non-load bearing module commonly called a pod.

The selection of module construction type is generally governed by the required building construction type, economy of design, structural capacity requirements and the availability of modular manufacturers. Lawson summarizes the limits of each module type and the general load resistance strategy as discussed in the following paragraphs (Lawson and Richards 2010).

Wall bearing modules constructed of CFS or wood framing are used for structures between four and eight stories in height. The compression resistance of the wall elements usually limits the story height. Some variation of a corner-post bearing modules is used in most cases for structures of greater height. In this case, the compression resistance of the corner-post governs the design. Square HSS sections are used commonly because of their high resistance to buckling. Lateral loads, such as wind or seismic are resisted by one of three methods:

- Diaphragm action of boards or bracing within walls of the modules; appropriate for four to six story buildings
- Separate braced structure using hot-rolled steel members located in lifts and stair area or in end gables
- Reinforced concrete or steel-plated core; suitable for taller buildings

In taller modular buildings structural integrity is a design consideration. Robustness is provided by ties between the modules (Lawson 2007). The ties help distribute the load to other modules in the event of a module within the system being destroyed. The interconnection and load sharing between modules help prevent a total building collapse.

Module to module connections typically involve a bolted connection and steel plates. The connections can be made at the corners of the modules where structural steel is typically present. Figure 5 shows an example of a typical CFS steel module to module connection. The detail can be repeated at the top and bottom and the modules can be connected both vertically and horizontally with the same detail.

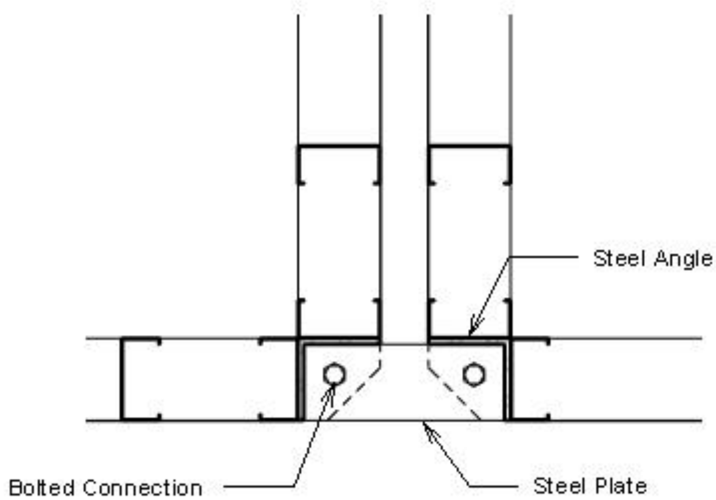

Figure 5. Typical CFS module to module connection

4. Discussion

Figure 6 presents a list of suggested steps to follow when considering a vertical expansion. A thorough review of building codes and zoning regulations should be conducted along with a detailed evaluation of the existing building in all cases. The construction type of the module should be carefully selected and the construction type of the existing building be evaluated to verify allowable heights and areas per IBC table 503. The most economical construction type is likely to be different for each project and the use of wood-framed modules will be restricted to lower expansions in most cases.

Wood framing can be an economical choice for vertical expansion if allowed. Wood-framed and CFS modules are comparable in weight and both are lighter than structural steel framing and corner-post bearing module construction. It is possible that the break-even point for wood-framed is lower than that of the corner-post bearing modules, due to the industry familiarity with the material. If this is true, then wood would be the ideal material for smaller vertical expansions involving less square-footage.

All CFS modules could be a logical choice in cases were non-combustible construction is required along with light-weight construction. However it appears that all CFS module construction is not popular in the U.S. Of the manufacturers reviewed in Pennsylvania only corner-post bearing modules were currently being used for multi-story modular construction. It is possible that the strict U.S. building code provisions make it economical to use this type of construction for multi-story projects.

The heavier weight of the corner-post bearing modules and the large break-even point make it questionable whether this type of modular construction would be the more appropriate for vertical expansion. However the use of some structural steel in an expansion is unavoidable. Structural steel will be needed in most cases were large openings are required in the floor plan and most likely will be used in the transfer mechanism as well.

Non-structural requirement such as the addition of elevators of a sprinkler system is likely to control the feasibility in smaller expansions. These costs can make it impossible to bring economy to a project.

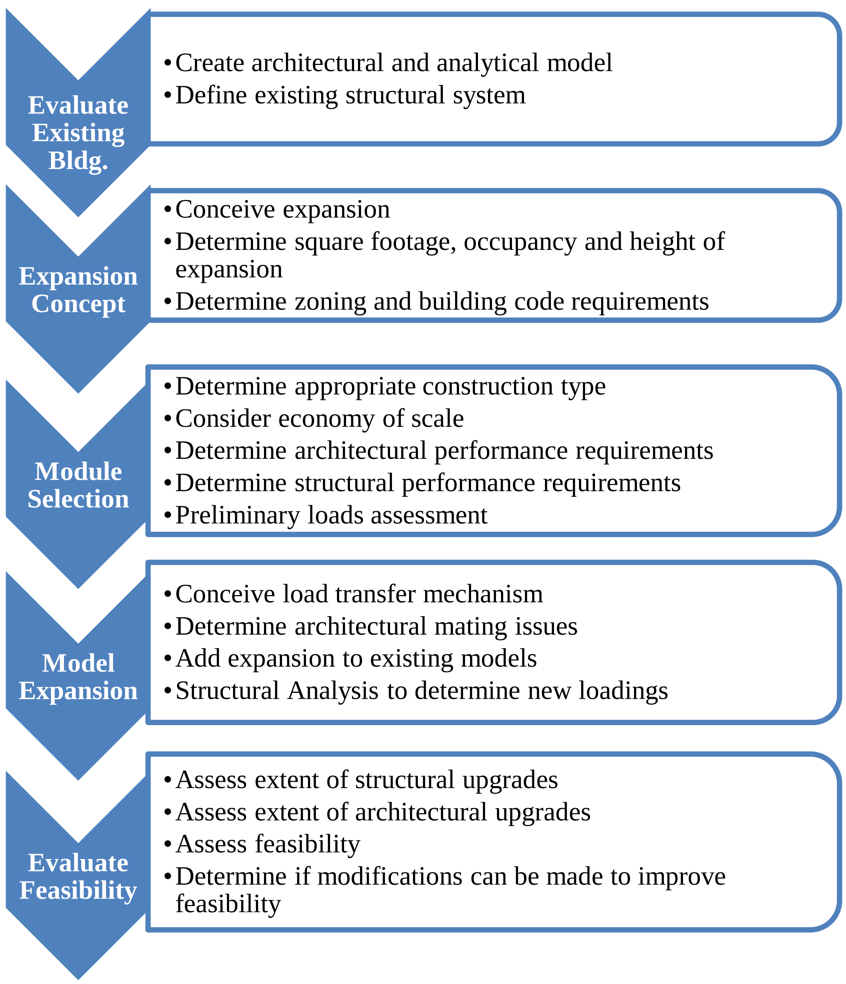

Figure 6. Feasibility analysis of a modular vertical expansion.

5. References

Black, Karen. 2010. “GOING MOD”. Building Industry Association of Philadelphia (BIA).

Cheung, Kevin. 2010. “Multi-Story Wood Frame Construction in North America.” In .

Goldschmidt, Leopold A. 1964. “Information Report #186 - Air Rights”. Chicago: American Society of Planning Officials.

Gustafson, Kurt. 2007. “Evaluation of Existing Structures.” *Steelwise* (February).

International Code Council. 2009. *2009 International Building Code*. Country Club Hills: International Code Council.

Lawson, Mark. 2008. “Review of Modular Construction in Building Renovation”. WP 3.1. Steel Construction Institute.

Lawson, R.M, R.G. Ogden, and R. Bergin. 2012. “Application of Modular Construction in High-Rise Buildings.” *Journal of Architectural Engineering* (June): 148–54.

Lawson, R.M. 2007. “Building Design Using Modules.” SCI P348. The Steel Construction Institute.

Lawson, R.M., N.R. Badoo, G. Vannier, B. Doering, M Kuhnhenne, J. Nieminen, P. Beguin, et al. 2013. “Renovation of Buildings Using Steel Technologies (Robust)”. Eur 25335 en. European Commission.

Lawson, R.M., and R.G. Ogden. 2008. “‘Hybrid’ Light Steel Panel and Mdular Systems.” *Thin-Walled Structures* (46): 720–30.

Lawson, R.M., and J. Richards. 2010. “Modular Design for High-Rise Buildings.” *Structures and Buildings 163* June 2010 (SB3): 151–52.

“NYC Zoning - Glossary.” 2014. Accessed January 24. http://www.nyc.gov/html/dcp/html/zone/glossary.shtml#development_rights.

O’Hara, Tom. 2013. “CAPSYS Facility Tour.”

“ROBUST - Renovation of Buildings Using Steel Technologies.” 2013. Accessed August 15. http://steel-renovation.org/.

Schwinger, Clifford. 2007. “Building Retrofits.” *Modern Steel Construction* (April).

SCI. 2001. “Value Benefits of Modular Construction in Building Extensions”. P284. Silverwood Park: The Steel Construction Institute (SCI).

Smith, Ryan E. 2010. *PREFAB ARCHITECTURE a Gudie to Modular Design and Construction*. John Wiley & Sons, Inc.

Squitiere, Jason, and Janis Vacca. 2013. “Making Up for Lost Time.” *Modern Steel Construction* January.

Thornton, Charles H., Udom Hungspruke, and Robert P. DeScenza. 1991a. “Vertical Expansion Of Vintage Buildings.” *Modern Steel Construction* (June).

———. 1991b. “Vertical Expansoin To Add 235,000 Sq. Ft.” *Modern Steel Construction* June.

W/E Consultants. 11/07. “Survey of the Best Practices State-of-the-Art of Implementation of Roof-Top Extension Retrofit for Energy Efficiency in Social Housing”. Part II of II. SuRE-FIT.