Supplemental Data #4

A Review of Structural Systems Relative to Whole-House/Systems Design and Construction

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Abstract:

The following report identifies the major interactions of non-structural systems with the framing and foundation of a house, identifies the major performance standards and guidelines for structural system design, and summarizes some examples where systems interactions between the structural and other systems were considered. The attachment provides a list and a discussion of interactions with the structural system.

Assessment of Structural Systems and Standards

The systems interactions associated with structural framing members may be some of the most important interactions in a home since they can impact the safety of the occupants. Careful attention needs to be given to the relationship of all systems in the house to assure that each can achieve its objectives and coexist in an efficient manner with the structure. This document identifies the major interactions of non-structural systems with the framing and foundation of a house, identifies the major performance standards and guidelines for structural system design, and summarizes some examples where systems interactions between the structural and other systems were considered. This document is based primarily on the experience of the project team members in their capacity as structural engineers, designers, and researchers. Where appropriate, this experienced-based information is supplemented with references from the literature.

Interactions with the structure

A list of interactions with the structural system is provided in the attachment. The most significant items can generally be grouped into four main categories:

1. Competition for the same space between the structure and mechanical, plumbing, and other utility systems, frequently resulting in unacceptable cutting of the structural framing members.
2. Placement of windows, doors and other openings or architectural features in exterior walls, resulting in a reduction in the building's resistance to lateral loads.
3. Moisture management and thermal systems in the home being compromised by openings in the structural sheathing and other coverings supported by above-grade structural framing members.
4. The foundation's impact on the utilities and moisture management system due to placement of utilities in or through the foundation and/or inadequate drainage.

A discussion of these issues follows:

Competition for space

Architectural and other systems including the building envelope, interior partitions, and special expression elements typically impose limitations over the structural system or vice-versa. The sizing and location of structural elements must consider these systems as part of the design process. For example, requirements for large open spaces without the presence of columns will result in framing consequences that, in turn, can affect spaces for other components, especially mechanical elements. Simple considerations such as the selection of wall thicknesses must be done in concert with structural engineering needs as well as accommodating mechanical and electrical elements within the walls. Provision must be made for sufficient space height to allow for fitting all elements of the construction. Allowances for the depth of framing, piping, ductwork, suspended ceilings and similar concealed items must be considered as part of the overall design, especially if any of the systems must be stacked within a space.

Mechanical systems including heating, ventilation and air conditioning, gas and water pipes and vents, and fire protection systems where applicable generally present the greatest impact on structural systems. The size of ductwork and piping elements and accommodation for the changes in direction of these systems requires provision for openings, chases and horizontal bulkheads that impact placement of structural framing.

Traditionally, attitudes such as “the first guy on the project gets to do the work his way” have commonly resulted in additional costs for reworking and repairing framing that interferes with mechanical components. Many times, the entire burden of resolving conflicts is placed on the workmen in the field. In worst cases, modifications are made by workmen to solve an immediate problem without concern as to whether their solution may compromise portions of the structural system. It is not uncommon to see large notches and holes placed in framing that destroys the strength of the members in order to allow runs of piping and ductwork. Such situations can result in awkward or costly repairs that may also compromise other aspects of the building such as architectural space reductions. Potential resolution of some system conflicts could involve locating the elements in walls and spaces which are not required for structural support such as non-structural interior walls or chases for ducts and piping. In some cases, the location of large, key elements of the mechanical system such as furnaces can create problems due to the presence of framing conflicts in overhead floors or adjacent walls.

Electrical systems which include electric power, lighting, communications (voice, media and data) and controls generally fit within the structural framing without major problems due the small size and flexibility of wiring and conduits. However, in newer homes, these systems have become increasingly more complex in terms of the amount of wiring. This complexity is of particular concern with advanced systems like Structural Insulated Panels or other closed panel products. In addition, lighting appurtenances such as fixtures, control panels, built-in components and similar features occasionally create problems which must be resolved by altering the framing design, moving framing elements or moving the electrical wiring or devices.

Placement of windows, doors, and other openings

Wall openings (windows, doors, wall cutouts, etc.) can have a major effect on lateral bracing systems such as shear walls as well as precluding space for columns and posts. In high seismic risk zones, placement of interior walls and openings between rooms can cause similar concerns. Likewise, a similar situation can exist with excessive floor or roof openings, which can interrupt the transfer of loads across the building. Placement of tie downs into the slab or foundation for transfer of lateral loads can also be influenced by the placement and size of openings. Last, there is some potential impact on the structural capacity of the building relative to the thermal envelope, especially in regard to the selection of the sheathing and/or insulation. This is discussed below in more detail.

Moisture and thermal interactions

The coverings that make up the typical structural system also interact in direct and indirect ways with the ability to keep moisture from becoming a problem in the home. The selection of certain materials that either attach to the structural system or are part of it can create a situation in some climates where the material acts as an unintended vapor retarder and thus retains moisture from either inside or outside the home.

Bulk water movement into the home also can be influenced by the structural system. For example, it often is necessary to cut through the structural sheathing to run plumbing and mechanical vents. To reduce the potential for leaks, the design of the venting systems should be coordinated with the structural system design. Even the slope of the roof's structural members can impact water penetration and should be considered by the complete design team.

In addition to the space limitations relative to mechanical systems discussed previously, there must also be adequate provision in terms of wall, floor, or roof thickness to accommodate insulation. For example, a 2x4 wall will not likely be adequate if R-19 is needed unless exterior insulation is added. Another thermal interaction is related to the spacing of structural members. For example, the designer should consider the impact that different stud spacing may have on the thermal bridges, or framing factor, in a home.

A thermal-structural interaction that is becoming more important as the industry strives to increase energy efficiency relates to the selection of wall sheathing. Typically, OSB or plywood contributes significant lateral resistance and increases the vertical load carrying capacity of studs. If exterior foam insulation is used in place of the structural sheathing, then the building's overall load carrying capacity must be reduced.

Foundation's impact on utilities and moisture

The foundation system can interact in at least two significant areas with other systems in the home - moisture management and utilities.

The elevation of the foundation can be too low for proper placement of utilities, or it can be placed to preclude effective drainage. The first case can lead to bulk water entry into the basement or crawlspace. It can also result in failure of the sanitary sewer if the slope is too low for adequate gravity discharge. In addition, just the very presence of utility openings creates potential routes for water entry. In the second case, the flow of water toward the home is one of the most common reasons for wet basements.

Utilities can also be damaged or destroyed if the foundation is not designed to accommodate them. Piping that runs through a foundation is a good example where the allowance for a sleeve should be part of the structural system design. Otherwise, it is not uncommon for plumbing supply and sewer pipes to be sheared at the point of entry through the foundation. Failures can also occur if copper piping is buried in aggressive soils or directly in contact with concrete. The structural system should consider these types of systems interactions in the design stage.

Finally, the foundation system can interact with the thermal envelope to create moisture problems under the right conditions, especially with crawl space construction. Placement of insulation in the floor of a crawlspace typically requires foundation ventilation. Under the right circumstances, this approach can contribute to the very moisture problems it is intended to prevent. Thus, an economical structural solution may create a negative outcome because of failure to reconcile it with the thermal envelope design.

Responsibility for Success

Traditionally, integrating all of the systems has been viewed as the responsibility of the architect, builder, or other designer. In reality, very little systems integration occurs in the residential construction industry. It is not unusual for an architect or designer to prepare the design with little or no input from other disciplines.

A proactive approach needs to be taken by the design team as part of the overall design in order for the various designers and installers to be aware of each system's needs. All through the design process, there needs to be active communication among the team members to trade information about system needs. Following the completion of the design, the contractor and the workmen assigned to construct the project need to have an understanding of the design requirements and sensitivity to limitations of the design.

Performance standards

The standards that govern structural systems are perhaps the best developed of all of the standards for systems in a home, mainly because they have been embedded in building codes for decades. Examples of significant code documents that cover structural requirements include the following:

1. *Minimum Property Standards* (MPS), U.S. Federal Housing Administration, (Now part of HUD), Washington, DC, The earliest versions of this document go back to at least 1958, with revisions every few years since then. In recent years, HUD has relied on the model building codes as the first preference for codes. Thus, the MPS has lost a lot of its influence on the way homes are built.
2. *One and Two Family Dwelling Code*, Council of American Building Officials (CABO), Falls Church, VA. The original version of this code was developed in the early 1970s and was revised about once every 3 years up through the late 1990s. This code is no longer in production. It has been replaced by the International Residential Code. Likewise, CABO has evolved into the International Code Council (ICC).
3. The *Uniform Building Code*[1], *Standard Building Code*[2], and *National Building Code*[3]. Like the CABO code above, these codes have been issued on a regular basis for several decades each. They are no longer being produced as a result of the merger of their respective organizations into the International Code Council.
4. *International Building Code* and *International Residential Code,* ICC, Falls Church, VA. The most recent full editions of these codes were released in 2003. They basically were produced as replacements for the CABO, Uniform, Standard, and National Building Codes.

The MPS and CABO codes were primarily prescriptive in nature. Thus, many of the structural performance standards were presented in terms of span tables, fastener schedules, and other design requirements that corresponded to a specific set of loads. Typically, they deferred to a reference standard or an engineered design in high risk seismic and wind areas or for unusual building configurations. The other building codes are more of a mix of performance and prescriptive requirements. However, even the traditionally prescriptive requirements in the residential codes have slowly been replaced with more and more references to performance standards.

It would be convenient if a home could be completely designed following the text contained wholly within one of the codes cited here. However, the inclusion of standards that are referenced in the building codes continues to grow, and the structural area is no exception. In the past, the ASCE 7-1998 standard (*Minimum Design Loads for Dwellings and Other Buildings*) was the most prominent of the standards that governed structural design from a loads standpoint. This standard has a long history in its current form and in the past as ANSI A58.1, prior to its transfer to ASCE.

On the resistance side, each of the major materials has historically been represented by its own consensus design standard. Some notable material-based standards that are appropriate for housing include:

1. ACI 318-1999, *Building Code Requirements for Structural Concrete*, American Concrete Institute, Farmington Hills, MI.
2. AFPA NDS-1997, *Wood Construction-Design Values for Wood Construction*, American Forest and Paper Association, Washington, DC.
3. ACI 530-1999, *Building Code Requirements for Masonry Structures*, American Concrete Institute, Farmington Hills, MI.

Other standards that address the structure are geared toward even more specific issues. For example, concerns over natural disasters in recent years have spurned specialty standards that address high-risk areas through prescriptive requirements. Examples of structural standards or guidelines in this category include:

1. AISI COFS PM 2001, *Standard for Cold-Formed Steel Framing – Prescriptive Method for One and Two Family Dwellings*, American Iron and Steel Institute, Washington, DC.
2. WFCM- 1996, Wood *Frame Construction Manual for One and Two Family Dwellings*, American Forest and Paper Association, Washington, DC.
3. FEMA/FIA-TB-1993, *Flood Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in Accordance with the National Flood Insurance Program*, Federal Emergency Management Agency, Washington, DC.

Note that there are other codes that have been developed over the years that are not included in the examples cited above. The National Fire Protection Association, for example, issues a series of codes addressing a variety of building issues. Likewise, some states and cities have their own codes. However, most of the codes tend to borrow heavily from each other and seldom differ significantly in their structural requirements.

Of all the consensus standards, ASCE 7 has become the main reference standard for determining building loads. In addition, many of the material-specific design standards were developed with the ASCE 7 load criteria. Thus, it is probably the most influential of the structural standards. It addresses live and dead loads for all types of buildings including wind, seismic, and snow loads. However, like the building codes in which it is referenced, the ASCE 7 standard only addresses the structure and not interactions with other systems.

In summary, the above-cited documents provide a comprehensive set of requirements and standards to address the structural design of homes, in terms of both the loads and resistance of the building. However, there are very few systems interactions that are addressed in these codes and standards. Thus, the structural designer or designer most often is developing plans with little information about the other systems' needs or objectives.

Examples of systems approaches involving the structural design of homes

The literature does not point to many examples where a home builder or organization has used a whole building design approach that specifically emphasized the integration of the structural system. The best examples are already described in the companion reports to this document. These include Operation Breakthrough (See *Supplemental Data #1*) and Bob Schmitt Homes and Bensonwood Homes (See *Supplemental Data #3).*

One other project worthy of discussion is the Marketable, Affordable, Durable, Entry-level (MADE) home project funded by HUD (*Final Report for Field Evaluation of PATH Technologies MADE to Last Homes*, July 2003, U.S Department of Housing and Urban Development, Washington, DC.) Initially, the MADE project was focused on developing a manual to assist builders in addressing the "Marketable, Affordable, Durable" criteria that defined the project. It was followed up by the construction of four homes that were completed in 2002.

The structure of the MADE home was an integral part of the systems approach adopted in this project. The design team developed a number of ways to integrate the structure with the other systems. For example, the structural design was specifically selected to allow the thermal envelope to be moved to the roof in the top story of the Cape Cod-style homes. This expanded the usable floor area and created a conditioned space in which to run the duct work that would have otherwise been placed in an unconditioned attic. Likewise, the structural supports were located specifically to accommodate future finished space in the basement. A prefabricated foundation system was selected to speed construction in two of the homes. This system allowed for insulation and utility integration in the foundation walls. The homes also were designed to protect the structure from water damage by focusing on durable flashing details that could easily be integrated into the framing process. No roof penetrations were permitted to further protect the structure from inadvertent water damage.

Although the design team looked at the structure and how it could be impacted by or exert influence on other systems in the home, the MADE designs tended to focus on only a few interactions between the structure and other systems.

Finally, it should be noted that there exist many different types of structural systems that take an integrated approach to building. SIPS, or structural insulated panels, are probably the best known of these systems. SIPS are building panels used for walls, roofs, and sometimes floors. They tend to be classified as a systems approach because their construction integrates multiple functions into a single product. With most SIPS, this includes an interior foam insulation layer that is sandwiched between two layers of OSB or plywood. Conduit or other measures are used to allow for wiring to be run in the panels. The result is a structural system that also provides the thermal envelope and is ready for drywall, siding, or other finishes.

Conclusion on structural systems

The following conclusions can be drawn regarding structural systems and whole-house or systems design:

1. The primary interactions of the structure with other systems generally are related to several areas. First is the competition for the same space, often resulting in unacceptable modifications to the

framing or re-work on one of the other systems such as the duct work or plumbing. Second, the structural capacity of the home, especially its resistance to lateral loads, is closely tied to the size and location of openings for widows and doors, as well as other architectural details. Finally, the structural system can have an impact on moisture entry or accumulation in a home, both above and below grade. This in turn relates to many other systems in the home that work together in managing moisture including the thermal envelope.

2. As with other systems in the home, there are numerous performance standards for the structural system. While these standards are more comprehensive and better developed than standards for many other systems, they suffer from the same lack of integration with other systems. The designer of a structural frame for a home, whether using prescriptive codes or a performance-based standard, is often unaware of the other systems' needs and objectives.
3. A few attempts have been tried to apply systems design that included a focus on how the structure relates to the rest of the home. However, a consistent approach has not yet developed and most of the cases to date have been relatively narrow in terms of the number of interactions that were examined.

Footnotes:
[1]The *Uniform Building Code* was published by the International Conference of Building Officials, Whittier, California.
[2]The *Standard Building Code* was published by the Southern Building Code Congress International, Inc. Birmingham, Alabama.
[3]The *National Building Code* was published by the Building Officials and Code Administrators International, Inc. Country Club Hills, Illinois.

Attachment - System Interactions Affecting Structural Framing

1. No coordination of studs, floor joists, and blocking or other support for point loads.

   Discussion: Typical framing using a double top plate does not intentionally account for point loads or duct runs between different stories. Framers are not always familiar with engineered wood products that require squash blocks and other special items at critical locations.
   - a. There are "soft" spots in the framing at large point loads.
   - b. HVAC ducts do not have a common space between joists and studs to travel between levels.
   - c. Installed wall framing may need to be ripped out and relocated or replaced by additional framing resulting in material and labor cost.

   Disciplines: Structural, mechanical

   Action:
   - a. Framing plans should coordinate location of studs and floor joists and appropriate blocking, columns or other methods at point loads.
   - b. Location of HVAC ducts should be considered well before the start of framing.

2. Open spaces within a floor plan prohibit or severely limit placement of lateral bracing.

   Discussion: Requirements for open spaces can limit locations for lateral bracing if the bracing is required within the house.

   Disciplines: Structural, architectural, mechanical

   Action:
   - a. Try to avoid the need for lateral bracing in interior walls.
   - b. DVW plumbing and HVAC duct locations need to avoid conflicts with lateral bracing.

3. Open spaces within a floor plan cause abnormally large/expensive framing sizes.

   Discussion: Requirements for open spaces can result in the need to span long distances and to provide columns or posts for heavy reaction loads.

   Disciplines: Structural, architectural

   Action:
   - a. Design should account for vibration and excessive deflection in long spans.
   - b. Use members that can free span between exterior walls.

4. Framing offsets between levels introduce excessive loads into framing.

   Discussion: Bearing walls on different levels that are offset from other similar walls on lower levels impart loads to floor framing that can cause excessive stresses. Adjustments to member sizes to accommodate the additional forces increase the complexity and cost of construction.

   Disciplines: Structural, architectural

   Action:
   - a. Try to align bearing walls on different levels.
   - b. Use trusses spanning between exterior walls to eliminate interior bearing walls.

5. Location of windows or doors do not allow space for lateral bracing.

Discussion: Bracing in the context of shear walls or diagonal bracing must be provided to resist lateral loads and transfer them to foundations. Sometimes the number and location of windows and doors prohibit the placement of lateral bracing.

Disciplines: Structural, architectural

Action:
a. Coordinate window and door locations to accommodate sufficient space for lateral bracing.

6. Foundations not placed sufficiently low for electrical entry service conduits.

Discussion: Large diameter, rigid conduits require large bend radii. If this material is to be used, coordinate locations with the foundation wall, footings and details to prevent interference with conduits.

Disciplines: Structural, electrical

Action:
a. Identify location of electrical entry service.
b. Identify if large diameter, rigid conduits are to be used.
c. Lower footings where the conduits occur to allow passage of the conduits through the foundation walls.
d. Use deepened footings with clearance sleeves around conduits to allow the conduits to penetrate footings.

7. Location of sewage discharge lines not shown on plans: footings too high.

Discussion: Large diameter waste pipes must pass through foundation walls or footings. Coordinate the pipe locations with foundation wall, footings and details to prevent interference with pipes.

Disciplines: Structural, plumbing

Action:
a. Identify location of waste pipe location.
b. Lower footings where the pipes occur to allow passage of the conduits through the foundation walls.
c. Use deepened footings with clearance sleeves around pipes to allow the pipes to penetrate footings.

8. Potential soil capacity is not determined before construction.

Discussion: Frequently, soil data is not obtained and bearing strengths are not determined for housing construction. In cases of low soil bearing strength, compressible soil (clay), expansive soils (clay) or the presence of rock, the soil conditions can cause extensive damage to structures and/or add to the cost of construction.

Disciplines: Structural, geotechnical, mechanicals

Action:
a. Perform test pits or take soil borings to obtain soil samples and determine soil bearing capacity, especially in areas where soil maps or local experience indicate the potential for problem soils.
b. Design the foundations to accommodate the soil conditions.
c. Coordinate the structural design with other systems that go through or are located in the foundation such as plumbing and duct work.

9. Potential groundwater problems are not determined before construction.

Discussion: Frequently, groundwater data is not determined for housing construction. High groundwater can result in water problems, moisture-related problems such as mold and mildew and higher construction cost for removal, diversion or barriers against groundwater.

Disciplines: Structural, geotechnical

Action:
- a. Perform test pits or take soil borings to obtain soil groundwater depth and its effects on soil bearing strength.
- b. Design water drainage, diversion or moisture protection systems.
- c. Consider locating the dwelling on another part of the site to avoid higher construction cost.

10. Lack of modular coordination by and among disciplines.

Discussion: Inattention to modular coordination commonly creates problems of fit-up of materials and additional costs due to material waste and more difficult or lengthy labor. With modular coordination:
- a. Location of construction features and material placement is simplified
- b. Labor hours are minimized.
- c. There is less material waste due to avoiding odd lengths and excessive scrap.

Disciplines: Structural, architectural, mechanical, electrical

Action: Plan all elements using modular coordination.

11. Lack of coordination between framing and MEP systems.

Discussion: Too often, framing will be largely finished by the time MEP trades arrive at the site. If there has not been proper planning for MEP systems prior to arrival at the site, conflicts are common between structural framing and MEP elements. The resolution to these conflicts is to frequently cut (shorten, notch, etc.) the framing.
- a. The strength of the cut members can be compromised.
- b. Obstructions can cause a need to construct unplanned chases and bulkheads which reduce floor space or head clearance.
- c. Corrections invariably cause additional costs and unwanted compromises to the design.

Disciplines: Structural, architectural, mechanical, electrical

Action:
- a. Coordinate framing and MEP systems prior to arriving at the job site.
- b. Adequately train tradesmen so that they understand construction needs and are empathetic of other trades' needs.
- c. Instruct all trades not to modify framing without field coordination.

12. Lateral bracing installed incorrectly.

Discussion: Frequently, lateral bracing elements will not be properly installed. As a result, they will not function as required to resist lateral loads.
- a. Lack of understanding by framers about lateral bracing elements.
- b. Insufficient documentation of lateral systems.
- c. Interferences from other systems.

Disciplines: Structural, architectural

Action:
- a. Be sure framers are properly trained about the lateral system needs.
- b. Properly document the design needs.
- c. Coordinate framing with other systems.

13. House geometry not accurately defined – dimensions, overhangs, cutouts, and roof plan.

Discussion: Roof plans for houses with sloping roofs or non-standard slopes must be accurately developed to assure proper coordination with other disciplines, especially structural.

Disciplines: Architectural, structural

Action:
a. Develop roof slopes and intersections accurately.
b. Coordinate structural and architectural plans carefully. Resolve all differences before construction begins.

14. MEP elements not identified or located until trades arrive at the construction site.

Discussion: MEP elements are often not well coordinated prior to the trades arriving at the construction site.
a. HVAC ducts do not always have a common space between joists and studs to travel between levels.
b. Installed wall framing needs to be ripped out and relocated or replaced by additional framing resulting in material and labor cost.
c. HVAC risers should be located on interior, i.e. warm, walls if possible do avoid heat loss due to interruption of exterior wall insulation and chilling of the riser itself.
d. Plumbing risers should be located away from exterior walls to minimize the potential of freezing.

Disciplines: Structural, mechanical

Action:
a. Framers must coordinate location of studs, floor joists and other framing with HVAC and plumbing systems.
b. Location of HVAC ducts and DWV system should be indicated prior to start of framing.

15. Utility penetrations through foundation walls or under slabs are not always adequately protected.

Discussion: Plumbing can be damaged if not sleeved as it passes through a foundation wall. Ducts in slabs need to be properly installed to avoid moisture entry. Metallic plumbing under slabs needs to be protected from contact with concrete and aggressive soils.

Disciplines: Structural, plumbing, HVAC

Action:
a. Coordinate foundation design with MEP design.

16 Grading and utility entry into the foundation do not prevent water entry.

Discussion: Electric and other service entry points can be significant pathways for water entry. Likewise, improper grading will facilitate water entry into a foundation.

Disciplines: Architectural, structural, electrical

Action:
a. Architectural plans should coordinate the aesthetic needs that can drive the location of service entry points with grading and house elevation plans.
b. Foundation design should specify how to protect openings for services in foundations from water penetration.

17. Floors and stairs are not coordinated with finish flooring selections.

Discussion: The first riser on stairs needs to be of sufficient height to allow for ¾' hardwood floors or it may not meet code. Some finishes require a stiffer floor than the code minimum.

Disciplines: Architectural, structural, stair design

Action:
a. Coordinate stair design with floor finish.
b. Coordinate structural and floor finish selection.