Some Design Considerations for Composite-frame Structures

LAWRENCE G. GRIFFIS

Over the past 25 years, numerous innovative structural systems have evolved in tall building design where structural steel and reinforced concrete have been combined to produce a building having the advantages of each material. The use of these so-called composite-frame structures has as its underlying principle the combination of these two distinctive and different building materials to benefit from the advantages of both—namely, the inherent stiffness and economy of reinforced concrete and the speed of construction, strength and light weight of structural steel.

The term composite-frame structure has taken on numerous meanings in recent years in utilizing several different building materials. As used here, it is taken to mean a building employing a structural steel and composite metal deck floor system and concrete encased steel columns. The composite beams use headed studs (shear connectors) to achieve composite action between the steel and concrete. The bare steel columns carry the initial gravity, construction and lateral loads until such time as the concrete is cast around them to form composite columns capable of resisting the total gravity and lateral loads of the completed structure.

Besides the economy of materials, composite structures have the advantage of speed of construction by allowing a vertical spread of the construction activity so that numerous trades can engage simultaneously in the construction of the building. Inherent stiffness is obtained with the reinforced concrete to more easily control building drift under lateral loads and perception to motion. The light weight and strength obtained with structural steel frequently translate to savings in foundation costs.

Traditionally, in structural steel buildings or reinforced concrete buildings, stability and resistance to lateral loads are automatically provided as the structure is built. Welded or bolted moment connections are made or braces are connected between columns in a steel building immediately behind erection of the steel frame to provide stability and resistance to lateral loads. Shear walls or the monolithic casting of beams and columns provides stability and resistance to lateral loads soon after the concrete has cured for reinforced concrete buildings. For composite frame structures, however, final stability and resistance to design lateral loads is not achieved typically until concrete around the erection steel frame has cured, which may occur anywhere from a minimum of 10 to as much as 18 floors behind the erection of the bare steel frame. Where the steel erector traditionally has not been concerned with the stability of the frames beyond the use of steel cables to stabilize and plumb the structure, he now is faced with a very light structural steel frame projecting 10 or more stories up in the air. The frame in this condition typically has been designed to resist only gravity loads during construction. The structural engineer now must address the concern for stability during erection to insure safety of the structure.

Lawrence G. Griffis is Senior Vice President and head of the Structural Engineering Division of Walter P. Moore and Associates, Inc., Houston, Texas.

COMPOSITE FRAME STRUCTURES—CASE STUDIES

The term composite-framed structures can best be understood by referring to several examples of actual structures built using the system.

The Three Houston Center Gulf Tower Building is a 52-story, composite-frame building in downtown Houston, Tex. The structural frame is all steel up to the third level with columns at 20-ft. centers and deep spandrel beams forming a tube structure. Above the third level, columns are spaced at 10-ft centers and the frame becomes composite with composite columns and steel spandrel beams (Figs. 1 and 2). All lateral loads are resisted by the perimeter composite tube. No internal bracing or walls are used. The perimeter frame was erected as a series of tree columns, two stories in height, consisting of the bare steel erection column (a light W14 column) shop-welded to the heavy (W36) spandrel wind beams (Fig. 3). Each tree was field-bolted at midspan of spandrel beams using A325 bolts in a double-plate web friction (slip-critical) connection. The tree column frame and floors were erected approximately 10 to 12 stories ahead of the level at which reinforced concrete was poured around the light steel erection columns.

Another slightly different variation on the composite frame structure can be seen in the 49-story First City Tower in downtown Houston. This particular structure uses composite columns on all four faces, with only the two short side faces having steel wide-flange, moment-connected wind girders acting integrally with the composite columns. Most of the lateral load resistance is provided

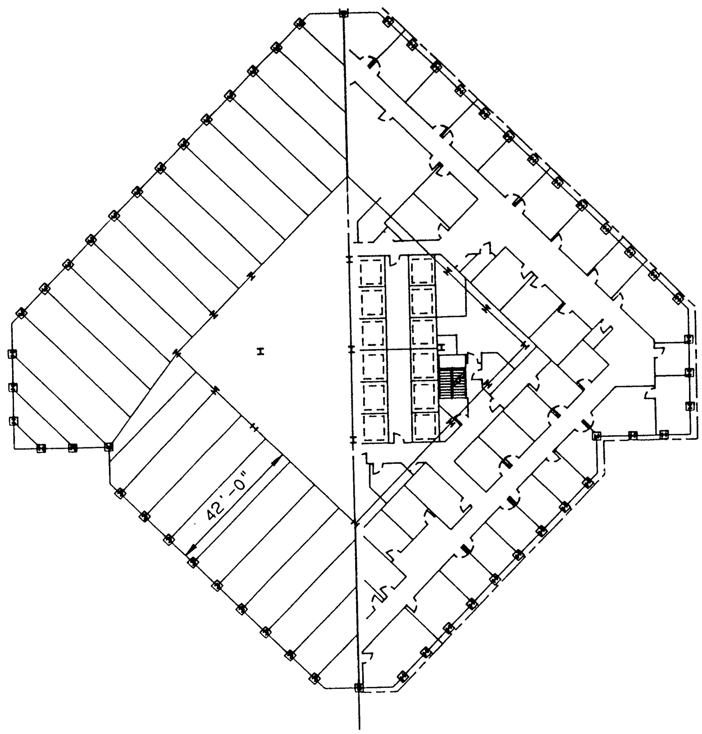

Fig. 2. Typical framing and office floor plan

Figure 1

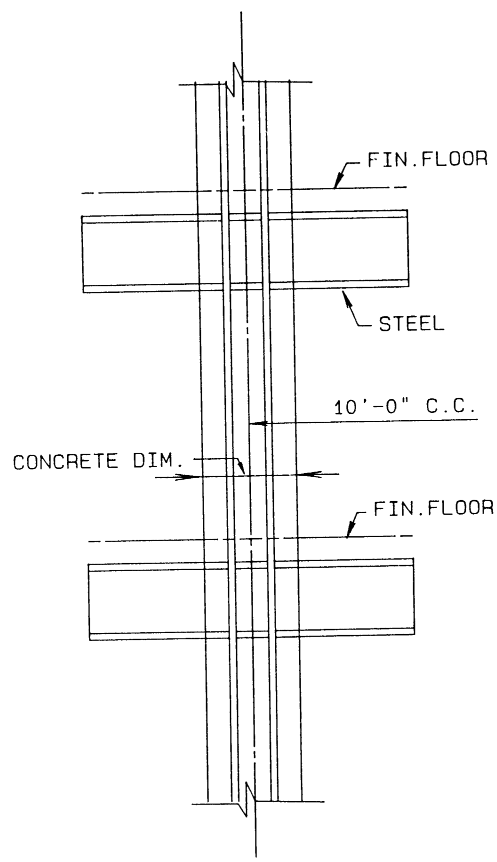

Fig. 3. Tree column

by composite shear walls in the central core (Figs. 4 and 5). The building core was framed with steel erection columns and beams at the same time as the perimeter erection columns. The stub girder floor system and erection columns are erected first. Composite columns and shear walls are constructed 10 to 12 floors behind the steel frame. Concreting of the core walls was accomplished in a similar gang form fashion as in a conventional concrete building, with the columns and beams in the core encased in the shear wall concrete.

SEQUENCE OF ERECTION

Experience gained from construction of these two buildings as well as others indicates that there exists an optimum construction sequence and spread in the various construction activities. Figure 6 shows schematically the various stages of construction activity. In the following discussion, the floor number refers to the number of levels above which concrete has encased the erection column. With the erection derrick or crane positioned on the 10th level, steel for Levels 11 and 12 is being set. On Levels 9 and 10, the frame is being welded (if required) and metal deck is being placed. On Levels 7 and 8, studs are being welded to the top of composite beams and welded wire fabric placed on the floor deck. At Levels 5 and 6, concrete is poured for the floor. On Levels 3 and 4, composite-column reinforcing steel cages are erected and tied. On Levels 1 and 2, column forms are placed and concrete is poured for the composite columns. Finished concrete floors are needed ahead of composite column and shear wall pouring so as to have a finished surface for stacking and tying reinforcing steel and setting the column forms.

If this relative staging is not maintained, then problems can occur. When the gap between setting steel and placing concrete becomes too wide, an overload of the erection columns can occur since they have been designed for a certain number of floors of construction. Also, the stability of

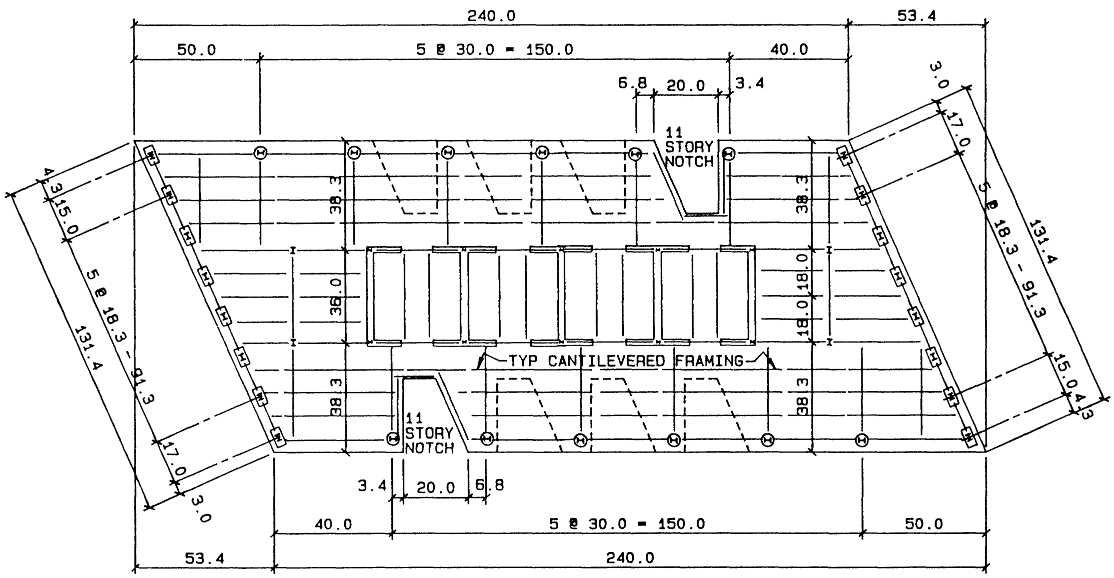

Fig. 4. Floor framing plan

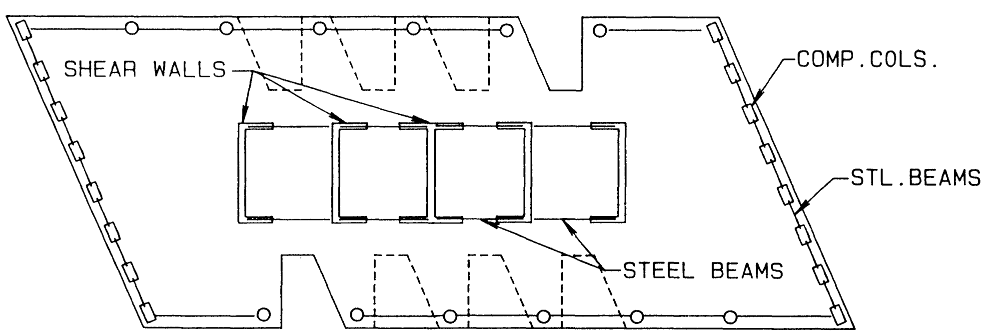

Fig. 5. Wind bracing system

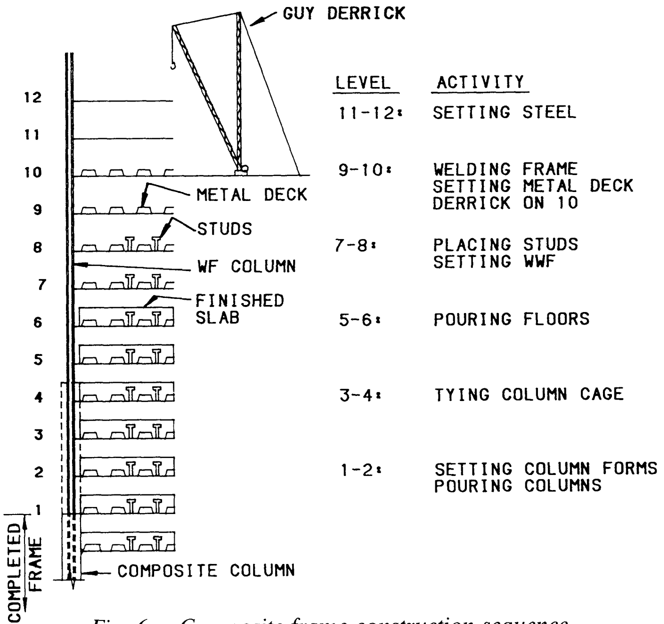

Fig. 6. Composite-frame construction sequence

the frame starts to become a concern. If the gap is too close, then construction activity becomes congested with a resulting loss of construction efficiency. Obviously, close coordination and control of the construction process is required for this type of construction.

DESIGN RESPONSIBILITY DURING ERECTION—TRADITIONAL STEEL FRAMES

Historically, the structural steel erector is accustomed to working with steel-frame structures that are stable and have their total lateral load resistance mobilized once each floor is placed and the braces or moment-connected beams and columns are welded or bolted up. This operation typically follows immediately behind, if not concurrently with, the frame erection. Since composite frames are not fully stable and completely lateral load resistant for the design loads until after concrete has been placed and cured some 10 floors behind, it is clear someone must be responsible for addressing frame stability during erection.

It is worthwhile to examine the AISC Code of Standard Practice[1] for guidance on the subject of erection design responsibility:

1.5.1 When the owner provides the design, plans and specifications, the fabricator and erector are not responsible for the suitability, adequacy or legality of the design.

1.5.2 If the owner desires the fabricator or erector to prepare the design, plans and specifications or to assume any responsibility for the suitability, adequacy or legality of the design, he clearly states his requirements in the contract documents.

3.1 .... Structural steel specifications include any special requirements controlling the fabrication and erection of the structural steel.

3.1.2 Plans include sufficient data concerning assumed loads, shears, moments and axial forces to be resisted by members and their connections, as may be required for the development of connection details on the shop drawings and the erection of the structure.

7.1 If the owner wishes to control the method and sequence of erection, or if certain members cannot be erected in their normal sequence, he so specifies in the contract.

7.9.1 Temporary supports, such as temporary guys, braces, falsework, cribbing or other elements required for the erection operation will be determined and furnished and installed by the erector. These temporary supports will secure the steel framing, or any partly assembled steel framing, against loads comparable in intensity to those for which the structure was designed, resulting from wind, seismic forces and erection operations.

7.9.2 A self supporting steel frame is one that provides the required stability and resistance to gravity loads and design wind and seismic forces without any interaction with other elements of the structure. The erector furnishes and installs only those temporary supports that are necessary to secure any element or elements of the steel framing until they are made stable without external support.

7.9.3 A non-self supporting steel frame is one that requires interaction with other elements not classified as structural steel to provide the required stability or resistance to wind and seismic forces. Such frames shall clearly be identified in the contract documents. The contract documents specify the sequence and schedule of placement of such elements. The erector determines the need and furnishes and installs the temporary supports in accordance with this information. The owner is responsible for the installation and timely completion of all elements not classified as structural steel that are required for stability of the frame.

DESIGN RESPONSIBILITY DURING ERECTION—COMPOSITE FRAME STRUCTURES

It is questionable whether the above statements in the AISC Code of Standard Practice[1] were written with composite-frame construction in mind. However, several conclusions can be drawn from them in so far as they relate to composite frame construction:

1. The engineer, as the owner's design representative, is responsible for stating clearly in the contract documents the design assumptions used in sizing the bare composite frame. These assumptions should clearly show the required erection sequence with any load limitations (i.e. the maximum number of floors ahead

that the steel erection may proceed from the finished concrete composite column installation). The bare composite frame may be viewed as a "non-self supporting steel frame." Clearly, the general contractor and erector must each be aware of the bare frame design assumptions and their effect on the timing and sequencing of the work so as to be able to submit a proper bid.

2. Once the design assumptions and erection sequence are defined on the contract documents, the erector is responsible for determining the required bracing and installing it as specified in Sect. 7.9.3 for a non-self supporting steel frame. However, many erectors will not assume responsibility for the erection stability of so complex a structure and are reluctant to bid under the terms as defined by AISC. The engineer of record has two choices in defining his role for the bare composite frame design. One, he can define the design criteria and assumptions used in sizing the bare composite frame for gravity loads only and require the general contractor to obtain a registered professional engineer to determine erection bracing required; or, he can design the bracing himself and so indicate it on the construction documents. The engineer's decision usually rests with his contractural arrangement with the architect or owner. Clearly, the engineer of record is the most appropriate person to determine the bracing requirements by virtue of his knowledge of the loads and familiarity with the structure. Practically speaking, time does not always exist in the normal design process for the erection bracing to be determined and shown on the construction documents. Regardless of which method is selected by the engineer of record he must clearly define his intentions in the contract documents.

DESIGN CONSIDERATIONS FOR COMPOSITE FRAME STRUCTURES

Both high-rise composite frame office buildings previously discussed, the Three Houston Center Gulf Tower and the First City Tower, were designed by the engineer of record to resist lateral wind load on the bare composite frame during erection. Such provisions were incorporated in the contract documents at the time of bidding.

For the Gulf Tower project, resistance to lateral load was provided in the perimeter tree-column frame. The erection column, sized for 16 floors of construction gravity floor loads (12 floors were specified on the drawings with 4 floors of contingency to be used if the general contractor requested it) was found to be adequate for resistance to lateral wind load. It was necessary, however, to specify a complete penetration weld splice from the erection column to the top and bottom of the girder flange with through-joint stiffeners, in order to develop the bending capacity of the columns, see Fig. 7. This extra welding was also required to resist wind loads transverse to the tree-column itself for the condition when the tree-column cantilevered above the splice point below. No additional or supplementary bracing was required in the building core or elsewhere.

A slightly different approach was necessary for the First City Tower project. Sufficient capacity did not exist at the welded-moment frames on the two short sides of the tower. It was necessary to add supplementary knee braces around the building perimeter and also in the building core. The braces at the perimeter were later removed while the ones in the core were left in place to become embedded in the composite shear walls.

Several factors must be considered in the design of the bare composite frame:

1. **Wind Load.** A decision must be made on the wind pressures to use in the design of the frame and the effective building area over which to apply the wind load. It is becoming more common to design buildings for the 50-year storm, as specified in the ANSI A58.1-82 *Building Code Requirements for Minimum Design Loads in Buildings and Other Structures.*[2] Consideration may be given to reducing the wind pressures used in the design of the bare frame from those used in the completed building design, the rationale being to reflect the reduced exposure time (approximately one year for a 50-story building) for the design storm. With this idea in mind, the two towers discussed were designed for the 25-year storm using the wind map present in the 1972 version of the ANSI A58.1 Code.

   The design engineer should discuss this design issue with the owner. The question, of course, is how many dollars should be spent on a temporary structural condition, and the risk involved. Considerable judgment is involved, weighing cost, safety and risk. The designer must consider applying wind pressure, with the appropriate aerodynamic drift factor, to all elements of the structure, including the edge of the floor deck, beams, trusses, columns and any materials stored on the floors. This practice may produce design wind forces larger than those calculated using only the final projected area of the building.

   Consideration also must be given to the design of structural framing elements for local wind load applied perpendicular to the surface of the element. This condition may control the design of cantilevering tree column elements prior to placement of the metal deck floors.

2. **Diaphragm Action.** Adequate consideration must be given by the design engineer to the ability of the floor diaphragm to distribute the wind load to the bracing elements. This warrants particular concern in the time period prior to placement of the concrete floor slabs. The floor deck must be attached to the steel frame with puddle welds or self tapping screws, sufficiently to carry in-plane floor shear. In some areas of a floor or roof, temporary or permanent hori-

zontal bracing may be required where the deck strength or stiffness are not adequate.

3. **Removal of Temporary Bracing.** The design engineer should make it clear on the contract documents as to what bracing (including connectors) and at what stage of construction the bracing may be removed to accommodate architectural or mechanical items that must be installed at a later date. Premature removal of temporary bracing could lead to overstress of the frame or out-of-plumb framing. Clear definition of these issues will avoid disputes and possible additional costs to the owner during construction.
4. **Drift Criteria.** The design engineer must give careful attention to drift criteria and lateral stiffness of the bare composite frame. With or without temporary bracing, the lateral stiffness of the initial structure must be sufficient to provide overall stability including P-delta effects.

DESIGN CRITERIA NEEDS

It is apparent that the use of composite-frame construction is widespread and will likely remain so, and expand. The national building codes and specifications must begin to address specific guidelines for the design and erection of this construction type. Additional research is badly needed to verify or alter assumptions used in the design of composite frames. The following list addresses some of the design and erection issues:

1. **Responsibility for Erection.** Design responsibility for the erection process must be clearly addressed in the *AISC Code of Standard Practice.*
2. **Shear Connectors on Composite Columns.** Many designers specify shear connectors on composite columns to insure composite action between the steel column and surrounding concrete. The question is, "are they required," and if so, "what is the proper design procedure?"
3. **Beam-Column Connection Design.** Research is needed to determine design guidelines on connections of composite columns to steel girders.
4. **Composite-Column Design Procedure.** Although recent publications have addressed this issue,[3] AISC and ACI must come together on column design procedures, specifically for composite columns.
5. **Frame Stiffness.** What stiffness values (EI) should be used in the lateral analysis of composite column frames? What contribution does the longitudinal reinforcement give to the stiffness of the columns? What effect does column tie spacing have on the stiffness of the columns?
6. **Load Sequence.** Does the fact the steel core is stressed to its allowable stress prior to load application on the composite column affect the ultimate strength or stiffness of the composite column?
7. **Creep.** Are there any concerns about creep of composite columns, particularly in light of the load application sequence of the composite columns?

SUMMARY AND CONCLUSIONS

Composite-frame construction and the use of mixed structural systems of steel and reinforced concrete has shown numerous advantages in high-rise building design. The stiffness and economy of concrete have been used with the speed of construction, strength and light weight of structural steel to produce economical structural systems for high-rise buildings. However, use of these systems requires additional consideration by the structural engineer to reflect the influence of loads and the response of the structure during construction. Adequate attention must be given by the design engineer to clearly define design assumptions on the contract documents and define the responsibility for providing lateral resistance during erection. The erector must be aware of the limitations on frame erection, and he must be advised if he is to be responsible for stability of the frame prior to the concrete-pouring operation.

Several design considerations must be addressed prior to the erection process, including the design storm to use, the effective tributary area over which to apply the wind load, floor diaphragm capability, the removal of any temporary bracing as well as the extent to which it must be removed and drift criteria of the bare frame during erection.

This paper represents an evaluation of a number of the requirements which must be considered in the design of composite frame structures. It is critical the designer consider the behavior of the structure during construction. A summary of current design criteria needs points out the areas where specific research is needed to quantify specific design requirements.

ACKNOWLEDGEMENTS

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REFERENCES

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3. *Task Group to Structural Stability Council* A Specification for the Design of Steel-Concrete Composite Columns *AISC Engineering Journal, 4th Qtr., 1979, Chicago, Ill. (pp. 101).*