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Construction Stability of Composite Frames

Stabilité des cadres mixtes acier-béton

Stabilität von Verbundrahmen im Bauzustand

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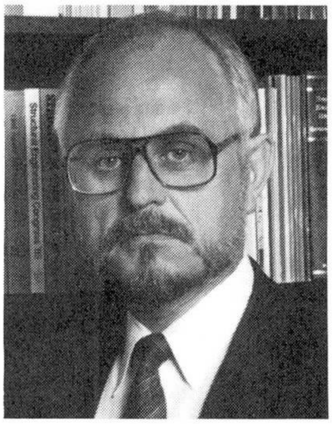

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SUMMARY
The past several years have seen the development of composite frames, where the advantages of steel and concrete are combined to provide structural systems of significant strength and stiffness. Their design and construction are very complex, in particular because the designer must also consider the construction method very carefully to ensure satisfactory performance. The unique design considerations that must be made are discussed, including modeling of the frame, assessment of loads, and the effects of construction sequence on overall stability and strength.

RÉSUMÉ
Le développement de la construction de cadres mixtes acier-béton, dans un passé récent, permet maintenant de tirer parti des propriétés des deux matériaux pour réaliser des structures performantes, tant vis-à-vis de la résistance que de la rigidité. La conception, le calcul et la réalisation sont très complexes, car les différentes phases d'exécution doivent être examinées soigneusement. La modélisation de la structure, les hypothèses sur les actions, et les conséquences des différentes étapes de l'exécution sur la stabilité d'ensemble et la résistance sont présentées.

ZUSAMMENFASSUNG
In den letzten Jahren wurden Rahmen in Verbundbauweise entwickelt, welche die Vorteile des Stahles und des Betons kombinieren und beachtliche Tragfähigkeiten und Steifigkeiten aufweisen. Bemessung und Herstellung sind relativ komplex, muss der Planer doch den Bauvorgang bei der Bemessung berücksichtigen, um ein befriedigendes Verhalten sicherstellen zu können. Die Bemessungsannahmen werden besprochen, ebenso die Modellbildung und der Einfluss des Bauablaufs.

1. INTRODUCTION

Composite frames for buildings utilize the interaction of steel and concrete components to resist gravity loads and external environmental forces. In general, these include frames that use isolated composite members such as beams and columns, or the entire frame may perform as a composite assembly.

Methods of analysis and design rules appropriate for composite construction in buildings have not yet been fully developed, in particular as far as the design of the frame as a whole is concerned. It is the purpose of this paper to examine some of the most important considerations that must be made in the design of such structures, including the checks for the governing limit states. The latter present novel problems, to the effect that composite structures are governed by additional limit states that are unique to such systems. The response of the structure during the construction phase, for example, needs to be developed through further analytical and experimental investigations.

2. COMPOSITE FRAMING SYSTEMS

Composite framing systems for high-rise buildings have gained acceptance as viable alternatives to pure structural steel and reinforced concrete systems. The stiffness and economy of the concrete is used along with the strength, speed of construction, and low weight of structural steel, to produce economical structural systems. However, their use requires that additional considerations be given to the contribution of each composite member to the overall behavior of the structure. In particular, the behavior during the construction phase is important.

Further, the stability of the frame is directly related to overall, as well as to bending and shear stiffnesses. For composite structures, the final stability and the resistance to lateral loads are typically not achieved until the concrete has been placed and cured. Depending on the type of concrete, this may mean that anywhere from eight to fifteen stories of bare steel frame have been erected ahead of the placement of the concrete.

Four basic types of composite building systems are currently in use, although modifications are easily made and continue to reflect the attention of the designer to the performance requirements of the structure. These are composite tubular systems, concrete core-braced systems, systems involving composite cladding of the exterior of the building, and concrete-encased steel frames. Sabnis [1] has given a discussion of each of these, and other studies have summarized the evolution of composite building systems [2].

3. CONSTRUCTION CONSIDERATIONS FOR COMPOSITE FRAMES

As one of the primary forms of composite frames, tubular systems combine an exterior structure of closely spaced composite columns with simply connected steel members that frame into the interior. The exterior frame resists all of the lateral loads due to wind and earthquake. The steel floor framing consists of composite steel beams, all simply supported for shear, and designed only for gravity loads. The frame requires that the erection of the steel frame can advance only to a predetermined number of stories ahead of the placement of the concrete. The wind-resisting elements are then encased, as illustrated in Fig. 1.

For large buildings, computer programs have been developed to analyze the behavior of the structure through equivalent plane frames. However, it is preferable to use

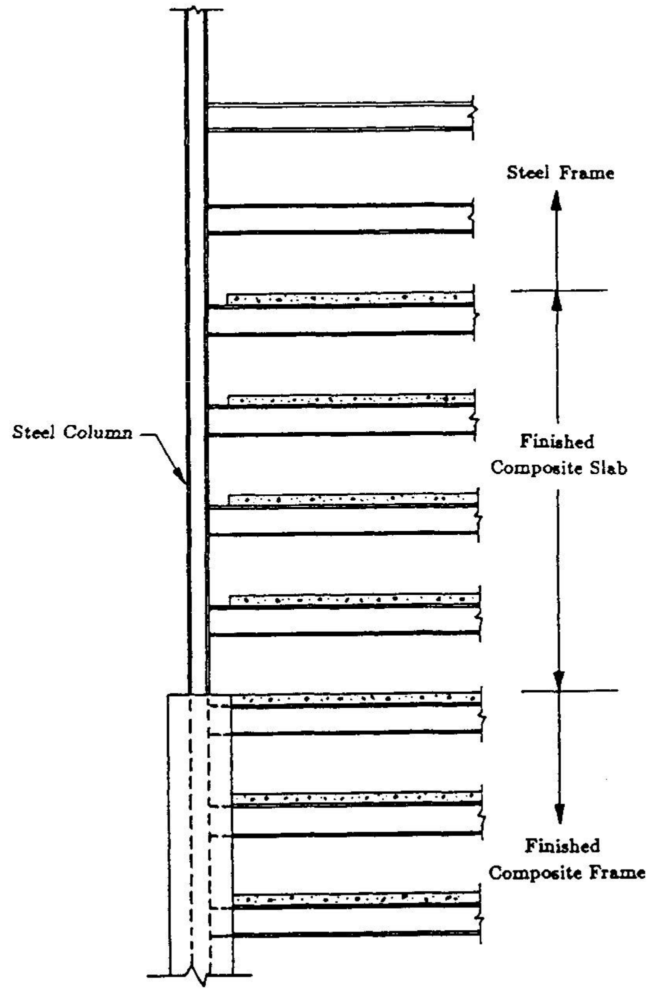

Figure 1 Construction Sequence of a Composite Frame

a three-dimensional structural analysis which includes the characteristics of all members and joints, as well as second order effects. The solution generally requires major computer capacity: whether a planar or a three-dimensional solution is sought, the fact that the construction sequence must be incorporated into the numerical procedure demands mainframe computer capacity.

For the other forms of composite frames, the construction process basically follows the same steps as outlined above, with some modifications that reflect the unique characteristics of each system. Any further discussion will therefore not be provided here; detailed data have been given by Moore and Gosain [3], Griffis [4], and Vallenilla [5].

4. DESIGN FOR CONSTRUCTION

4.1 General Comments

In the design of composite framing systems, the general criteria that need to be taken into account by the design engineer and the contractor are the behavior and strength of the structure during the construction phase. Thus, the structural engineer must address the question of erection stability, to ensure the safety of the structure and the workers. The erector has to evaluate the influence of a bare steel frame that is light, since it may have been designed only to resist gravity loads during the construction.

The use of the proper construction sequence is basic to achieving the above goals. As pointed out by Griffis [4], there is an optimum construction sequence and spread in timing between the various construction activities that need to be met, if problems such as frame stability and member overstress are to be avoided. Stability problems may occur if too many stories of bare steel are erected ahead of the placement of concrete for slabs and columns, thus possibly overstressing the lower steel members: These are usually designed to resist a limited number of floors during construction.

4.2 Composite Frame Example

To illustrate the behavior of a composite framing system during construction, an existing 52 story building was analyzed. The structure had a floor plan that satisfied the basic requirements of the method of analysis that was used in this study. A construction load of 2.4 kPa was applied, in addition to the self weight of the members. The wind load was based on results from a wind tunnel test, in addition to criteria given for loads on open grid works.

The procedure that was used for the introduction of the combined load effects on the frame in the construction phase was as follows: First, the gravity and lateral loads were applied, and the frame response was evaluated by means of a first order analysis. Then the original load vector was scaled with respect to the magnitude that caused first yielding in any member in the frame, as given by the first order analysis. Small load step increments of the scaled load vector were applied to trace the response of the structure due to the second order terms.

4.3 Construction Sequence

A construction sequence such as indicated in Fig. 1 is very cumbersome to analyze. A simplified method was therefore developed which incorporated the effects of the various construction stages. These include the behavior of the finished composite frame and of the bare steel frame additions above the composite columns at different frame levels.

For the composite frame that was investigated, levels 10, 20, 30 and 40 were analyzed as composite construction stages. For this case, at any level of completed composite framing, four floors of concrete slabs were already poured, and a number of stories of bare steel framing had been erected.

4.4 Composite Frame Behavior Characteristics

As the construction proceeds, the frame is subjected to larger P-Delta-effects. It is important to recognize the second order displacement increases for the composite frame during this phase. The analysis of the composite frame is therefore not complete without an overall stability check. For such a non-linear system, the distribution of the stress resultants at the service loads will not be an adequate index for structural design, if instability is the actual mode of failure.

4.5 Composite Frame with Bare Steel Frame Additions

Figure 2 illustrates the response of the composite frame due to an increasing number of bare steel stories that have been added beyond 20 stories of composite structure. The lateral deflection increases rapidly as the number of added stories increases. Thus, large sway deflections occur after the number of added stories exceed 12 for levels 10 and 20, and after 10 and 8 stories for levels 30 and 40, respectively. It is therefore apparent that the construction sequence should take frame elevations into account, such that bare steel can be allowed to move ahead of the composite frame by fewer and fewer stories as the overall height goes up.

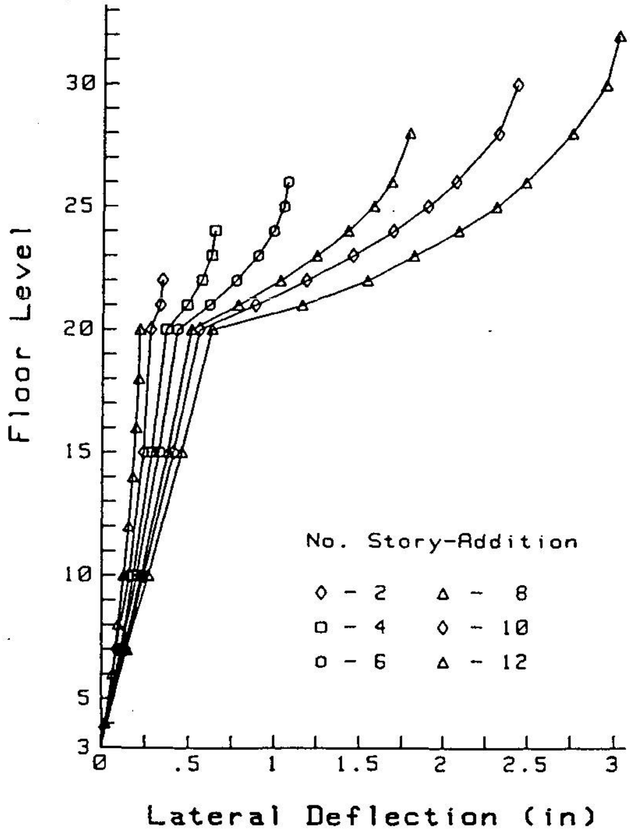

Figure 2 Deflections of Bare Steel Framing Additions to a Composite Frame, and Composite Frame Deflection (1 in = 25.4 mm; 1 kip = 4.45 kN)

The solution for the frame of this study shows that the incremental number of bare steel stories that are erected ahead of the completed composite frame is controlled by either of the following stability criteria: (1) the value of the determinant of the stiffness matrix is equal to zero; or (2) the sidesway displacement of the structure at service load is within a reasonable limit. Although the former is an ultimate and the latter a serviceability limit state, for the case of composite frames during construction, deflections should be treated as ultimate conditions. This led to the concept of the Construction Limit State (CLS) [5].

Another approach to the erection stability is to consider the construction drift and its effects on the frame at different stages. Thus, the magnitude and variation of this drift must be considered for every story that is added. This includes examining the drift of individual frame assemblies, but it is essential to evaluate the drift characteristics of the bare steel frame as it is erected ahead of the concrete placement. The study demonstrated that frame stability should not be of concern for the finished composite frame at any stage.

Frame displacements can be presented in non-dimensional form as Construction Drift Indices (CDI's). The CDI is defined as the horizontal displacement at the top of any story level of the frame, divided by the frame height to that level. When the bare steel framing is considered in the analysis, the height used is that of the steel itself, measured relative to the composite frame top level.

Drift limitations are set by the individual designer to assure satisfactory structural behavior. For the frame that was analyzed in this study, the drift of the overall frame as well as for the story additions and individual stories were evaluated. Figure 3 shows the drift variation for the finished composite frame and the bare steel story additions for different construction levels. Considering that the frame height-to-width ratios vary during construction, the range of drift indices that were found in the analysis is considered acceptable.

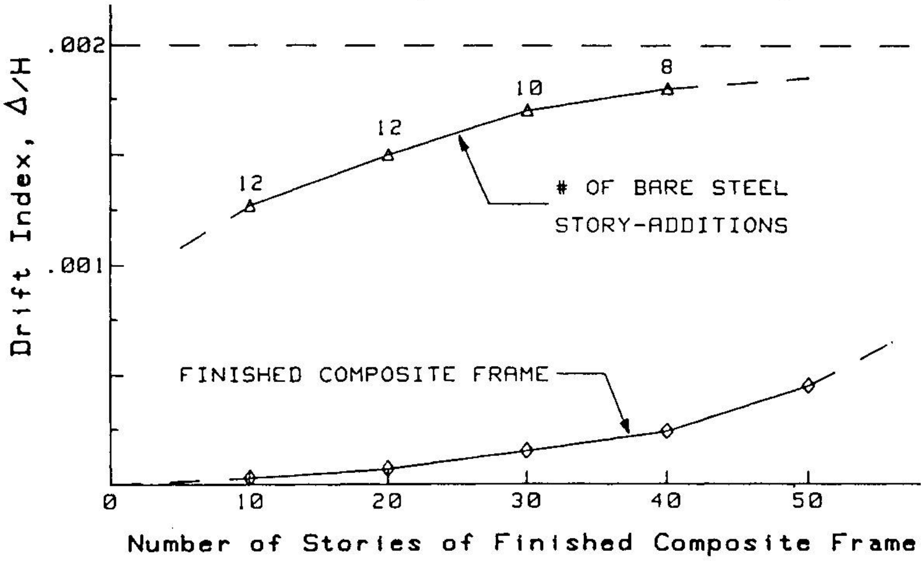

Figure 3 Drift vs. Number of Stories of Finished Composite Frame

5. CONCLUDING REMARKS

The study has shown that certain limitations must be applied to the construction sequence, specifically such that as the building proceeds, a smaller number of stories can be added above the finished composite frame. The construction sequences for a particular composite frame can be determined by developing story addition ranges such as the ones arrived at for the frame of this study.

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