STEEL & PRECAST SLAB CONSTRUCTION SYSTEM FOR MID AND HIGH-RISE RESIDENTIAL BUILDINGS

Peter A. Naccarato

Peter A. Naccarato, P.E., Vice-president of O'Donnell & Naccarato, Inc., in Philadelphia, has been practicing structural engineering since 1965. Educated at Villanova University, Mr. Naccarato is known as an expert in structural engineering and building construction. During his 37-year career Mr. Naccarato and his partner of 27 years, William F. O'Donnell have designed thousands of buildings in the Philadelphia area and opened branch offices in West Palm Beach, Florida; Princeton, New Jersey; Wilmington, Delaware and Doylestown, Pennsylvania.

They provide creative solutions using structural materials and systems. The Flex-Frame, L.L.C. company of Cherry Hill, New Jersey in conjunction with Mr. Naccarato sought to develop an innovative use of structural steel. The result of that ten year collaboration is technology known as the composite girder and slab construction system.

Summary

Flex-Frame L.L.C. has aimed this technology specifically towards high-rise residential buildings. It is an assembly of precast concrete hollow-core slabs supported by structural steel.

The steel-precast hybrid is the first to use long-span precast hollow-core slabs with an integral steel beam to form a monolithic structural slab assembly. The lightweight assembly develops composite action enabling it to support residential loads within permissible deflection ranges.

An inverted "T" shaped beam (fabricated from a wide-flange section) used as an interior girder supports the slab on its bottom flange. The beam, concealed within the plane of the slab with only its thin bottom flange exposed produces a flat structural slab similar to flat-plate concrete. Elimination of conventional steel beams beneath the slab, which provide support from the top flange, permits minimum floor-to-floor heights.

The composite assembly meets BOCA and International Building Code fire classification requirements when constructed in accordance with Underwriters Laboratories Inc. Floor-Ceiling Assembly Design No. UL K912.

The composite girder and slab technology in combination with a structural steel frame offers a complete steel and concrete superstructure as an alternative to flat-plate concrete. Flat-plate concrete which is formed and cast-in-place is a lengthy process which requires a large skilled labor force. In contrast the Flex-Frame technology employs the use of prefabricated components which are assembled-in-place in a fraction of the time required for flat plate concrete.

NORTH AMERICAN STEEL CONSTRUCTION CONFERENCE

Development of the Composite Girder and Slab Construction Technology

Flex-Frame, L.L.C. set out to develop a more efficient and flexible steel based framing system for the mid and high-rise residential construction market. It specifically targeted apartments, condos, retirement communities, hotels, dormitories and other multi-story residential buildings.

To date, such residential buildings in the USA have been typically constructed with cementitious structural systems that provide low floor-to-floor heights, (8′-8″ minimum) and are non-combustible. Low to mid-rise buildings (less than ten stories) often utilize reinforced masonry bearing walls supporting precast, prestressed hollow-core slabs. High-rise buildings utilize cast-in-place concrete which can be either reinforced or post tensioned. The primary disadvantages of these systems are that they are expensive, slow, weather sensitive and require large skilled field labor forces.

For the industry there has been a long standing desire to bring the advantages of structural steel to the construction of multi-story residential buildings. Owners, architects, engineers and contractors have recognized steel's qualities and benefits within the commercial construction market. While there are proven products within the industry that work with a structural steel frame, they tend to be an adaptation from the commercial market and not ideal for residential construction. For example, some approaches do not provide a uniform solution or are proprietary. Others cannot provide the 8´-8´´ minimum floor-to-floor height and require ceilings to conceal beams or joists and metal form deck, and some are only practical for very tall buildings with identical architectural floor plans for all floors.

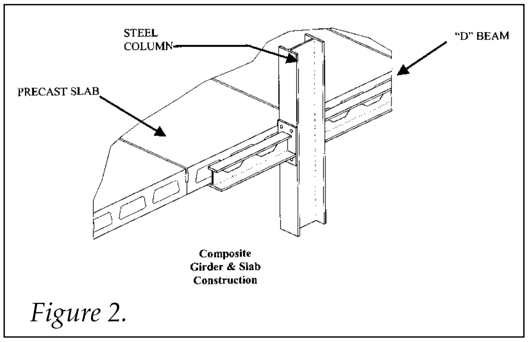


Figure 2.

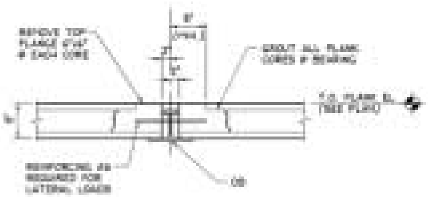


Figure 1.

In contrast to conventional steel design which uses long-span members in a variety of commercial building applications, Flex-Frame, L.L.C. chose what some would consider to be an unorthodox approach to finding a solution. First, they determined that precast slab units which are common in multi-story residential construction combined with a steel frame would offer maximum flexibility and economy. They then analyzed the characteristics of residential construction and determined that relatively short spans for girders are appropriate and efficient for modular residential construction. Although apartment unit design layouts typically vary within a floor, they generally "stack" vertically for structural support, utilities and shafts. The solution was a unique universal girder that would be used exclusively for these types of buildings.

Thus, Flex-Frame's composite girder and slab technology has been developed specifically to meet all of the residential building's requirements. The primary floor component is an eight inch (8″) thick precast hollow- core slab. It provides an 8′-8″minimum floor-to-floor height, is non-combustible, and the slab underside can become a finished ceiling. The floor girders are eight inch (8″) deep dissymmetric steel beams (inverted tees) known as "D"-beams, contained within the plane of the floor. Its cross section is depicted in Figure 1.

The girder and slab assembly is supported by a conventional steel frame which resists all gravity and lateral loads (See Figure 2). The building's floor-ceiling assembly fire rating is achieved when constructed in accordance with Underwriter Laboratories Inc. Assembly Design No. UL K912.

History

In Flex-Frame's quest to perfect its steel and precast concept, it conceived of a design that could take the place of either masonry bearing wall construction or flat plate concrete. The principals of the new company having designed and built several residential buildings with the use of conventional structural steel and prestressed precast slabs, recognized that this approach had both pros and cons. Its advantage was low cost when compared to cast-in-place flat-plate concrete construction; its disadvantage was that the rolled steel shapes beneath the floor slab necessitated an increase in the floor-to-floor height, resulting in an increased building height of 1′ to 2′ minimum per floor. Also, ceilings and soffits were needed to conceal the steel beams, as were accommodations to go through and around the beams for pipes and ducts.

In order to solve the floor-to-floor and interference problems, the company implemented a research and development program. It wanted an interior structural steel girder to be placed within the plane of the precast slab units, thereby producing a "flat-plate like" system with a minimum floor to ceiling height of 8´-0´´. The key to this technology would be the development of a steel section, which could provide the slab support with only an 8´´ depth while spanning a respectable distance. Conceivably the beam could be designed and fabricated to develop composite action with the precast slab in order to achieve such spans.

Structural Development

Initially, a steel section was fabricated for experimental testing purposes. The beam, which resembled a large rail section, was a combination of two split tees. The lower tee was cut from a W8 x 40 and the upper tee from an S3 x 7.5. When welded together the result was a dissymmetric beam 8´´ deep. It provided a bearing ledge for the slab, which could be set in place from above in a level position. The girder and slab were interlocked by cement grout. This assembly was load tested and it was conclusive that composite action was developed between the steel section, the grout and the precast slab. Based on the results, Flex-Frame, L.L.C. initiated a formal professional testing program with an independent laboratory.

The Structural Engineering Department at Philadelphia's Drexel University was selected to perform the testing and research program. Professor of Structural Engineering Mohamed Elgaaly, Sc.D., P.E., headed up the project for Drexel University. Prior to beginning the testing program, calculations were performed to predict the load carrying capacity of various sections. During that time, it was decided that the steel section should be changed in order to guarantee a homogenous and uniform bond between the structural steel and the precast concrete. An improved beam was formed by castellating a W10 x 49, so as to provide two equal tees with "half castellations" or openings in the web of each tee. A 1´´ x 3´´ continuous flat bar was welded to the high points of the web sections. The resulting dissymmetric beam measured 10´´ wide across the bottom and 3´´ wide along the top, leaving 3 ½´´ for precast slab bearing on either side of the beam. The trapezoid shaped openings in the web permitted the free flow of grout through the beam. The initial round of testing was in accordance with the BOCA Code's requirements for a structural system that could not be designed or analyzed with readily available data. This testing utilized load factors along with deflection and rebound criteria dictated by BOCA. While this approach was sufficient for building official approval, Flex-Frame, L.C.C. realized that engineers and architects would prefer a method of rational analysis that would permit maximum flexibility and creativity in the use of the technology. Drexel University was commissioned for a second round of testing to accomplish this end.

Figure 3.

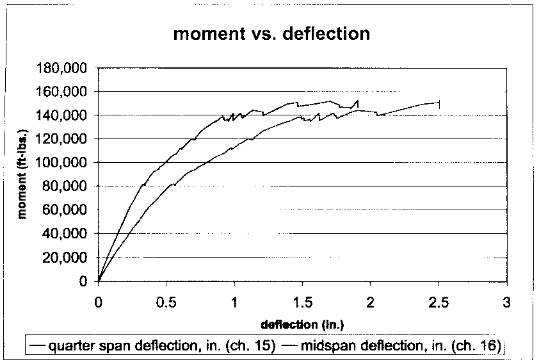


Figure 4.

Prior to the second round of testing, it was decided that a full-scale test should be performed in order to uncover any problems that might arise during construction of the actual system. A full-scale two bay system was constructed (See Figure 3). A structural steel "D" beam spanning 16′ -0″ between supports, supported precast slabs spanning 28′-0″ on either side of the "D" beam. The tested area measured 16′-0 x 56′-0 (896 sq. ft.). The system was loaded with a series of solid concrete "dead men" weighing 2,400 pounds each. The system when loaded to 140 psf, was almost four times the design live load. At that point, one of the precast slabs developed a shear failure, thereby ending the test. The "D" beam did not fail.

In the spring of 2000 Dr. Elgaaly began a series of tests to determine the mechanical properties of the composite section. Test specimens consisted of "D" beams sixteen feet (16´-0´´) long embedded between sections of hollow core slab units one foot-six inches (1′-6″) long on either side of the "D" beam. The resultant specimen was three foot-six inches (3′-6″) wide by sixteen feet (16′-0″) long. The test specimens were assembled at Drexel's

Hess Lab in Philadelphia. Three specimens were tested for each cross section to be analyzed. See Figure 4 for the moment/deflection curve for one of the 8″ specimens.

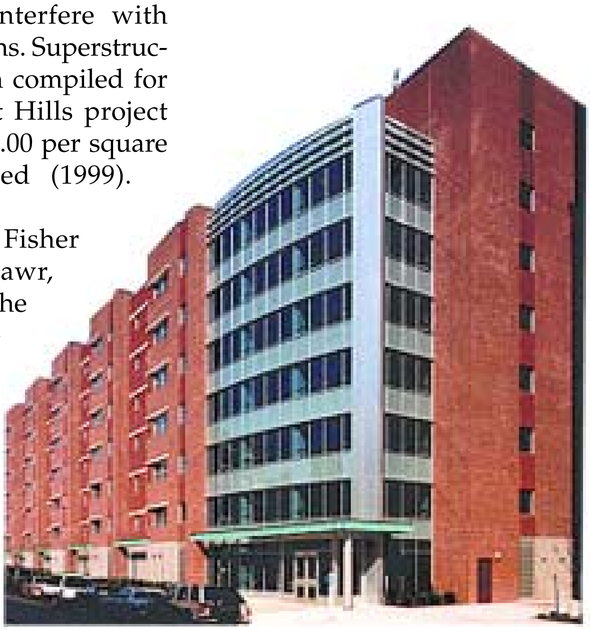
As can be seen testing was carried to failure unlike the BOCA tests which required rebound measurements. The tests revealed the classic stress/strain shaped curves. Also, the testing highlighted the difference between steel only and composite load carrying capacity.

These tests reveal that the effective width of the composite section varies and is on average approximately 28 inches. The location of the neutral axis also varies and is approximately 4.85″ above the bottom of the bottom flange. With this information Dr. Elgaaly will derive equations which can be used by structural engineers to analyze and design buildings using the technology.

Case Study No. 1

This completed project is a four-story, 70,000 square foot hotel, "The Inn at Somerset Hills" in Somerset County, New Jersey. Steel, precast, and grout were installed in 18 working days. The Flex-Frame technology brought economy and flexibility to the hotel project. Precast and masonry bearing wall could not be used because the bearing walls would interfere with ground floor functions. Superstructure costs have been compiled for the Inn at Somerset Hills project and estimates of $16.00 per square foot were confirmed (1999). (See Figures 5 & 6)

AISC member Fisher Steel, Inc. of Bellmawr, NJ fabricated all of the structural steel including the "D" beams for this project. They employed a service center to provide the split castellated tee. Fisher attached the top flange flat bar with his own certified welders. The automated cutting procedure utilized by the service center produced a castellated tee for approximately the same cost as a split tee.



Drexel University dormitory.

Case Study No. 2

Drexel University promised three hundred and fifteen incoming freshmen dormitory rooms for the September, 2000 semester and in October 1999 the University was ready to receive construction bids. Their plans called for a structural system of precast hollow-core slabs supported by reinforced masonry bearing walls. The University's construction staff did not hold out much hope for delivering the building on time, since they had to construct a pile foundation delaying the start of the superstructure until December. They knew that a winter start with masonry bearing wall construction could risk the critical opening in the fall.

The University solicited bids but also asked the contractors to submit alternate structural system bids which could guarantee the opening date. They received an alternate bid based on the Flex-Frame technology. This bid confirmed the steel and precast system direct cost (approximately $16.50 per square foot) to be less than the direct cost of the precast and bearing wall structure. This was due, in part, to the fact that the masonry walls had to be heavily reinforced to satisfy seismic requirements. In addition to the direct construction cost savings, Drexel realized significant soft cost savings.

The superstructure components were completely designed and fabricated off-site during the installation of the pile foundations, and were ready for installation by the end of foundation construction. The first steel col-

Figure 5.

Figure 6.

umn was set on January 10, 2000 and the final hollow core slab was placed on February 28, 2000. The entire superstructure was assembled-in-place in 31 working days, few of which achieved an above freezing temperature, and in spite of four snow storms. (See Figure 7)

The project was completed on schedule and the September 15, 2000 occupancy occurred as planned. Drexel built two dormitories in four years. The first was constructed of hollow-core slabs on masonry bearing walls. The second utilized the steel and precast assembly. They found the steel-framed building had numerous advantages over the wall bearing (masonry) approach. Cost and speed of construction were foremost but almost as important was the flexibility in architectural layout introduced by the elimination of the masonry bearing walls.

The Future

What lies ahead for Flex-Frame's girder slab technology are many exciting new projects featuring its use including a variety of distinguished high-rise residential buildings.

Flex-Frame's technology reflects the wave of the future responding to many current trends within the construction industry such as design-build, pre-engineered and pre-fabricated components and systems, fewer on-site skilled construction workers, single source & trade responsibility, and compressed time for design and procurement. The steel industry offers sophisticated advancements to further enhance this technology with computer aided designs, detailing and fabrication to automate and integrate shop procurement and production.

This ground breaking technological approach to the building process offers a new paradigm not attainable with a cast-in-place superstructure. By its nature cast-in-place methodology in comparison to modern day pre-fab capability is inefficient. Its many dependencies and required resources are difficult to manage and control considering for example its; transient workforce, series of multi-layered tasks, rigid sequence of events, and differing weather and site conditions. The complexity associated with quality control and production of a "field built" superstructure is eliminated through shop fabricated components, delivered and assembled-in-place.

This open market technology is being introduced to AISC, the structural engineering community and the construction industry at large for consideration on upcoming mid and high-rise projects. The D-beam composite girder load table provides span and load criteria for each girder-slab thickness for use by the design engineer similar to bar joists. The system components including the D-beam and precast slabs are available from customary sources of supply and are not proprietary products of Flex-Frame L.L.C. The steel industry's contractors will not only fabricate and erect the steel frame but are poised for the first time to assemble a complete superstructure including slabs.

Flex-Frame L.L.C. has expanded its research and development program to include engineering and testing of new girder-slab assemblies for both 10" and 12" thick precast slabs. While its premier 8" girder-slab technology is currently available to the construction industry, it intends to offer updated engineering information covering its latest technology advancements by 3rd quarter 2001.

Technical and engineering assistance will be provided to architects and engineers by a Flex-Frame L.L.C. associate consulting engineer. Assembly and construction of the system and its components shall be in strict compliance with Flex-Frame L.L.C specifications, guidelines and requirements.