Process Improvements in Precast Concrete Construction Using Top-Down Parametric 3-D Computer Modeling

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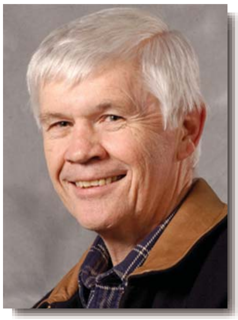

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Design professionals worldwide have applied the technology of computer-aided design and drafting (CAD) on a broad scale, primarily to increase the efficiency of manual design and drafting methods and to promote standards, rather than to improve the process itself. Even with improvements in the technology, however, errors in design and drafting remain common. Taking the 2-D CAD technology further, the application of three-dimensional integrated parametric modeling of precast buildings at the assembly and piece levels may enable producers to greatly reduce design errors, resulting in significant improvements in project quality, cost, and schedule. An examination of a number of case studies of precast/prestressed concrete projects has revealed that the common causes of construction problems are design, detailing, and drafting errors, a lack of coordination between different disciplines, and inadequate management of changes. An analysis of the cases presented in this paper indicates that the application of 3-D top-down modeling and automated production of shop drawings holds the potential to eliminate most of the sources of error.

Although computer-aided drafting has become prevalent in all branches of the construction industry, a significant portion of construction dollars is still spent on correcting errors made in the design stage.[1] Building parts that do not align correctly, spatial conflicts between components of different systems, and work that must be demolished because drawings were not updated to reflect design changes are among the common errors.

A recent comprehensive study of seven large construction projects (employing structural steel, masonry, and cast-in-place concrete construction methods) showed that design errors accounted for an average of 26 percent of all construction defects.[2] A similar field survey of cast-in-place reinforced concrete construction revealed numerous and diverse reinforcing bar constructibility problems. These deficiencies arose largely from inadequate detailing, lack of construction experience among designers, poor coordination between the design of the various disciplines (structural, electrical, and other trades), and insufficient involvement of contractors in detailing.[3]

In a recent survey of U.S. precast/prestressed concrete producers, 41 percent of respondents reported encountering problems in production due to ambiguities in design "often" or "very often."[4] This situation still remains despite the industry's full adoption of computers for design and drafting work. In another recent survey of producers, all of the respondents reported using CAD drawings, with 96.3 percent produced in house, and the remainder outsourced to consultants).[5]

The Precast Concrete Software Consortium (PCSC) is currently specifying and procuring three-dimensional (3-D) automated and integrated design and management software for its members.*

One primary goal of the PCSC is to enable precast producers to reduce lead time on projects from months to just one week,[6] and to make production-related activities (such as procurement, control, and shipping) more efficient. Another goal is to generate the engineering information needed to support automation, such as bending of reinforcement, steel cutting, and mold design.

In addition to these benefits, the authors hypothesize that 3-D computer modeling of buildings, if performed with well-structured top-down parametric dependencies between assemblies, pieces and components, has the potential to reduce or eliminate many sources of error. Case studies of failures and successes provide an effective and convenient resource for initial examination of this hypothesis; its proof will require extensive implementation and adoption of such systems.

In this research, eight case studies of precast/prestressed concrete projects, each of which required significant remedial work, were collected, documented, and examined. The studies allow qualitative tracing of the root causes of the errors that led to the rework. In some cases, sufficient detailed cost information was provided to allow a quantitative assessment of the impact of the rework on project budgets and schedules.

In the first part of this paper, we describe the integrated assembly and piece modeling approach to computerized design. Next, we classify the design and drafting errors reported in the case studies. Each classification is illustrated with examples tracing the cause and effect of the error. Lastly, we trace the ways in which each type of error would be prevented in such a design environment.

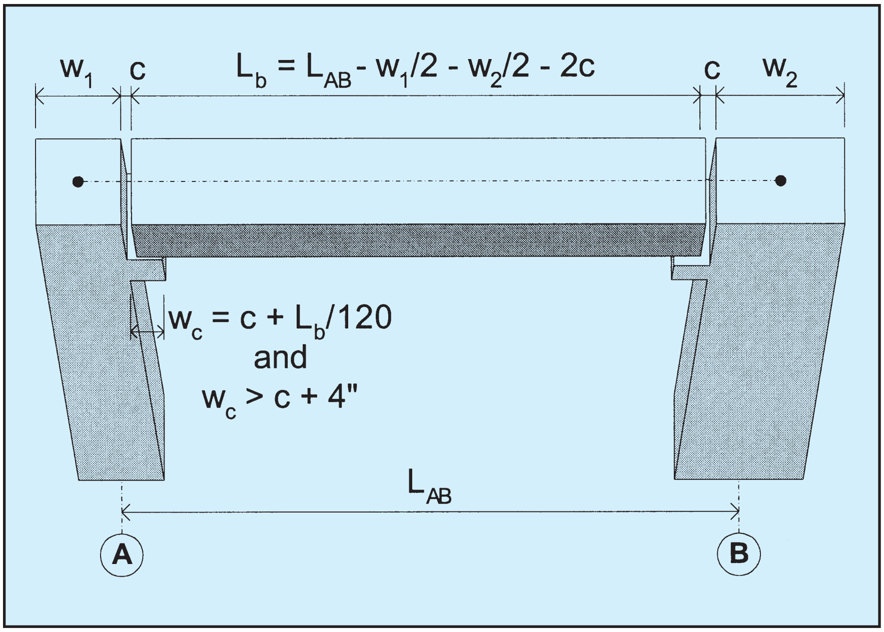

Fig. 1. Parametric model of a beam between two columns.

INTEGRATED PARAMETRIC ASSEMBLY AND PIECE 3-D MODELING

The following two principles for precast concrete modeling software are central to reducing the incidence of errors and consequent rework:

1. Modeling versus drafting. Instead of generating multiple and discrete drawings to represent a building and its parts, the operator builds an integrated model of the building assembly and its components. Both assembly and piece drawings are generated from the model. Drawings are reports of the information, rather than containing the information itself.

2. Maintenance of integrity from the assembly to the parts, rather than from the parts to the assembly. Instead of composing a building model as a collection of instances of typical pieces with fixed geometry, the geometry of each piece is derived from the spatial topological relationships between it, its neighbors, and the building grid. In this way changes at higher levels of an assembly can be propagated to lower level parts automatically.

Fig. 1 illustrates the principle: the beam is automatically sized to fit between the columns, and the corbel supports are automatically sized to fit

* The PCSC is an LLC formed in 2001 by a group of Precast/Prestressed Producer companies in order to collectively specify and foster procurement of 3D parametric modeling software, and to develop a Precast Product Model for integration of precast engineering systems with other information systems.

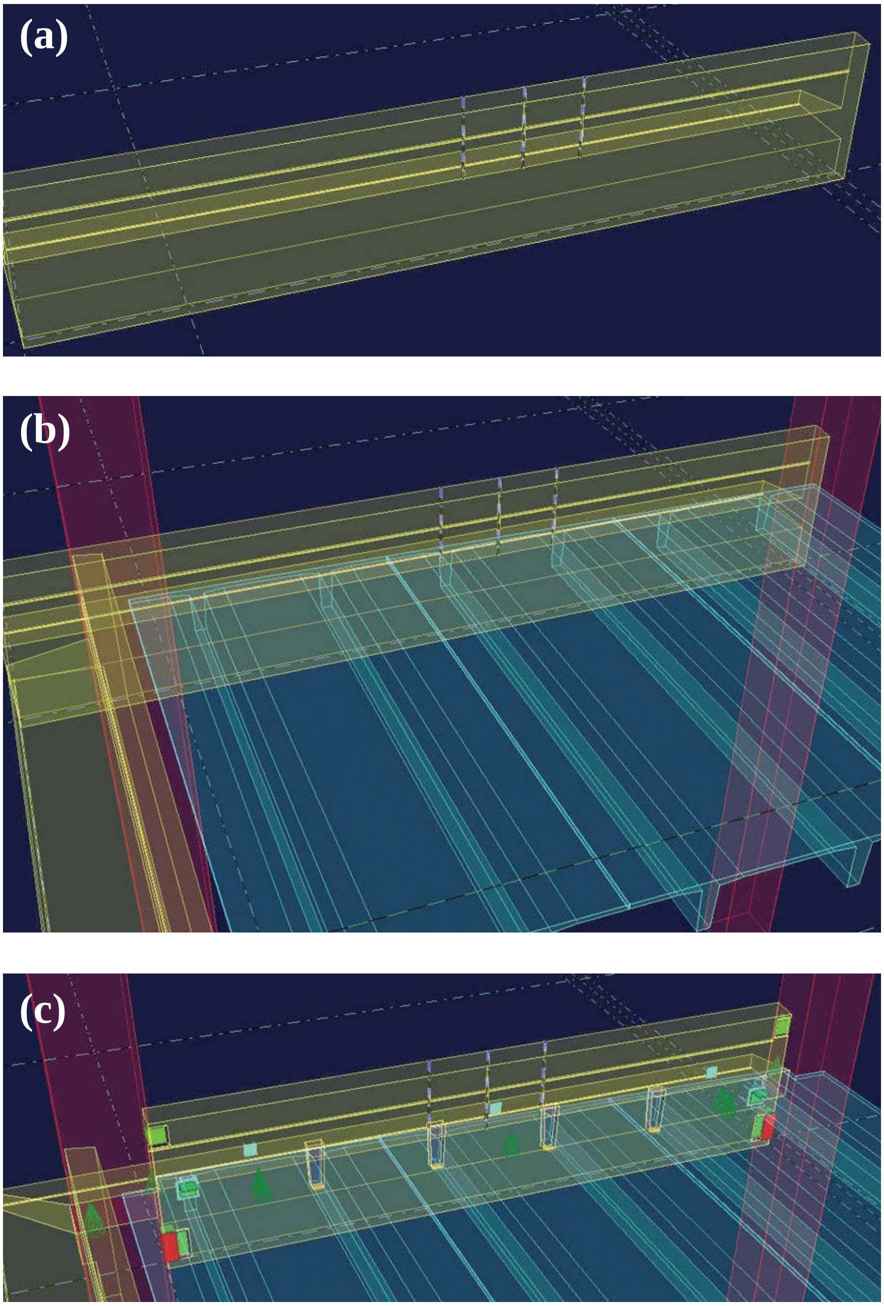

Fig. 2. Top-down 3-D modeling of a precast concrete spandrel (prepared using Tekla prototype Xengineer software[7]).

the beam. Any change made to any of the independent dimensions (L_{AB}, w_1, w_2, or c) will result in propagation of the change to the beam and to the supports. Also, if the beam is removed, the supports are automatically removed (i.e., recognition of connections between pieces as a separate logical entity is crucial to enabling this behavior).

The first principle was incorporated in pioneering 3-D modeling software for precast concrete design (EDGE),[8] which has enabled its developers to significantly reduce the frequency of errors in their projects. The second principle has yet to be applied in precast concrete software. It has, however, been applied with success in a number of other industries, including structural steel detailing.

Unlike traditional CAD files, the behavior of pieces in a top-down parametric building model closely mirrors the conceptual thinking of an engineer in executing the design of a precast concrete building. The engineer is concerned first with the structure as a whole assembly, then with the pieces that make up that assembly and the connections between them, and lastly with the details of each individual piece. When changes are made at any level, the elements at a lower level should adapt to the changes made.

The approach is effectively illustrated in the sequence of captured screen shots shown in Fig. 2. Standard or user-defined parametric cross sections are extruded to form the basic volume of each piece (Fig. 2a shows a spandrel beam). All of the pieces are placed in the assembly (in Fig. 2b, columns are red, spandrels are yellow, and double tees are cyan). The user does not define the length of the spandrel; rather, the system automatically sets the length parametrically as the distance between the columns.

Next, connections are modeled (see Fig. 2c). These are selected from a parametric library of connections and automatically adapted to fit the appropriate pieces. The resulting piece model can be seen in Fig. 3a, and, with embedded hardware, in Fig. 3b. If any change is made to the position or cross section of any of the pieces in the assembly, the software automatically propagates the effect of the change to all the other pieces and connections, ensuring that the integrity of the model as a whole is maintained.

Piece prestress and reinforcement design will be performed directly in the model using plug-in professional software. At any time, production drawings and bills of material can be automatically generated by the system. The drawings are derived directly from, and are, therefore, fully consistent with, the 3-D model. Any subsequent change must be made to the 3-D model to ensure that all future piece drawings and assembly drawings will be mutually consistent.

This corner spandrel, shown in Fig. 3, was taken from an office building (not included in the case studies). Preparation of the full piece-ticket drawing file using conventional 2-D CAD, including all dimensions and a bill of materials, required more than one week. Modeling the piece and its immediate neighbors, including all connections and reinforcement in the 3-D prototype software, and generating the piece tickets and bill of materials (without annotations and exploded details) required approximately two hours.

It could be argued that top-down building modeling can be done using conventional CAD systems, even in 2-D, with sophisticated and disciplined use of drawing layers and model/paper view separation. However, in most systems, individual pieces are inserted in assemblies as instances of piece production series (piece-marks) (e.g., "blocks" in AutoCAD® or "cells" in Microstation®). Their parameters are set at the time of insertion, and so assembly geometry is driven "bottom-up" from the CAD blocks.

This means that any localized change to one piece in a series requires the user to separate that piece from the series, create a new piece-mark, adjust the changed locations of other dependent elements in the assembly, and produce a new piece-mark drawing. In contrast, none of this effort is necessary in systems in which top-down parametric dependencies are maintained between assemblies, pieces, and components.

The PCSC has specified and tendered for a comprehensive 3-D and knowledge-rich software design tool, which will be integrated with other design, analysis, scheduling, accounting, and production management software.[6] Identified in this specification are the following priorities:

• The 3-D modeling software must support a top-down design process with the three distinct phases of assembly layout, assembly detailing, and piece detailing.

• All assemblies, pieces, and connections must be parametrically related to a building grid and to each other, and changes must be propagated automatically so that integrity is maintained.

• The 3-D computer model must be the only repository and source for all product design information. Drawings, bills of material, and other documents are to be *reports* of the project information, rather than separate repositories of that information.

• Most of the routine layout, analysis, and detailing tasks are to be automated.

These priorities distinguish the proposed system solicited by the PCSC from traditional CAD drafting, as commonly practiced, in terms of the two principles established above.

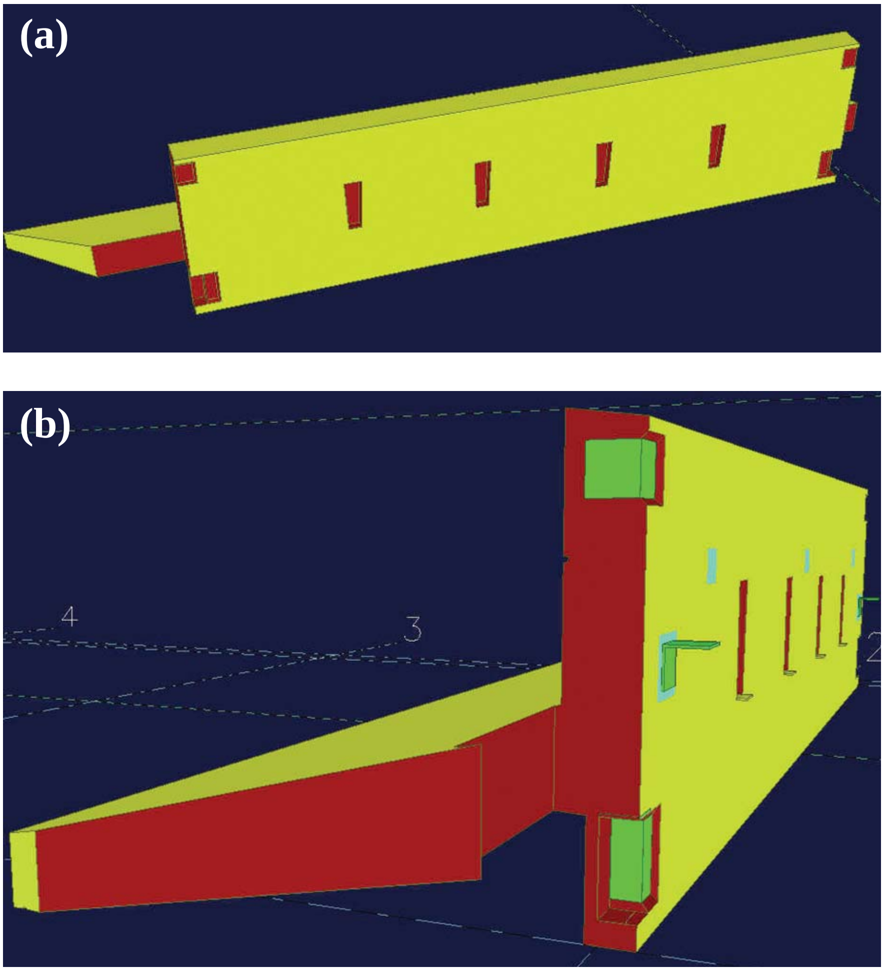

Fig. 3. Spandrel piece model.[7]

COMMON DESIGN AND DRAFTING ERRORS

Seven precast/prestressed concrete projects in this study were examined: four parking decks with structural pieces, one office building with architectural and structural pieces, one indoor arena with precast concrete rakers and walls, and one jail complex with precast concrete boxed cell modules (see Table 1).

The largest project had 3211 precast components, covered an area of 688,000 sq ft (63,915 m^2), and had a contract price of $13.4 million. The smallest project had 259 components, covered 75,000 sq ft (6968 m^2), and had a contract price of $1.2 million. In total, 22 distinct and significant errors were uncovered, each of which affected the project duration and cost. In the most severe case, the estimated cost of a single error amounted to 9.9 percent of the contract price.

These case studies were collected from companies participating in the PCSC, and were selected to reflect the variety of design, drafting, and coordination problems common in their daily work. Even though these companies were helpful in assessing the nature and the effect of the errors encountered, they provide only a rough, empirical indication of how widespread such errors are, or how broad their cumulative financial impact is on the precasting companies, their clients, and the other companies in the construction supply chain.

The identified errors were classified into the following five categories:

1. Errors in design;

2. Errors of inconsistency between assembly drawings and piece production drawings (i.e., shop tickets),

Table 1. Precast concrete project case studies.

Project key (1)	Description (2)	Precast piece type (3)	Floor area (sq ft) (4)	Other data (5)	Number of pieces (6)	Contract value (7)
A	County jail	3D modular cells	688,000	Façade area 140,000 sq ft	3211	$13,400,000
B	Multi-use building	Structural & architectural	220,000		700	$5,000,000
C	Parking structure	Structural	75,000		259	$1,161,000
D	Basketball arena	Structural - stadium		15,000 seats	528	$4,000,000
E	Parking structure	Structural	95,000		332	$1,850,000
F	Parking structure	Structural	460,500	2400 cars	1442	
G	Parking structure	Structural	162,000		815	$1,943,000

Note: 1 sq ft = 0.0929 m^2.

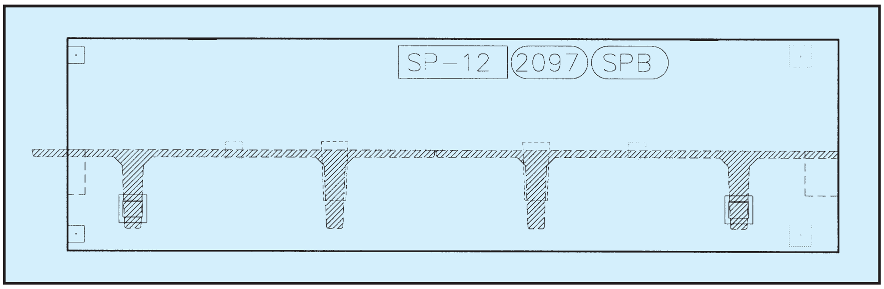

Fig. 4. Two double tees bearing on Spandrel SP-12.

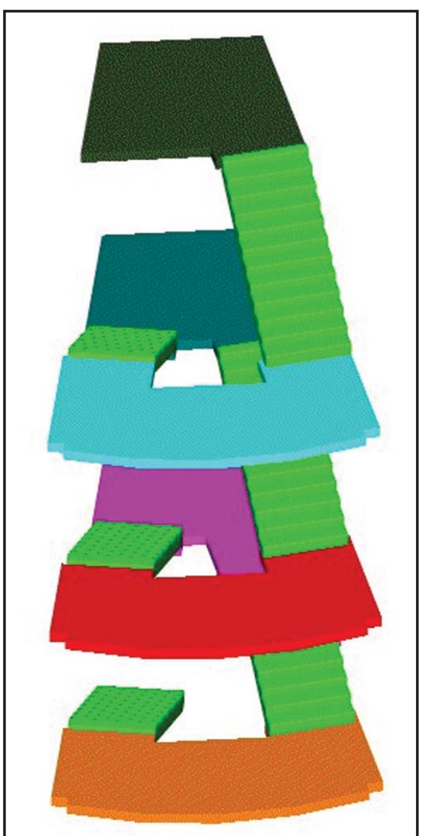

Fig. 5. Precast stairwell.

caused by errors in drafting assembly drawings;

3. Errors of inconsistency between assembly drawings and piece production drawings caused by piece detailing errors;

4. Errors caused by lack of coordination between different building systems; and

5. Errors caused by inadequate management of design and detailing changes.

Other types of errors that can occur on precast projects were not included in this investigation. For example, errors in bills of material (e.g., wrong quantities, wrong items specified, or items missing) are commonly corrected by field personnel, and not reported as errors in design or drafting. The five identified error types are described below, each with an example from a case study.

Design Errors

The design errors in the case study include errors of judgment or detailing in the engineering design decisions that determine a building's assembly details. Errors in structural calculations, or in setting prestress or reinforcement, are not included for the current purpose. Design errors were rare in the cases reported, although their effects can be far-reaching.

Project B provides an example. In this five-story multi-use building, the floors are composed of double tees, which are supported at the edge of the building on spandrels. This precaster commonly designs double tee stems to be supported in pockets in the interior face of the spandrels. The engineer explained that, in this case, problems arose for the following reason:

"The tee was drawn and detailed on the shop drawings as if both stems were to bear in 6 in. [152 mm] deep pockets in the spandrel. Due to the production schedule, the framing and double tees were drawn and checked several months before the spandrels needed to be. However, when the elevations were drawn and the spandrels were checked against the elevations, one stem of the tee was shown held back and bearing on a haunch [see Fig. 4]. Normally, when this error is found before erection, the stem can be cut back and properly reinforced. However, in this case, the stem being discussed was dapped 10 in. [254 mm]. This prohibited the stem from being cut back, because it would be very difficult to properly reinforce the stem after removing the dapped section. We looked at placing this tee in another location in the building and re-pouring a corrected tee in that production slot (of the alternative tee), but to no avail. The tee had to be thrown away and re-poured correctly. A total cost of a 12DT28 with all the materials, labor, and disposal is about $750 per cu yd [$981/m^3]. Therefore, this tee cost us about $8000."

Assembly Drawing Errors

Assembly drawings are the medium that enables design engineers to develop, record, and communicate their concept of the building as a whole. They are usually developed at the start of a project. The main purpose of piece drawings, on the other hand, is to define the individual pieces of a building for production. If disparities between the assembly drawing set and any piece drawing are introduced, it is likely that the resulting piece produced will not function properly in the overall structure.

This was the single most common type of error found in this study. This type of error is common to all construction industry trade sectors in which parts are prefabricated off-site according to custom project specifications; these include structural steel, HVAC, curtain-walls, ironwork, reinforcing bar fabrication, and others.

To illustrate the nature and the potential impact of inconsistencies between assembly and piece production drawings, consider Project G, a typical precast concrete parking structure. The interior ramp spandrels in this building were detailed with the batter length (the distance by which the top and bottom edges of a spandrel must be increased to account for its slope) subtracted instead of added. As a result, 75 spandrels were cast too short, costing the precaster $193,000 (9.9 percent of the contract value).

Another example is provided by the design of a geometrically complex stairwell that was built using separate precast pieces for landings and stair

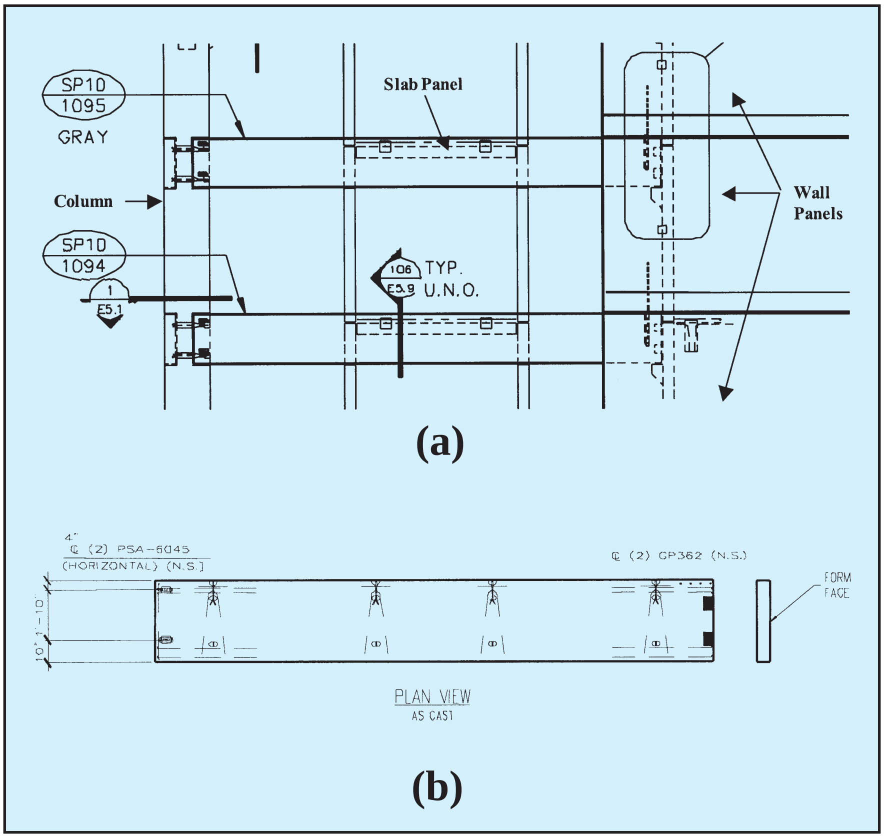

Fig. 6. Spandrels in Project F: (a) Elevation; (b) Piece detail.

sections (see Fig. 5). Frustration with conventional methods led this precaster to pursue an ad-hoc top-down design of the pieces using 3-D solid-modeling software, although with no automation. The engineer noted:

"Each set of stairs connected a series of curved landings in a triangular pattern. Location of doors, railings, and electrical units in relation to the stair

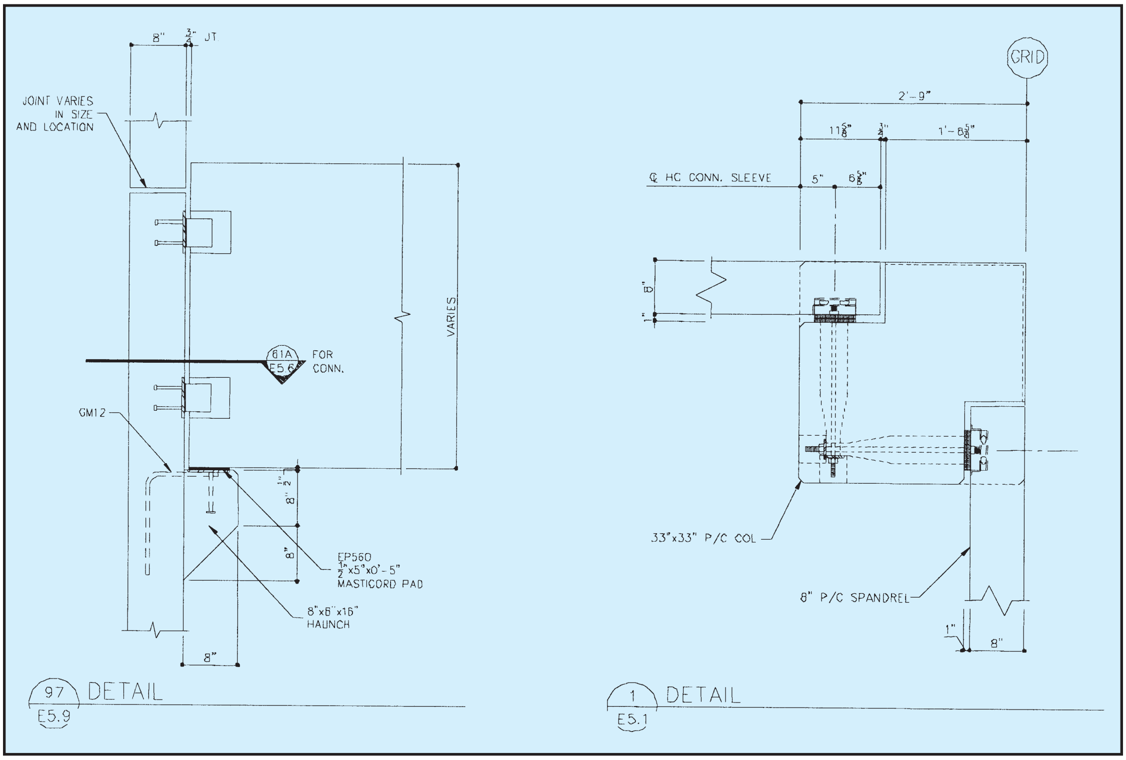

Fig. 7. Spandrel connections to wall and column: as designed.

Fig. 8. Spandrel connections to wall and column: as built.

locations were critical. Calculating locations and dimensions manually devoured much valuable time and created frustration when calculated figures would not agree with the information given. [Applying 3-D modeling] cleared up many misunderstandings and brought everyone into agreement. It also assured us that the landings and the stairs all fit together properly."

Piece Detailing Errors

In current 2-D design practice, the detailed cast-in accessories for each component piece are not shown in assembly drawings. Such details are shown in piece drawings, in which the pieces are designed and drawn for production. Improper coordination between this detail and the overall assembly can introduce inconsistencies between multiple assembly drawings and piece drawings.

A typical example of this type of error occurred in Project F. On the eastern façade of the elevator core, spandrel beams connect the corner column to the wall panels at all eight levels of the structure (see Fig. 6a). The connections to the corner column are designed to consist of threaded bars passed through holes through the width of the columns and screwed into sockets embedded in the spandrel, which sits in a recess in the column on its outer face (see Fig. 7). At their opposite ends, the spandrels are designed to connect to the wall panels with welded plates.

When the first spandrel was hoisted into place, it became clear that the two connection hardware types had each been embedded at the wrong ends of the piece (see Fig. 8). The bolts through the columns could not be anchored, and the welds to the wall plates could not be made because there were no connection plates embedded in the spandrel. The detailing error can be seen in the piece drawing in Fig. 6b. Work on the core was halted for consultations, as it appeared that the spandrels would have to be abandoned and that erection would have to wait for replacement pieces. The elevator shafts were on the critical path of the general contractors' project schedule. It was decided that the slab connections to the spandrels would suffice to hold the spandrels in place until new field connections could be designed, fabricated, and implemented. The event had a negative effect on all three key measures of project success, namely, time, cost, and quality.

Similar detailing errors were reported in Project C:

- "One column was missing all the corbels necessary to support an entire stack of double tee stems. (This is an unusual condition, and even though it was clear in plan view in the layout drawings, the fabrication drawing detailer referenced the building elevations where the support requirement wasn't shown.) We had to bolt on major remedials which shutdown erection for several days."
- "Several ramp columns were detailed too short. This wasn't discovered until after most of the deck had been erected, and necessitated $50,000 [i.e., 4.3 percent of contract value] worth of shoring, jacking, and shimming."

Building System Coordination Errors

This classification includes all conflicts between precast pieces and parts of other building systems. These errors result from insufficient coordination between different system designs. They are common and insidious, and, as with the other error types reported, they are often not discovered until the time of erection.

Project A, a large prison (see Fig. 9), suffered over $500,000 (3.7 percent of contract value) in overruns as a direct result of lack of coordination between the precast concrete cell modules and various cast-in-place, mechanical, plumbing, and architectural systems. The project manager reported:

"One of the biggest problems of all was the coordination of openings for ducts, vents, draws, sprinklers, and other utilities. Usually when an opening was added or changed, it affected many other adjacent modules."

A unique problem in this case was coordination of steel anchors embedded in the exterior walls of each prison cell module for the sliding cell doors. The doors of all the cells along a row are connected together with a mechanism that allows automatic opening of all the doors in an emergency. As design of the mechanism developed, the anchor positions and sizes had to be propagated to each cell module throughout the building. This sequence is complex to monitor because the door mechanisms are designed at the assembly level, but the modular cells are drawn on separate piece-mark drawings.

Errors Resulting from Design Changes

Changes in architectural designs or other building systems require that precast designs be updated to match. The difficulty is exacerbated by the relatively long duration of design detailing in most precast projects; late changes must be coordinated through assembly drawings and a complete set of piece drawings. Nevertheless, owners and architects expect the precaster to respond quickly to changes submitted before physical production of each piece. Inadequate management of those changes often results in significant rework on the site, and, in certain cases, the need to replace incorrect pieces.

In the case of Project D, the indoor arena, precast concrete raker beams and walls were supplied to rest on a cast-in-place substructure. Many electrical and railing embeds were required. An architect's design change, which occurred relatively late in the project, aggravated the task of coordination. Precast erection, scheduled for 16 weeks, was extended by more than one month for correction of railing posts, lighting fixtures, and other embeds and holes, all at the precaster's expense. Fig. 10 shows a situation in which the location of a 6 x 6 in. (152 x 152 mm) hole was changed in a cast-in-place wall, but not updated in the production drawing of the adjacent precast piece. The impact is not only in the cost of rework and schedule delay, but also in the quality of the finished product and damage to the precaster's reputation.

Project A, the prison project provides an additional example: "Holes for the shear pins (in the bottom of the module walls) were field drilled in the cast-in-place slab on grade. Due to changes in the modules used to make up the space, the location of these kept changing daily; some module locations had three sets of holes by the time the module arrived."

Fig. 9. Prison construction using precast modular cell units.

Fig. 10. Misaligned 6 x 6 in. (150 x 150 mm) holes between a precast piece and a cast-in-place wall.

THE POTENTIAL FOR ELIMINATION OF ERRORS

The following features of a knowledge-rich integrated assembly and part 3-D modeling system can contribute to eliminating or reducing errors:

1. The logical relationships between connections and pieces are embedded within the system. This feature combined with the parametric behavior of the assembly and of the pieces means that the spatial integrity of the 3-D model is maintained as changes are made without the need for the user to propagate the changes.

2. The 3-D model is the single source for all the product information; 2-D drawings are generated as reports from the 3-D model information. This single-source concept means that inconsistencies cannot occur. Errors of coordination between assembly drawings and piece drawings are essentially eliminated.

3. Automated detailing, such as placing connection hardware and making all the necessary geometrical adaptations to the connected pieces, removes further opportunities for human error. Even in unique design situations, where automated detailing cannot be applied and the detailing must be done manually, the detailing is done in the context of all other pieces so that the probability of making an error is significantly reduced.

4. Any building system that impacts on the precast pieces can be imported or directly modeled in three dimensions (possibly requiring significant additional 3-D modeling layout work).

Table 2. Probability of elimination of case study errors.

Error	Project	Error Classification	System Feature	Confidence Level
Holes for shear pins drilled three times over	A	Change management	1, 4	Complete
Could not maintain integrity through changes	C	Change management	2	Complete
Holes did not align on different pieces	D	Change management	1, 4	Complete
Architectural changes not dealt with correctly	D	Change management	1,2	High
Sliding door mechanism alignment	A	Systems coordination	2, 4	High
Holes for ducts, draws, vents, sprinklers	A	Systems coordination	4	Medium
Railing and electrical embeds not detailed correctly	D	Systems coordination	4	Medium
Lighting and railing embeds not coordinated	D	Systems coordination	4	Medium
Inverted T detailed too long for CIP support	E	Systems coordination	1, 4	High
3-D design for placement of electrical, doors, railings	F	Systems coordination	1, 4	High/Medium
Designed pocket instead of haunch for double tee at end of spandrel	B	Design error	1, 3	High
Angles on slabs and panels incorrect	A	Drafting error	1, 2	Complete
Ramp columns too short (shored and jacked)	C	Drafting error	1, 2	Complete
Horizontal block-outs for sloped spandrels	E	Drafting error	1, 3	Complete
Incorrect length for batter on sloped spandrels	G	Drafting error	1, 2, 3	Complete
Varying wall thicknesses due to varying modules and triangular building	A	Drafting errors	1, 2	Complete
Column detailed without double tee corbels	C	Piece detailing	5	Complete
No end finish detailed for strands in spandrels	E	Piece detailing	5	Medium
Spandrels with wrong connections (mirrored)	F	Piece detailing	1, 2, 3	Complete
Incorrect thickness for ledger beam bearing pads	F	Piece detailing	1, 3	High
Spandrel and double tee detailed with different connections	B	Piece detailing	1, 2, 3	Complete
Block-outs missing from inverted tee beam supported on CIP concrete	E	Piece detailing; Systems coordination	1, 3, 4, 5	Medium

If these are updated over time to reflect all changes, then any piece drawings produced will correctly show any holes that are required, and any automated detailing procedures can account for the building systems' components. An associated benefit is that the lead time required to produce piece drawings is reduced from months to days, so that changes can be accommodated much later in the process than is currently possible.

5. The 3-D building model provides a platform for automated design checking routines. For example, pieces without adequate connections, spatial conflicts, and other errors can be automatically identified and reported to the user.

Case Study Errors Re-examined

The errors encountered in the case studies were each re-examined in light of the 3-D modeling system as specified by the PCSC. For example, the mirrored spandrel connections in Project F could not have occurred if the shop drawings had been produced automatically from a 3-D model. This is because the stage of transfer from assembly to piece drawings, currently performed by a human operator, is eliminated entirely in the proposed software paradigm (Items 1, 2, and 3). The level of confidence is considered "complete."

Errors related to coordination between building systems, such as in Project A, are dealt with as described in Item 4. However, these can only be considered eliminated with "medium" confidence – that is, human error can still be introduced if the various building systems are not updated in the 3-D model.

Table 2 summarizes this analysis for all the cases. It lists the features of such a system that would apply in each case and provides an assessment of the likelihood that each would be eliminated. Of the 22 errors listed, all are considered eliminated with at least medium confidence, 16 (73 percent) with at least high confidence, and 11 (50 percent) with complete confidence.

CONCLUSIONS

Modeling a building in a computer, rather than drafting multiple representations of it and of its parts in drawings (whether CAD or manual), holds the potential to reduce the occurrence of errors and the need for rework in construction projects. Employing 3-D CAD is necessary, but not sufficient: the building model must be developed in an integrated parametric fashion, must be comprehensive, must cover as much of the project scope as possible, and must drive the production of all drawings and reports, if the benefits are to be fully realized.

The seven case studies of precast concrete construction projects show that errors related to design and drafting occur despite the use of 2-D CAD technology. It seems reasonable to assume that many more errors occurred, which were intercepted and corrected; the case studies do not allow estimation of their frequency or severity. All of the errors reported in these cases resulted in the precast concrete producers losing time and money.

The PCSC has specified, and is currently procuring, 3-D modeling and knowledge-rich software for precast assembly design and detailed engineering. The authors expect that introduction and use of such software will eliminate multiple types of errors that are common today. Additional benefits will accrue from the drastic reduction in time required to produce both assembly and piece drawings.

The PCSC has also begun development of a precast data model, which will enable integration of all of the information technologies throughout the precast construction business process. (For background information on the subject of Building Product Modeling, see Reference 9). This will extend the benefits gained in adopting 3-D computer modeling by allowing immediate communication of engineering changes to scheduling, procurement and other non-engineering activities, further reducing errors, and improving the overall management of changes as they inevitably occur.

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