Proposed Developments in Computer Modeling of Cast-in-place Concrete

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ABSTRACT

Building Information Modeling (BIM) of cast-in-place (CIP) concrete has not kept pace with technologically developments in the representation of structural steel. Current practices allow for vertically integrated structural steel models that transfer data through all phases of a project from conceptual design through construction coordination. Typical data transactions include interfaces that follow the traditional steel supply chain including: conceptual geometry, analysis, member design, determination of member end forces, connection design and detailing, shop drawing production, input to computer numerically controlled (CNC) fabricating equipment, material tracking, and erection simulation. Although a number of stand alone applications address some of these operation for CIP concrete, little if any interoperability exists between these models.

INTRODUCTION

The fossil power and process industries have been using computer models to facilitate the design, construction and maintenance of these projects for more than twenty years. Computer modeling will play a significant role in designing the next generation of commercial nuclear power generating facilities. These models represent more than the geometric arrangements of structures, systems and components. The objects that are modeled are linked to a significant amount of associated information. For example a concrete object such as a turbine pedestal may be linked to material information such as compressive strength or maximum aggregate size, etc. The linking of three dimensional representations of structural objects with associated data is the basis for Building Information Modeling (BIM). The effective use of BIM can add value for owners, designer and regulators over the full life cycle of the facility.

BUILDING INFORMATION MODELING

BIM has been defined as “a model-based technology linked with a database of project information.” BIM can represent almost any aspect of a structure system or component including; geometry, material properties, codes and standard, construction sequences, maintenance operations, etc. BIM allows for the interoperability of multiple software applications such as estimating, scheduling, structural analysis, detailing and manufacturing.

The basic building blocks of BIM are standard naming conventions for component attributes. It is common for different software applications to not use the same characters to identify a specific building component. A classic example of this can be found in the structural steel world where a typical wide flange beam that is sixteen inches deep and weighs forty pound per linear foot may be “named” a W16X40 or W16x40 or WF16X40. All of these names are human readable as the same wide flange beam but would not be the same for a given computer application. The International Alliance for Interoperability (IAI also know as Building Smart) has developed standard naming conventions for a number of building components. These naming conventions are termed Industry Foundation Classes (IFCs) by the IAI.

As an example of an IFC consider a common building component such as a door. IfcDoor is defined by two sets of data; geometry and properties. IFC data is specified using a computer schema known as EXPRESS. A portion of the EXPRESS schema for IfcDoor geometry follows:

```
ENTITY  IfcDoor
        SUBTYPE OF (IfcBuldingElement);
                OPTIONAL  IfcPositiveLengthMeasurement;
                                Overall Length
                OPTIONAL IfcPositiveLengthMeasurement;
                                Overall Height
                        END_ENTITY;
```

Property definitions for IfcDoor include the following attributes:

- Fire Rating
- Acoustic Rating
- Security
- Is External
- Infiltration
- Thermal Transmittance
- Glazing Area Fraction
- Handicap Accessible
- Fire Exit
- Self Closing
- Smoke Stop

The key to successfully implementation of BIM is interoperability. Interoperability relates to both the exchange and management of electronic information, where individuals and systems would be able to identify and access information seamlessly, as well as comprehend and integrate information across multiple systems [1]. Simply stated, interoperability means that a number of software applications are able to read and write from a common database of building information. The wide variety of data addressed by IFCs presents a challenge for the exchange process, which can lead to unique results. Figure 1 shows an unsuccessful attempt at interoperability in which one piece of software interpreted a roofing system incorrectly trees for landscaping.

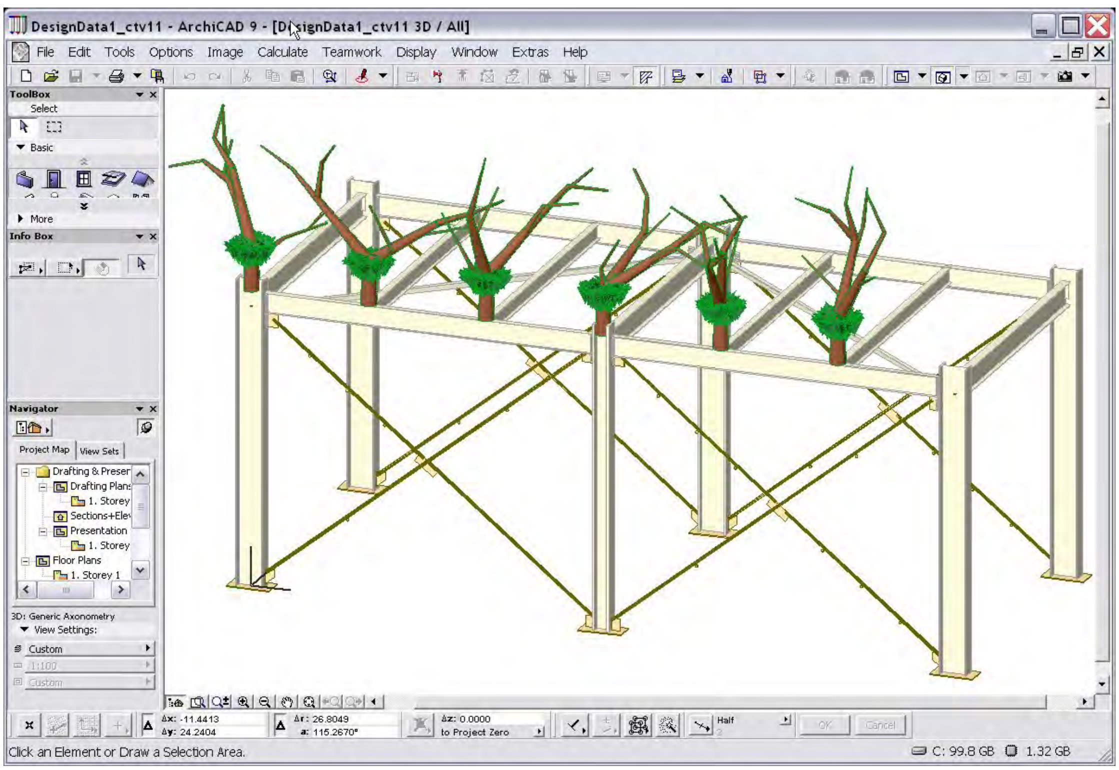

Figure 1 Interoperability Error

Structural steel

One of the most successful BIM applications is structural steel. The steel industry, lead by the American Institute for Steel Construction (AISC), adopted an EXPRESS based data exchange standard a number of years before the general acceptance of the steel IFC. The American Institute of Steel Construction (AISC) recognized the potential benefits of controlling structural data in a 3D model in the late 1990's. By promoting the use of the CIM Steel Integration Standard Version 2 (CIS/2) [2] as a worldwide electronic data exchange protocol for structural steel, the AISC provided important leadership in defining the technology necessary for multiple software applications to work together. The selection of a single data exchange protocol coupled with a long history of use of electronic data has led to a structural steel industry that is technically equipped to realize significant cost and schedule benefits for the use of 3D model data [3].

The relationship between CIS/2 and the steel IFC is a working example of how extremely detailed information for a specific building component can interact with higher level data intended to interact with other components. For example CIS/2 will allow a software application to define all aspects of a structural bolt including thread making processes like cutting, forging or rolling. This data is important to the bolt supplier so that they may comply with the technical requirements for manufacturing the fastener, but has virtually no value when considering how the bolt will fit into the overall building model. Data require for the global model includes information such as diameter, length, material grade and surface finish. This information is necessary for interaction with other structural components like checking installation clearances from an adjacent concrete wall, or that the surface finish matches the finish of the beam in which it is inserted. The higher level data, diameter, length etc will be common to both the IFC and CIS/2 schemas. When multiple data exchange standards share a protocol for common data they are said to be "harmonized." CIS/2 and the steel IFC are an example of harmonized standards.

In addition to the higher level data such a size, length, weight, material grade, etc, it is common for structural steel models to contain a significant amount of more detail information for each beam, brace and column, such as:

- Pay category
- Shipping information (truck, rail, boat)
- Design status (preliminary, final etc)
- Date of latest revision
- Delivery status (at shop, on site, etc)
- Erection sequence
- Advance bill of material number
- Controlling load combination
- Member end forces for connection design
- Fabricator information (name, location, etc)

Figure 2 shows the typical level of detail found in a structural steel model. The graphical information shown in this figure is reflective of typical IFC information that when taken together with CIS/2 supported data provides a wealth of building information.

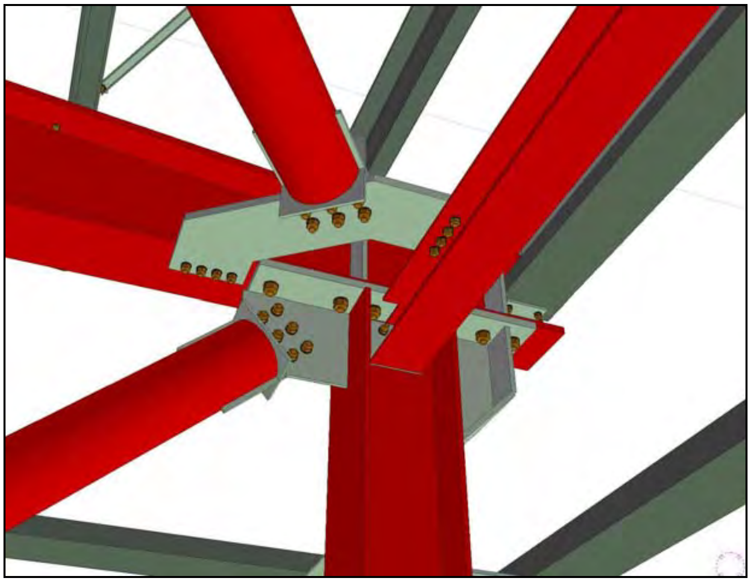

Figure 2 Typical Detail of a Structural Steel Model

CONCRETE BIM

Successful implementation of BIM for a cast-in-place concrete structure faces a number of challenges that are not encountered for a conventional steel structure [4]. These challenges can be characterized by three basic differences between these two materials of construction:

- Steel components have fixed (generally linear) geometries, cast-in-place concrete structures may take virtually any form
- Steel connections are easily recognized and have standard forms, concrete connections are relatively free form

- Steel is produced in a controlled environment long before it is placed into a structure, concrete is manufactured (often on the jobsite) just prior to placing in the structure

Each of these differences and their potential impact on implementation of BIM are discussed.

Geometry

The geometric definition for cast-in-place concrete structures can be considerably more complex and data intensive than for structural steel or even pre-cast concrete structures using primarily linear components. The BIM for cast-in-place concrete could include geometry definitions for the following:

- Outline - Overall spatial definition of exterior concrete surfaces
- Reinforcement – size and placement of reinforcement including splices tendon sheaths, mechanical couplers and other reinforcing features
- Special features – attachments and embeds, component curvature under pre/post-tension loadings, piles and tension connectors
- Analytical – analytical member geometry, node locations, and boundary constraints
- Installation – definition of planned placement boundaries, pour stops (placement interruptions caused by weather or material conditions), tolerances, as built changes from design
- Implied – features such as concrete formwork which is controlled both by Outline geometry and Installation geometry

The geometric definitions become inter-related as well as being controlled by relationships to other, non-geometric model data, in a parametric modeling environment. As example, the layout of reinforcement would be expected to follow code placement requirements (rules), which must ultimately fall within the outline geometry constraints of the component. Similarly, the placement of certain reinforcement splices would logically be linked to the construction placement plan. Reinforcing bar placement geometry would be linked to the aggregate size thus ensuring proper placement of concrete in congested areas. Each inter-relationship adds to the model complexity and data volume.

Nevertheless, one of the key strengths of cast-in-place concrete is the flexibility it affords the designer to customize components within the structure to fit functional or aesthetic requirements. Basically any structural component: beam; column; walls; floor or other, can be defined by a combination of multiple regular and irregular overlapping shapes and volumes. This freedom and flexibility accounts for a lack of standard libraries for component definitions as found in CAD modeling application for steel and pre-cast concrete. Concrete components may be placed, using a basic set of logical members (columns, beams, floors, etc.) wherein they have overlapping volumes. As example, a wall that is bounded by columns, in which the outside face of the columns and the wall are aligned, may be modeled by overlapping volumes between the wall and the columns. Most 3D solid modeling applications can resolve these types of overlaps using various Boolean operations. Thus, with the complexity of the shapes that can be defined in cast-in-place concrete, and the continuity of components in concrete structures (where components are joined to one another) makes the delineation between components conceptual and not clearly physical.

Multiple model representations are required for reinforced concrete structures: 1) physical model: represents the actual dimensional outline and profiles of components. In the physical model, overlapping volumes are not resolved allowing the application of reinforcement detailing in the overlapped volumes. 2) functional model: similar to the physical model other that overlapping volumes are resolved by functional need. The physical model serves as the parent of all other model and drawing representations, each model and related data will service a variety of tasks:

- Reinforcement Details: Use of the physical model with overlapping volumes to allow the proper placement of reinforcement. Reinforcement commonly overlaps and extends from one component into another for continuity.
- Material Quantities: Use of the functional model would assure no duplication of concrete volumes. Use of the physical model would consider reinforcement extending beyond the extents of the logical components. For example, floor slab reinforcing passing through a simultaneously cast beam would need to consider the continuity of the bars through the beam.
- Structural analysis: Use of the functional model containing discreet boundary definitions for individual beams, columns and slabs.
- Drawing representation: Drawings should not represent overlapping volumes or separate adjacent elements, rather, the concrete should be represented as a single cast unit.

Connection

Connections in linear component building models are easily definable as they are located directly at the interface between two such components, this concept holds true whether viewed from the engineer, the detailer or the constructor. With the continuity of components in cast-in-place concrete structures, the boundaries between components and thus the connections become somewhat less precise and definitions vary by perspective. As an example in the beam - column – slab configuration (Figure 3), three professionals would likely not consider the reinforcement connections the same. The contractor might place the column up to the bottom face of the beam leaving column reinforcement exposed. He would then likely place the beam and slab together with the thus having no distinction between the function or component specific reinforcement. The engineer and detailer would likely view these as three separate elements with the detailer paying close attention to the placement of connecting reinforcement placement into the first of the two concrete placements.

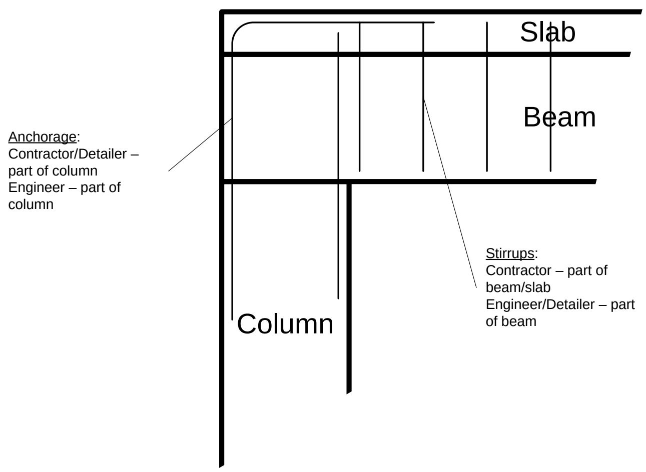

Figure 3 Column-beam-slab Connection

Another example would be a large foundation slab, which the contractor needs to place in separate sections. The engineer would have analyzed the slab as a single element having no connecting elements. Clearly the contractor and detailer need to consider reinforcement details and connecting splices at the planned placement limits so to allow for a continuous behavior of the segmented slab. It is thus imperative that the reinforcement be controlled by the installation work flow geometry to ensure proper association with construction placement drawings and reports.

Concrete connections unlike steel do not always occur at the ends of members. The classic example is a lap splice. The location of this type of connection is not always determined by the design engineer but can be a function of the length of reinforcing steel available to the contractor. Since lap splices can take up lots of volume a robust method of modeling this connection is needed.

A vital aspect of a BIM for cast-in-place concrete structures is a robust ability to perform clash detection in the reinforcement congested areas for component connections. Congestion of reinforcing steel is a major consideration in construction planning. It can affect not only the placement sequence for the steel but can also influence the concrete mix design. Congested areas often require a mix that uses smaller aggregate than the balance of the project. Clash density, the number of clashes per unit volume of concrete is one way to define the level of congestions in a model. Clash detection needs to consider that reinforcement internal to the concrete element is not a clash, though conditions when the reinforcement penetrates the surface may be. Clash detection should consider both soft and hard clashes.

A soft clash is when two items do not necessarily occupy the same volume. An example of a soft clash would occur when the tolerance of placing items is considered. The face of a concrete element is modeled at its intended location. The actual in-place location includes the tolerance on the form work ± ½ inch or more. There are similar tolerances on placement of reinforcing steel. When modeling these two components it is desirable to have a "cloud" around the object that accounts for the tolerance of placement. If the tolerance clouds from two objects intersect a "soft clash" should be detected.

A hard clash is when two objects occupy the same volume. There are varying degrees to hard clashes. A lap splice theoretically is a hard clash i.e. the edges of both bars are occupying the same space. A more traditional hard clash would occur when the headed studs on the back of an embedded plate attempt to pass through reinforcing steel behind the plate. Clashes should also consider building information that is not necessarily modeled as an object such as aggregate size.

Material

Cast-in-place concrete construction will require the definition and recording of significant amounts of material related data. Some of this data is continuously updated depending on production variables and weather conditions. Concrete material definition in the modeling process can be accomplished through direct specification of required material properties such as design strength, water/cement ratio and cement type. Alternately concrete materials can be defined by mix designs specifically prepared for the site and supplier conditions. Mix criteria would be based upon cement type, aggregate sizes and type, water content, slump limitations, and add mixtures. Additional mix design features could include special mixes designed to meet desired density, heavy or light. Mix designs would serve design requirements for concrete strength, service conditions, exposure, placement method and compaction. After placement, additional data for curing process and the monitoring of concrete maturity via cylinder strength measurements. Construction related parameters are not based upon only the component constructed but also by subsets of placement size and individual concrete delivery.

Building information modeling provides a tool that can facilitate the quality control process that is so vital to successful cast-in-place concrete construction. An object that defines a pour volume can be given attributes that will help to track in place material quality. Possible attributes that could be tied to a pour volume might include:

- Cylinder strength
- Slump
- Humidity at time of pour
- Wind speed at time of pour
- Mix designation
- Name of testing lab
- Air content
- Air temperature at time of pour
- Placement method (pump, bucket, etc)
- Batch ticket information

For the structural analysis of concrete components parameters such as modulus of elasticity, poisons ratio, shrinkage and creep properties are also needed. Similarly for reinforcing materials, design properties of tensile strength, grade, deformation patterns and coating materials all play a role in the design, analysis and specification of BIM for cast-in-place concrete structures.

CONCLUSION

Building information models of cast-in-place concrete structures with complexity similar to that shown in Figure 4 are becoming commonplace. The potential benefit to using this technology for designing nuclear power facilities is vast. It is expected that all aspects of the project including; design, procurement, fabrication, construction, quality control and facility management, will benefit from BIM

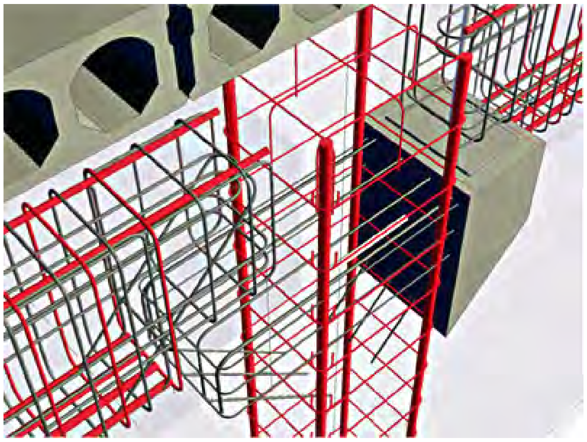

Figure 4 Typical Detail of a Cast-in-place Concrete Model

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