Interoperability Between Analysis and Detailing Software for Cast-in-place Concrete

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1 ABSTRACT

Software interoperability allows data to be exchanged among various applications. Exchanging data that is common to multiple applications, rather than inputting the same data several times provides significant efficiency in the design process. Sharing common data not only minimizes the design effort but it virtually eliminates transcription errors associated with the shared data set. The sharing of data also facilitates design evolution by allowing multiple potential solutions to be evaluated rapidly, as well as ensuring a more holistic design, specifically between the processes of structural analysis, structural design and construction.

In the design of reinforced concrete structures, such as those in a nuclear power plant, a significant amount of data can be shared between the analysis software and software used to detail the reinforcing steel. Specific data that is common to both applications are neat line dimension of the concrete and required reinforcing ratios to resist both shear and tension. This paper discusses the concept of interoperability between analysis and detailing software by identifying potential opportunities for sharing of common data.

The current state of software interoperability is presented. Applications for potential interchange of data are discussed. Conclusions related to challenges and rewards associated with developing fully functioning interoperability between analyses and detailing software for reinforced concrete are provided.

2 INTRODUCTION

2.1 Definition of 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]. In the context of this paper interoperability is the ability of software used to analyze and design cast-in-place reinforced concrete to exchange data with software used to detail the concrete elements.

Typically finite element analysis is performed for the structure which results in element or nodal forces and moments as well as nodal displacements. Results of the finite element analysis are then post processed to obtain design forces and moments on critical sections of the structure. These design forces and moments are then further processed using appropriate building code requirements to determine the required area of reinforcing steel and to ensure that concrete stresses are acceptable.

For the purpose of this paper “detailing” of concrete includes preparing complete three dimensional models of the final structure from which a variety of reports can be extracted. Reports may be graphical representations of the structure such as conventional neat-line and reinforcing bar placement drawing, or isometric drawings of unique or complicated reinforcing arrangements. Other forms of reports include; reinforcing bar bending schedules, quantity take offs for both reinforcing steel and concrete, programs of
construction activities, shuttering and shoring information, etc. Detailing may include the use of multiple software tools; one to develop the physical arrangement of the reinforcing steel, embedded plates, etc, one to extract computer numerical control data to drive bar bending and shearing equipment, one to manage material by automatic preparation of bar bundle and tag information.

2.2 Applications in Nuclear Power Plants

Nuclear power plant structures are dominated by cast-in-place concrete construction. Due to the wide variety of loads and load combinations that must be evaluated, detailed analytical models are common. The complex physical arrangement of mechanical, piping and electrical components and systems is typically managed using a three dimensional electronic plant model. The combination of cast-in-place concrete construction with the availability of both precise analytical and physical models of these structures provides the nuclear power plant design team an ideal opportunity to capitalize on existing interoperability between software tools. Equally as important is the potential to expand the ability of the various software applications to interoperate with each other. Developing building information models for cast-in-place concrete structures presents a number of challenges to the engineering and software design community [2].

There are a number of benefits that the project team may receive from truly interoperable analytical and detailing software. Some of these benefits include:

- Sharing concrete neat-line dimensions thus eliminating re-entering data multiple times
- Coupling construction consideration with design decisions such as the preferred location of pour breaks and lap splices, areas for shored construction or re-shoring
- A seamless interface between analysis and quantities take-off for both reinforcing steel and concrete
- An interface with sub-suppliers software such as that used for shuttering and formwork design
- Integrating reinforcing steel analysis and design with the purchasing and fabrication process which will facilitate rapid decision-making based on engineering and economic criteria

Currently there are very limited opportunities for analysis and detailing software to interact. These opportunities are discussed below and the potential for improvements addressed.

3 PROBLEM STATEMENT

3.1 Current Analysis Tools

Finite element modelling and analysis techniques used for concrete structures can vary widely. Both element type and material properties can change depending on; the knowledge and experience of the engineer, the features and options available in the software, the complexity of the structure, and whether the loads are static or dynamic, to mention a few of the potential variables that can affect the analysis.

Selection of material properties is a function of the level of concrete cracking intended to be modelled. One technique for modelling cracking is to introduce a reduced modulus of elasticity into the finite element model.

Cast-in-place concrete structures typically found in nuclear power plants can be successfully modelled using a wide range of types of finite elements including, beam or truss, plates or shell, tetrahedrons and brick elements. In addition to the variety of elements types that may be used the precision of the element mesh is another parameter that is highly variable.

Figure 1 illustrates a number of possible finite element models that could be successfully used to model a portion of a cast-in-place concrete structure. Figure 1a shows the concrete neat-line of structure. Figure 1b shows a model of the structure using plate elements. Notice that the plate elements are modelled at the centre-line of the concrete floor and walls. Figure 1c shows the structure modelled using brick elements in which each brick models the actual thickness of the concrete element. Figure 1d shows a more refined brick element model that uses multiple elements through the thickness of the floor and walls. Figure 1e show a more refined brick element model that has a greater mesh density in the vicinity of the wall to floor junction. Finally Figure 1f shows a mesh of tetrahedron elements that was automatically generated by the analysis software based on the surfaces that form the outline of the structure (concrete neat-line).
Variations in FEM Modelling of Concrete Structures

Each of these models could be successfully used to analyse this structure, each presents a different set of results that can be subsequently used to design the reinforcing steel and check the concrete stresses, and each presents its own special set of geometric and material data that could be shared with software used for concrete detailing.

Depending on the element type and mesh density used a number of different options are available for post-processing the results of the analysis. When plate elements are used (Figure 1b) forces and moments calculated at the nodes or element centroid may be used directly in determining concrete stresses and reinforcing steel sizes. A significant challenge facing the designer is where to make these determinations, should this be done for every element, should the results from a number of adjacent elements be averaged before checking stresses, should only certain portions of the structure such as those at critically stressed areas be considered? These questions become more complex when brick or tetrahedral elements are used, especially in models that use a very fine mesh such as that shown in Figure 1f.

Solid elements such as brick and tetrahedrons only calculated forces at nodal locations. Thus an additional step of post-processing is required to determine bending moments within a concrete structure. Post-processing can be done either as a module within the analysis software or buy using an additional process such as a spreadsheet.

3.2 Current Cast-in-place Concrete Modelling Tools

Current cast-in-place modelling tools range from simple 3D graphical object modelling, to a 3D parametric solids object-oriented visual database. Such tools have been used for conducting visual clash detection with other structural elements and with non-structural objects such as pipes and equipment, as well as to generate deliverables such as bill of materials and production drawings. The use of 3D modelling to truly simulate the design and construction of cast-in-place concrete structures brings forth unique challenges because the “physical” 3D model can serve multiple functions that go beyond its use for construction:

- Physical-to-analytical neat line geometry – Finite elements generated from the physical model neat line geometry may have distinctly different or approximate geometries compared to that of their parent physical objects. (see Fig 2a).
• Reinforcement detailing – The way concrete volumes are modeled can affect how the concrete reinforcement will associate with it, both in terms of structural design and constructability (See Fig 2b).
• Concrete quantity takeoffs – Quantity takeoffs can be categorized based on parameters not explicitly defined as physical objects in the model such as pour breaks (See Fig 2c).

![Figure 2a.](image1)
![Figure 2b.](image2)
![Figure 2c.](image3)

Figure 2. Functional Variations in Physical Modelling (Analytical – Detailing – Site Fabrication)

In addition to these varying functions of the physical model, there is a need for the modelling software to precisely represent higher-order curves and complex geometries found in nuclear projects. Different modelling software use different methods to model parametric solids. Extrusion-based vs. solids-based modelling methods are two examples. Differences in these modelling methodologies can affect how the software and professionals using it approach the creation of the physical model and the functional variations discussed above. Furthermore, the compatibility of such models with different functions like structural analysis must be considered when interoperating the different software.

3.3 Current Reinforcing Steel Modelling Tools

Most current concrete reinforcement modelling tools are 2D drafting applications utilized for detailing reinforcing steel. Many are integrated with fabrication technologies through the computer numerical control of machinery in the fabrication shop. The few 3D modelling programs that do exist have been utilized for generating reinforcing steel quantity takeoffs, constructability analysis to anticipate fit-up issues in the field, and in some cases for detailing. However, limited interoperability exists between the modelling software and structural analysis or fabrication software. Such interoperability will bring new challenges similar to cast-in-place neat line modelling because reinforcement modelling has to meet different functional requirements. Some examples include:

• Quantity takeoffs – Reinforcing steel quantities based on both pre-fabricated and post-installed cut lengths may be required, or specific cost codes per structural system type may be required.
• Design intent – Per the engineer’s structural design, cross-sectional area requirements for tensile and shear reinforcement varying across a member cross section and its length. These parameters may or may not correlate with the physical aspects of the reinforcement.
• Detailing – Requirements such as bending radii, hook lengths and lap lengths, as well as cage assemblies define unique parameters to the reinforcement itself
• Pour breaks - Requirements to define reinforcement within pour breaks and the splice laps at intersecting boundaries is needed (Fig 2b).

These different functional requirements highlight a need for multi-dimensional physical relationships between concrete volumes, their associate reinforcement and other construction parameters like formwork and pour breaks.

3.4 Current Production Management Tools

Product management tools in the reinforcement industry can be classified into bar bending and shearing tools and material tracking, estimating and accounting tools. Bar bending schedules include detailed quantity take-offs which are essential for reinforcement production and construction. Their format may vary based on detailing software but generally they show standard shape code, quantity, length, size, weight, in addition to
all the dimensions which are required for shearing and bend. Traditionally bar bending schedules were made in spread-sheets by counting all the rebar in the 2D shop drawing and categorizing based on their shape and length by the detailer. Currently most 2D CAD systems for detailing reinforced concrete can produce bar bending schedule based on attributes which the detailer defines when shop drawing are being prepared. Note that many 3D modelling software packages can produce bar bending schedules directly from 3D reinforced concrete model in most required format.

Rebar production is the next step after bar bending schedules. In the past, small projects would specify reinforcement that was cut and bent on site. Currently it is more common to have reinforcement cut and bent in rebar fabrication facilities and sent to the site for installing. There are a few software solutions which can read all the reinforcement data from 2D CAD or 3D reinforcement modelling software in particular numerical file formats like BVBS or SDI. These software packages will minimize material waste by nesting the reinforcement based on maximum stock length and print individual tags for each rebar mark. (See Fig. 3).

![Image](image.png)

Figure 3. Reinforcing Steel Bundle Tags

4 OPPORTUNITIES FOR INTEROPERATION

4.1 Current Work Flow Between Modelling and Analysis of Concrete Structures

The flow of data between the model of a solid object, such as a concrete structure, and finite element analysis package is well established. During the 1970’s the process for transferring data for solid objects was developed primarily by mechanical engineers for machine parts. This process went by the acronym CAD/CAM which was a short hand way to describe the interface between Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM).

In the late 1970 a group of manufacturing companies with the assistance of the United States National Institute for Standards and Technology (NIST) developed a protocol for exchanging geometric data. In 1980 the Initial Graphics Exchange Specification (IGES) was first published. IGES became the standard for this data exchange and was actively supported until 1996 [3]. Numerous computer modelling and finite element analysis programs still support the IGES standard. In 1994 the “Standard for the Exchange of Product model data” (STEP) was introduced. STEP was originally recognized as standard ISO 10303, which is now embodied in Application Protocol AP 203.

At the same time that the IGES standard was being developed, a specialty programs were being written to facilitate the exchange of data between the analysis of solids and their graphical model was written. The best known program for parametric translation of solid objects is PATRAN. First issued in 1979, PATRAN allowed for exchanging geometric data for solids with a number of finite element programs, including ANSYS, ABAQUS, ADINA and NASTRAN [4]. Recent advances in transfer of geometric data include software used for rapid prototyping such as Solid Edge, Pro/Engineer and SolidWorks. All of these tools,
although develop primarily for designing and fabricating machine parts, are well suited for application to cast-in-place concrete modelling and analysis.

Building Information Modelling (BIM) in its current form relies on Industry Foundation Classes (IFC) to transfer data between applications. Unfortunately there is no IFC that embodies all of the objects found in cast-in-place concrete. Instead there are fragmented components such as an IFC for reinforcing steel and an IFC for concrete finish.

4.2 Current Work Flow Between Modelling and Reinforcing Steel Production

The current workflow between modelling tools and reinforcing steel production tools is similar to that utilized in the structural steel industry. Modelling applications can be thought of as visual databases of information that can be used to extract the structural data in various forms, including bar bend reports to reinforcing layout drawings. This information can be exported to the production tools where it can be utilized for ordering, fabrication, shipping, and installation of reinforcement steel. The workflow is typically one directional, in that it flows from the modelling tool to the production tool. Some modelling tools have their own reinforcing steel detailing capabilities to produce shop drawings. In this case, the drawing information such as bar bend types can be exported to other reinforcing steel production tools that would read in this data for procurement purposes only.

The current limitations to interoperate between modelling and production tools vary. For example, some modelling tools have strong interoperability with leading reinforcing steel production tools, but their modelling capabilities are limited to only a few structural system types. Furthermore, modelling tools that are strong in generating the 3D detailed reinforcement may only be beginning its interoperability with leading production and fabrication tools. Because some of the existing reinforcing steel production tools have mature drawing production interfaces, more immediate workflows that combine modelling and production may try to utilize those existing capabilities. Therefore, the current challenges would lie in how data rich and how dynamic the information is when it enters the drawing production tools.

5 FUTURE APPLICATION OF INTEROPERABILITY

5.1 Transfer of Neat Line Concrete Data

For many nuclear projects, the layout of the concrete structure (i.e., wall locations, floor locations, penetrations, etc) will be determined based on functional requirements of the facility. The inter-discipline coordination during the early stages of the project will drive and control the concrete boundaries within the modelling tools. This geometry may be transferrable, earlier in the design stages of the project, to begin the analysis process, even before reinforcement details are known. Therefore, it appears to be more of value to transfer the geometric properties from the modelling tool to the structural analysis tool initially. Changes made to volumes such as wall or floor thicknesses could be updated back into the modelling tool.

Because of the specialized and complex concrete layout in nuclear projects, formwork design, fabrication and logistics becomes an important concern. Thus transferring concrete layout coordinates from the physical modelling tool to formwork design software will result in more accurate concrete placement. Bringing back in the detailed formwork design into the modelling tool for purposes of coordination with other disciplines and to actually visualize the logistics of shipping, installing and breaking down the formwork within a project and between projects would be beneficial.

5.2 Transfer of Reinforcing Steel Data

There are several benefits to integrating reinforcing steel data between the modelling tool and the structural analysis and design tools. Because the level of reinforcing complexity requires a constructible and well-coordinate design, the decision-making in designing the reinforcement may not be solely within the analysis interface. For example, frequent changes to mechanical penetrations and embedment locations will change the reinforcement layouts. Making engineered decisions aided by the construction model is possible. However, the construction model is not directly being used for analysis which is critical to supporting engineering decisions.
A possible solution is that the design intent envelopes from structural analysis be shared back into the modelling tool to be able to assess if the changes made in the model are in compliance with the engineer’s structural design. The design intent could be as simple as visual representations of required tensile and shear reinforcement in various regions of the 3D model (see Fig 4). The level of discretization of these required reinforcement ranges would be dependent upon the method of analysis used by the engineer and the level of detail put into the determination of reinforcement bar spacing, size and development lengths. A key factor affecting the success of this approach is defining common data sets between the modelling and analysis tools that define specific reinforcement traits. For example, the required area of longitudinal reinforcement steel for the top layer of bars in concrete beams would have a unique data set of information that could be shared between software.

![Figure 4. Using the Analysis Results within 3D Model](image)

With regard to future interoperability between modelling tools and reinforcement production and fabrication tools, opportunities exist to eliminate the redundant information in both sets of tools. Numerical file formats like BVBS (BundesVereinigung der BauSoftwarehäuser) can make a fast data exchange between 3D modelling tools for cast-in-place concrete structures and reinforcement production machinery without manual intervention. A possible workflow is where the details of reinforcement such as splice, standard hook, bending radius, etc. are modelled in 3D modelling tool, all the reinforcement data will be transferred to shear and bend machinery.

6 CONCLUSIONS

Interaction between software used in all phases of the cast-in-place concrete supply chain, from design through construction, will provide greater economy to nuclear power plant projects than the current methods being employed. The greatest potential for immediately realizing these savings is by exchanging concrete neat-line data. The data exchange will allow for sharing geometry between analysis and detailing software, providing input to shuttering and form-work applications, and facilitating quantity take-offs. An equally important data exchange is for reinforcing steel. This data currently flows from detailing to the fabrication shop floor. Near term opportunities exist for transferring this information from 3D modelling software to detailing and machine control applications. The most challenging data exchange is that between analysis and design software and 3D modelling tools. Meeting this challenge is a critical step in achieving true interoperability within the cast-in-place concrete work process.

REFERENCES