MODULARIZED CONSTRUCTION, STRUCTURAL DESIGN AND ANALYSIS OF CANDU 3 PLANT

J. K. Biswas, S. Wollin, S. Selvadurai and A. M. Saudy

AECL CANDU, Civil Engineering Branch, Saskatoon, Saskatchewan, Canada S7K 2C3
Tel.: (306) 665-4800 Fax: (306) 975-6159

SUMMARY

Part I (Modularized Construction)

The design of the CANDU 3 Nuclear Power Plant is being developed by AECL CANDU's Saskatchewan office. CANDU 3 is rated at 450 MW of net electrical power and is a smaller and advanced version of the successfully operating CANDU plants in Canada and abroad. The design of the CANDU 3 nuclear power plant uses modularization to minimize the construction schedule and thereby reduce the plant cost. Major portions of the plant will be built in a shop and take the form of equipment modules. There are many advantages of modularized construction over conventional in-situ construction. Modularization has been used on other major construction projects in petrochemical and off-shore oil platform industries for many years.

Design of a modularized CANDU plant requires special considerations from the very beginning. During the conceptual design work, modularization influences the layout and structural arrangement of the plant. Moreover the sequencing of various design activities are to be done differently. Since the module fabrication has to start well ahead of site activities, engineering work in all disciplines must also be done quite early. Modularization therefore affects the planning of various design activities of the plant.

In the CANDU 3 reactor building, a large portion of the internal structure is built using several modules. These modules consist of structural steel frame-work complete with equipment, piping and electrical components. After fabrication, these modules are transported to the construction site and lifted in place. Lifting and installation of such modules requires very heavy lift (VHL) cranes. A number of VHL cranes are available throughout the world and can be leased during construction. Modules and equipment are installed through the open top of the reactor building. Because the modules are fabricated in a shop, the work on the modules is not dependent on completion of the internal structure. As a result, a higher degree of latitude exists in planning the construction activities with less constraints due to activities falling in the critical path.

Modules can either be built in off-site fabrication shops or in module fabrication facilities located at the site area. One advantage of shop built modules is the improved access to the modules from all sides which makes it much easier to install equipment. Fabrication of modules in a shop environment enhances productivity and improves quality control due to the availability of a controlled work environment in a shop compared to the construction site. In a fabrication shop, generally well trained and experienced work personnel are available and better quality control measures can be implemented. Shop fabrication of modules also provides flexibility of dividing the work between a number of shops in different locations. In this way many modules can be fabricated at the same time which reduces the total overall fabrication time considerably.

Another advantage of modular construction is the reduction of the work force at the construction site. Construction of a CANDU plant in the conventional way requires a large on-site work force. Construction contractors of many different trades work in the site at the same time and compete for space which can cause congestion in construction areas and create interferences and delays. Housing and other facilities are also needed for the large number of construction personnel. When using modularization, parts of the work will be done in the shop away from the site thus reducing the number of people needed at the site in a given time. The reduction of site facilities thus results in a reduction in construction costs.

This part of the paper describes the concept of modularization, its advantages and elaborates on various considerations that are required during the design of the CANDU 3 nuclear power plant.

Part II (Design and Analysis)

A CANDU Nuclear Power Plant consists of a number of buildings and structures. These buildings provide enclosures and house the reactor, equipment, piping, electrical cables and other components. These buildings provide protection of the plant against environmental hazards such as rain, tornado and earthquake. Consequently, the structural members are designed against loads due to normal operating conditions and abnormal/environmental conditions. An analysis of the structure is performed prior to its design in order to determine the distribution of forces in an individual structural component. The present paper gives an overview of different types of analyses of civil structures that are commonly undertaken for the design of CANDU nuclear power plants.

Depending on the complexity of the structure, the analyses can be done by manual calculations or by the use of the finite element method. For manual calculations, closed-form solutions available in texts of engineering mechanics and strength of materials are used. Manual calculations can give satisfactory results for relatively simple structures. For complicated structures, a finite element discrete idealization is used. The structure is discretized (meshed) into finite elements that are connected at their nodes. The physical structure is thus represented by a set of equations. The solution of the set of equations is obtained with the use of commercially developed computer programs. Computer programs such as ANSYS and STARDYNE are commonly used. Along with these finite element computer programs, pre-processors are used to simplify building a model of the structure. Post-processors extract solution data and simplify handling of output information. Loads due to normal operating conditions such as the dead load, the live load, the equipment load, the thermal load and the effects of creep and shrinkage are considered in the analysis. Loads due to abnormal/environmental conditions such as the seismic load, the pressure load and other loads resulting from a loss of cooling accident (LOCA) are also considered. The methodologies, modelling and loading considerations for analyses of CANDU structures follow the requirements of Canadian Standards CSA-N287.3 and CSA-N289.3.

The reactor building consists of the containment structure, the internal concrete structure, the internal steel structure, and the base slab. Analyses are performed for these structures generally using the finite element method. The containment structure is a reinforced concrete cylinder covered with a dome and supported on the base slab. The containment structure is idealized as an axi-symmetric finite element model and also as a three-dimensional finite element model. The axi-symmetric model is a planar (two-dimensional) model that employs the symmetry inherited in the containment. The three-dimensional model is also used in order to account for the containment structure openings for the equipment hatch and airlocks. A separate finite element model is developed for the analysis of the internal concrete structure. The internal steel structure consists of steel modules. The steel modules are fabricated off-site and transported to the site and erected inside the containment structure. The design of the steel modules together with the composite walls are assessed with the use of appropriate finite element models.

For the reactor auxiliary building, the service buildings, and the pump house, the structural system of each individual building consists of a substructure and a superstructure. The substructure includes concrete footings supporting reinforced concrete foundation walls. The superstructure includes a steel braced frames, reinforced concrete walls and slabs. The analysis considers a three-dimensional model of each building subjected to the different loading conditions. The protection against tornado effects for these buildings are provided by tornado-qualified walls and roof slabs. The wind pressures, the pressure air-drops, and the impact loading of tornado-borne missiles are considered in the analyses and design.

The seismic responses of each building are determined using either a stick model or a condensed three-dimensional model. The design response spectra are used as seismic inputs when using the response spectrum method. The results of such analyses in the form of maximum absolute displacement, velocity, and acceleration are used for the design. The maximum shear force and bending moment in any wall, beam or column can also be obtained. The results include the maximum base shear and overturning moment of the whole building. Another method that is used in the seismic analysis of structures is the time-history method. In this method, the seismic input is defined using a time-history of acceleration that is compatible with the design response spectrum. The results of such analyses include displacement and acceleration histories of the response at any point in the building which can be used for the design of structures. Seismic analyses are also performed to generate the floor response spectra at different locations in the reactor building and other buildings. These floor response spectra define the input level for seismic-qualification of safety-related systems and equipment.

The analysis of CANDU nuclear power plant civil structures provides useful information about the behaviour of different buildings subjected to various loads. This information is used for the structural design and the sizing of the structural components. It is used to determine the extent of reinforcement for concrete structures and selection of members for steel structures, and to undertake detailed design of connections and supports. The seismic responses and the floor response spectra generated from the analyses are used for seismic qualification of equipment and systems located in a CANDU nuclear power plant. Various analyses that are performed for the civil structures provide assurance of structural integrity and safety of the plant due to different conditions during the life of the plant.