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Structural Design of Replacement Emergency Core Cooling Filtration System

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1 ABSTRACT

This paper summarizes the results from recent design experience of ECC (Emergency Core Cooling) strainers. During a postulated loss of coolant accident (LOCA), water that leaks out of the reactor cooling system collects in a sump in the basement of the reactor building, where it is then pumped back using ECC pumps which maintain cooling of the reactor core. ECC strainers located in the sump prevent debris that might have been generated during the LOCA from entering the reactor cooling system. After the incident at Barsebäck-2, a Swedish BWR, nuclear regulators around the world started re-evaluating ECC systems in place at operational NPPs. Considerable research has been done to determine adequate design parameters. Based on new debris definitions it was determined that present filtering systems did not have sufficient capacity to provide reliable coolant circulation in case of a LOCA. The existing filtration surface was found to be very small compared to that needed per new research. As a result of this, new design solutions had to be implemented and AECL developed its modular *Finned Strainer*™* design. This strainer consists of porous fins attached to a common header and can be adapted to fit a wide variety of conditions. The design process for replacement of a containment sump strainer is a very complex one due to limited spacing in RB basements and the need for compact and at the same time adequate in suction surface strainers. The challenge for complex design was not only space limitation, but also significant suction pressure and temperature variations. In addition to this, design requirement for considering a seismic event during or following a LOCA imposes that seismic design be done for submerged structures. The performance of the equipment had to be evaluated for all those loads, the major of which are suction pressure, thermal, and seismic in submerged conditions. Each one of those is challenging on its own, but their simultaneous presence further added complexity to the problem. The suction pressure challenge was the need for relatively large plate surfaces with limited options for stiffening due to hydraulic flow limitations to avoid flow blockage. Thermal elongation was significant and because of the need for long suction trains, modularization and special consideration to sealing had to be given, together with allowing thermal expansion within each module. Seismic design under submerged condition requires that hydrodynamic loads due to fluid-structure interaction be considered in addition to seismic inertia load due to selfweight. In the area of fluid-structure interaction, a number of research studies have been published, however, there are no prescriptive design standards. The event that causes the most critical loading combination is a Safe Shutdown Earthquake occurring during a Loss of Coolant Accident (LOCA) i.e. while the strainer is in a submerged condition.

The ability of the strainer to perform its safety function during and after this event has been demonstrated by analysis. Its ability to function during and/or following one safe shutdown earthquake (SSE) event, preceded by a number of operation basis earthquake (OBE) events has been demonstrated as well. Special design of interconnecting ducts and pipes to the pumps had to avoid imposing any additional loads on the pump inlet. Due to congested environment, drilling limitations and the presence of Reactor Building liner, supporting and anchoring the equipment was a challenge itself. This paper describes the structural design experience of the *Finned Strainer* type design on a number of NPPs. As a result of approaches used, all challenges were successfully overcome and a reliable and robust design was produced by AECL.

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* *Finned Strainer* is a registered trademark of Atomic Energy of Canada Limited

2 INTRODUCTION

Deposits of foreign material on the surfaces of strainers can reduce the hydraulic head at the suction nozzles of Emergency Core Cooling pumps. This may lead to cavitation and pumps may fail to deliver adequate flow to maintain proper functioning of the ECC system. To reduce the head losses at the pump suction, the ECC system needs strainers with a large filtration surface. The strainers in a Nuclear Power Plant (NPP) are required to perform their safety functions during and/or after the time they are subjected to Safe Shutdown Earthquake event (SSE).The major challenges faced by the designers include the limitation of available space, restrictions on height, effect of hydrodynamic loads on the strainer during an earthquake, high containment temperature and pressure following Loss Of Coolant Accident (LOCA).

AECL has performed design for this equipment for fifty nuclear power stations around the world. Some typical structural design challenges and their solutions are presented below.

3 STRUCTURAL DESIGN

3.1 Design description

The necessity for improved ECC filtration systems became obvious in recent years as a result of problems identified as early as 1992. Subsequent research [6], [7] has identified a few key issues for this system, which comprised the technical background for the replacement of the strainers. The major issue was the source of deposits of foreign material. The main sources for these deposits were found to be insulation, paints and long-term erosion. [6], [7]. These deposits of debris tend to restrict the flow of water leading to head loss. Air ingestion, debris ingestion cause additional head loss. These problems were investigated through a thorough research program at AECL and based on their results the necessary input parameters for the new strainer were determined. The outcome of the research that has the biggest impact on the design was the vastly increased need for suction area on the strainers, when compared to the previous ones, which were based on unrestricted flow assumptions. In order to provide adequate suction area in a limited space, a number of innovative layout and shapes are considered to suit individual site. To allow significant increase of the suction area in a given floor space, AECL has come up with its *Finned Strainer* design. In addition, long suction trains consisting of strainer units have often replaced the small existing suction headers. These long suction trains are generally to be placed in the basement of the Reactor Building (RB), from where emergency water supply is drawn. Typically, the basement area of reactor building are congested with equipment and the layout of suction train and the size of strainer units have to be flexible enough to steer clear of the existing objects. A simplified example of such a train is shown in Figure 1. To overcome layout difficulties, a precise data collection to document the existing condition is performed.

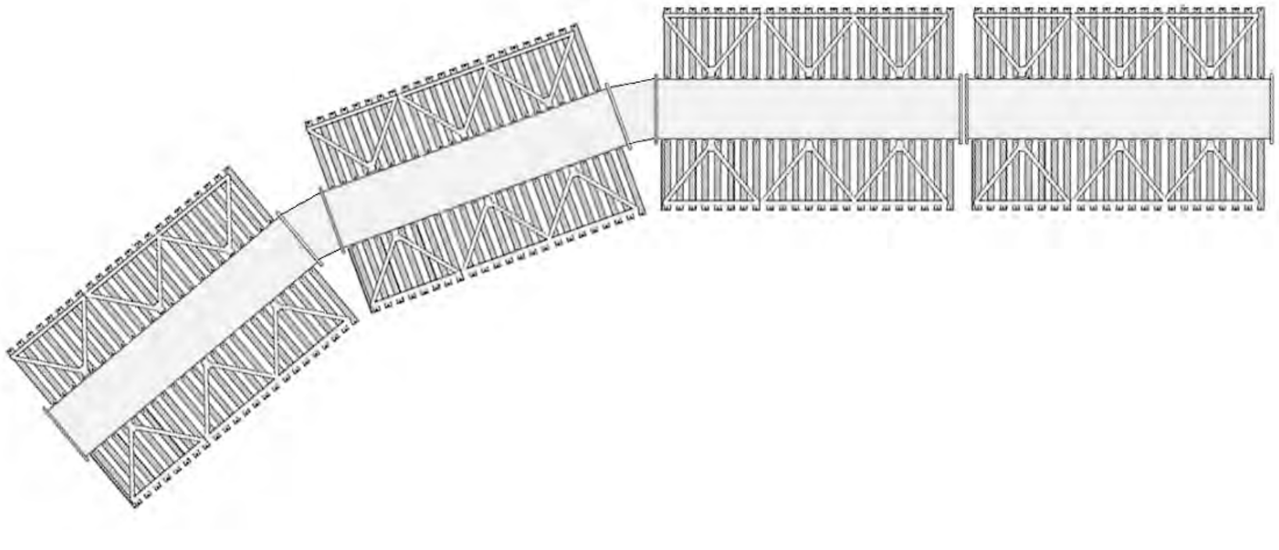

Figure 1. Typical layout of a strainer train

Each strainer unit itself is sized to suit overall layout; and its fins are shaped to suit the local conditions. Strainers are made entirely of Type 304 stainless steel or similar. The design is modularised on macro (train) and micro (module and subcomponents) level to allow for ease of inspection, transportation, installation and to be removable during outages as necessary. This is important since access to the basement area is generally very congested and restricts the size of members that can be carried to the location. Maximum size of the individual components is limited to the size permitted by accessibility to the area and the units are usually assembled in-situ. Concrete anchor arrangements for the strainer module had to be minimal and flexible in layout to allow the avoidance of interference with embedded parts and reinforcement. The design permits alternative locations for anchor bolts to allow avoidance of reinforcement or any other embedded objects. Different strainer configurations have been considered and implemented. Layouts of typical base plate models are shown on Figure 2 and Figure 3 (see 3.3.2 for further discussion on base plate modelling and analysis); and some configuration options for strainer modules are shown on Figure 4, Figure 5 and Figure 6.

Figure 2. Typical base plate modelled with compression only springs

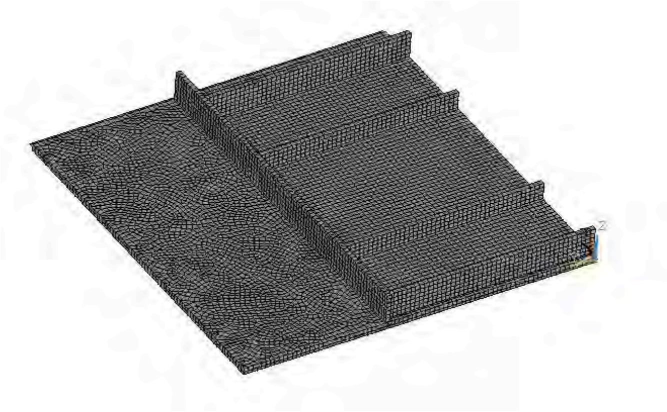

Figure 3. Typical base plate modelled with contact elements

3.2 Loading

A passive strainer is designed to operate under normal reactor building atmospheric conditions and also accident conditions. In addition, the strainers may be designed to carry a live load during outages due to maintenance activities. The following type of loading, under normal and accident conditions would typically be included in the analysis:

1. Dead Weight (DW)
2. Live Load (LL) (not always considered)
3. Suction Pressure (SP)
4. Reactor Building Internal Pressure (RBP)

5. Operating Basis Earthquake (OBE) [4]
6. Safe Shutdown Earthquake (SSE) [4]
7. Hydrostatic pressure when the R/B floor is flooded.
8. Hydrodynamic effects due to water sloshing and hydrodynamic mass effects during earthquake
9. Reactor Building Internal Temperature (T)

Various load combinations for the strainer analysis are considered and, based on applicability, the loading combinations used in the analysis for justification of one particular strainer design are presented in Table 1.

Table 1
LOADING COMBINATIONS

Service Limits	Load Combination	Loadings	Atmosphere	Sump Condition	Comment
Level A	LC-1	DW+LL	Normal Condition	Dry	Material Properties at T1
Level B	LC-2	DW+0.25LL+OBE	Upset Condition	Dry	Material Properties at T1
Level C	LC-3	DW+0.25LL+SP	Accident Condition	Wet (submerged)	Material Properties at T2
Level C	LC-4	DW+0.25LL+SP+SSE +Hydrostatic+Hydrodynamic	Accident Condition	Wet (submerged)	Material Properties at T2

Reference ambient air temperature	Tref
Maximum air temp under normal condition	T1
Maximum air temperature under accident condition	T2
Differential suction pressure	SP
Hydrostatic head pressure due to submergence of strainer module	

All members are required to be able to withstand a post accident peak pressure of RBP.

3.3 Finite element modelling

3.3.1 Strainer Unit

One of the loading conditions that is considered is a Design Base Event (DBE) during which an SSE occurs while the strainer is in submerged condition after a Loss of Coolant Accident (LOCA). Under this condition the surrounding water mass influences the response behaviour of the strainer.

Fluid-structure interaction is accounted by added mass as given by [1]. In addition, sloshing force and impulsive forces in a confined basin based on Housner's approach [5] have been considered, but have been found to be small compared to the added mass effects. In cases where the relative motion between the strainer and the surrounding water is restricted due to the layout geometry, calculations for added mass will take into account the relative motion and reduce the added mass accordingly.

A typical strainer module consists of several structural components such as collection header, a number of perforated and corrugated fins, structural framework, and support brackets. The sidewalls in the example shown are formed from vertical channels that are welded to the top cover and bottom plates of the header.

A structural dynamic finite element model of the strainer is prepared that accurately reflects the geometry, dimensions and material properties of all the constituent structural components. The mass of each structural component is included in the model by specifying its density; and the mass of non-structural components included as a lumped mass. No credit is taken from the stiffness of the non-structural members in calculating the response of the strainer due to seismic loading.

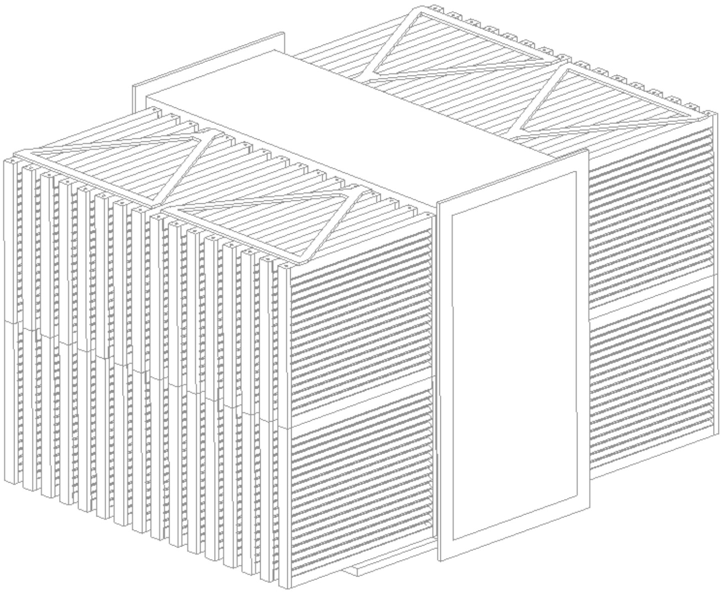

Figure 4. Typical Strainer view

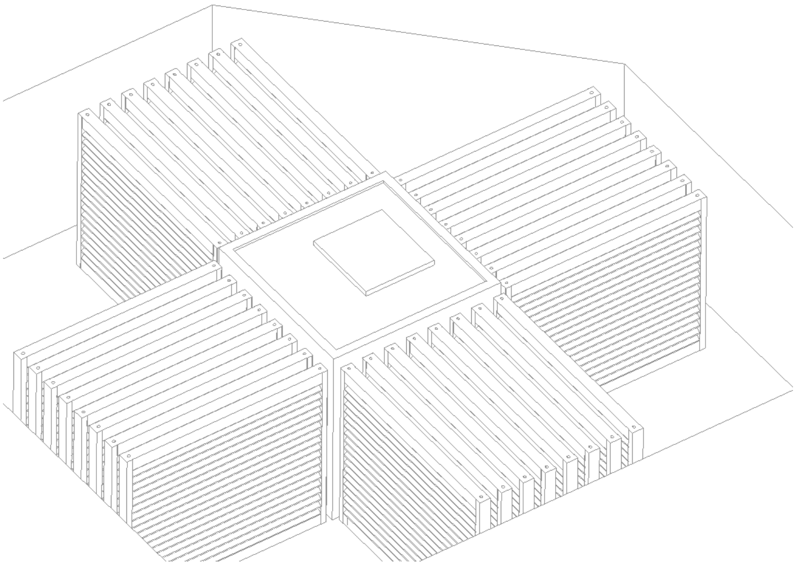

Figure 5. Variation of strainer when installed in a sump

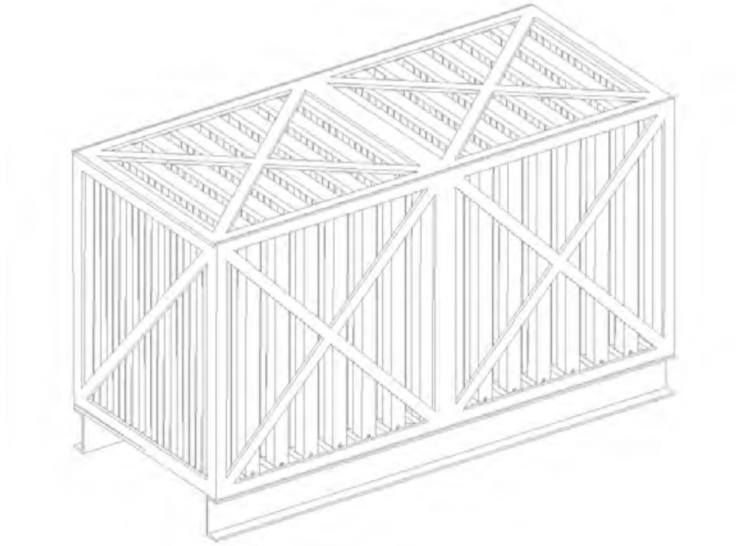

Figure 6. Variation of strainer when mounted on steel supporting members

Representation of each perforated fin requires several thousands of elements and hence the finite element model of the strainer assembly could be very large and difficult to handle. By reducing a fin model into a 'super element' using the sub-structuring technique, the size of the strainer model can be significantly reduced. Sub-structuring is a computational economizer that condenses the stiffness and the mass matrices of a group of finite elements into a single element according to the prescribed Master Degrees Of Freedom (MDOF). ANSYS computer program [3] is used to perform this analysis. ANSYS is commercial package that is widely used in carrying out static and dynamic analysis and in particular in the nuclear industry and it is validated and verified in accordance with standard procedures. ANSYS calls this single element with condensed matrices a '*super element*'.

The analysis involves representation of the dynamic system by a finite element model and solution of the equations of motion to obtain the seismic responses of the system. The responses can be determined using the response spectrum method if the seismic input is in the form of a response spectrum.

3.3.2 Base plate

Base plate analysis involves consideration of the boundary cases for base plate behaviour, namely, rigid base plate and flexible one. As it is shown on Figure 2 and Figure 3, the base plates' geometry was far from the typical one. Because of space constraints, many base plates were flexible—and even base plates possessing sufficient stiffness for global "rigid" behaviour have been found to experience local bending and prying effects. For that reason a typical base plate is usually analysed for the two bounding cases to determine its behaviour. For modelling of the support conditions under the base plates, two approaches have been used. The first one involved the use of compression only springs, whereas the second one used contact elements and incremental analysis. As a result of the extensive analysis work done it was concluded that in order to consider local stresses, and especially prying effects, the actual stiffness model has to be used.

3.4 Modal Analysis

The finite element model is used to perform a modal (eigenvalue) analysis to determine whether the equipment can be considered rigid. The equipment will be considered rigid if the modal analysis shows that the first resonant or natural frequency for the strainer is above the cut-off frequency of the Required Response Spectrum; and if it is below the cut-off frequency, the strainer will be considered flexible. The mathematical model has a sufficient number of node points, properly spaced, to capture all significant degrees-of-freedom. The rotational and the torsional degrees-of-freedom are considered for off-set masses.

3.5 Seismic Analysis

The equipment is loaded with hydrodynamic forces due to the coupled fluid-structure interaction. It is typically analysed using added mass terms as input for dynamic analysis procedure.

3.5.1 Static Coefficient Method

If the modal analysis indicates that the strainer equipment can be considered as rigid then the analysis may be done using the Static Coefficient Method of analysis subject to acceleration level equal to Zero Period Acceleration (ZPA) as per applicable seismic response spectrum.

If the equipment cannot be considered as rigid, a pseudo-static analysis or full dynamic analysis using Response Spectrum Method is done as outlined below:

3.5.2 Pseudo-Dynamic Analysis

If the modal analysis results indicate that there is only one main mode which is flexible (frequency less than 30 Hz) but on the down-slope of the FRS and has a significant modal participation factor, a static analysis can be done using an acceleration in the modal direction equal to the FRS acceleration corresponding to the calculated frequency, multiplied by a factor of 1.5.

If the lowest natural frequency is on the rising slope of the FRS (i.e., left of the peak acceleration) or if there are multiple flexible modes in the same direction then an equivalent static analysis can still be done provided the peak spectra acceleration is used along with a multi-mode factor of 1.5.

A cluster of local modes from individual fins is considered as a single mode. Also non-significant local modes (based on participation factor and effective mass) can be ignored in determining the applicable acceleration in the pseudo-static method.

3.5.3 Dynamic Analysis

When this equivalent static method cannot be applied, a dynamic analysis using the response spectrum method will be performed [2]. Depending on how close the modes are the modal responses are combined by the Square-Root-of-Sum-of-Square (SRSS) rule when the natural frequencies are widely spaced or Complete Quadratic Combination (CQC) rule when the natural frequencies are closely spaced, to get more accurate results.

3.5.4 Thermal Analysis

During a LOCA event there are elevated temperatures and so the equipment has to either be able to withstand the loads arising from them, or allow for thermal growth without compromising support structures or allowing any gaps from opening up. For this purpose, designs typically allow for thermal growth rather than trying to design restraints strong enough to prevent such growth. Special seal designs are used to allow for relative growth between component without allowing gaps in the filtration system.

4 CONCLUSIONS

The structural design of the ECC filtration equipment performed at AECL possesses excellent performance characteristics due to the implementation of advanced analysis features, technologically optimised detailing and built-in flexibility. Based on the approaches used, practical and economical equipment able to safely perform its functions has been fabricated and put into service in many nuclear plants.

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