SEISMIC ANALYSIS OF AN ON-POWER FUELLING MACHINE FOR A 4 X 850 MWe CANDU NUCLEAR POWER PLANT

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ABSTRACT

The CANDU (CANadian Deuterium-Uranium) nuclear power plant is refuelled on-power, utilizing a system of computer-controlled components. This paper describes the seismic analysis of a portion of this system emphasizing the problems encountered due to the complex functions and characteristics of the equipment and the methods used to solve these problems successfully. Particular attention is focussed on the means by which design adequacy, in terms of structural safety and integrity, is ensured, while at the same time providing for an economical analytical approach.

INTRODUCTION

An on-power method of refuelling has been designed and developed for use in the CANDU reactor. It is this feature, among others, that has helped to produce an excellent performance factor and gained the CANDU system an international reputation.

On-power refuelling requires the fuelling machine to connect to and become part of the primary heat transport system of an operating reactor on a routine daily basis while performing its required functions of inserting and removing fuel. The fuelling machine to be discussed in this paper will be installed in a nuclear power plant consisting of 4 units rated at 850 MWe each.

In the 4x850 MWe plant to be owned and operated by Ontario Hydro, fuelling will take place on the average of 19 times per day over 4 reactors, making the probability of an earthquake during fuelling sufficiently high to require consideration. As part of the overall CANDU safety philosophy, it is a requirement to prevent a seismically induced loss of coolant from the primary heat transport system (PHTS).

In performing a fuelling cycle, the fuelling machine is connected to the PHTS by attaching to a reactor fuel channel. It is necessary then to seismically qualify the fuelling machine and its supports for this condition. Also, because of the close proximity of the fuelling machine to the reactor face, seismic qualification is necessary when the fuelling machine is not attached to a channel. This will ensure the integrity of the fuelling machine and supports, preventing their possible failure and subsequent damage of the reactor face.

The task of seismically qualifying the fuelling machine when it is attached to a fuel channel is complicated by the fact that there are 480 horizontally positioned fuel channels in each reactor that could be in the process of being fuelled during an earthquake. To understand the significance of this, a brief description of the fuelling machine and its support is necessary.

DESCRIPTION OF THE ON-POWER NUCLEAR FUELLING MACHINE AND SUPPORTS

The fuelling machine, which is the heart of the on-power fuelling system is illustrated in Figure 1. It must be capable of attaching to any of the 480 horizontal fuel channels in an 850 MWe unit; to do this it must be delivered to the channel that requires fuelling. This is accomplished by the reactor area bridge which is an assembly of two columns that are spanned by a horizontal beam suspended from the columns via ball screw jacks. The ball screw jacks provide vertical motion of the bridge beam which in turn supports the fuelling machine by a carriage and suspension. The carriage provides lateral translation of the fuelling machine across the face of the reactor. Through a series of computer commands, the fuelling machine is moved to any one of the 480 fuel channels positioned on a rectangular lattice in the reactor. Since the earthquake could occur during the fuelling of any channel, 480 possible structural geometries must be considered.

Analytical seismic qualification of the on-power fuelling machine has evolved over the past decade to its present state of complexity. Further refinement in technique is still being pursued to achieve a more cost effective method of analysis at a time when the ever-increasing safety requirements have dictated an escalation of safety related analysis. In this paper the authors will review the problems that have been encountered in performing such an analysis and the methods that have been used to circumvent them.

ANALYSIS BACKGROUND

In a previous seismic analysis of a reactor area bridge assembly, the reactor area bridge and fuelling machine were modelled using the STARDYNE code (1). Each of the two assemblies consisted of 2 lumped masses with 3 degrees of freedom per node. This approach yielded clues as to the behavior of fuelling machines in several configurations coupled to and uncoupled from a reactor fuel channel. Higher frequency modes were omitted, directional cross coupling was prevented and differential anchor point displacement was not accounted for. The resulting analysis was meant to be conservative; however, as the analysis progressed, it became obvious that assumptions made regarding load transfer in localized areas might not have been conservative.

It was necessary to increase the detail of the model in order to study localized effects, to determine whether design changes that were indicated by the conservative analysis were required and to ensure that joint loading was not underestimated.

A beam-element model was then constructed to provide a more detailed model for determining loads in the components of the structure. Many simplifications were necessary to fit the model size into the limitations of the STARDYNE code. In mechanical equipment, many sliding and rolling connections may be required to provide the necessary degrees of freedom and these can lead to significant and unusual dynamic response. These types of mechanisms are present in the fuelling equipment and some were modelled but, because of model size limitations, others were not. This is a problem that may be present in the analysis of most mechanisms and their importance must be considered on a case-by-case basis. In the present case, small inaccuracies were introduced. Though these were not sufficient to affect overall dynamic behaviour, they did influence the accuracy of localized stresses.

Initial examination of this detailed model centered on the application of 1g static accelerations along the three orthogonal axes. Based on symmetry, 240 lattice positions could be immediately ruled out from further analysis. Of the remaining 240 positions, about 30 analytical configurations were chosen representing different positions of the fuelling machine on the reactor face. Examination of deflections in these 30 positions allowed a study of the relative stiffnesses of various components and the change of stiffness of these components with bridge position.

For dynamic analysis, this model was coupled to a simplified model of the reactor building. Ten positions of the bridge structure in front of, but not attached to, the reactor were chosen based on the findings of the relative stiffness comparisons undertaken previously. These were examined using three orthogonal earthquakes applied simultaneously and employing the SRSS-10% rule for modal summation. If the dynamic response of the structure correlated well with the extrapolations made from the statics study, the worst dynamic cases would have been found without the need for an exhaustive search of all

480 channel positions. The results correlated very well in 9 of 10 cases. The exception produced a very large vertical response in the structure due to a large participation factor in the fundamental vertical bridge mode. The cause was traced to a classic case of mass coupling effect (2) at closely spaced frequencies between the fundamental bridge vertical mode, with a relatively small generalized weight, and a fundamental lateral building mode. By varying the geometry of the structure the natural frequency had been tuned to the fundamental building frequency. Since the mass of the fuelling machine and supports was small compared to that of the building, the two could be decoupled at the expense of losing relative anchor point displacement loads (3). This would solve the problem of mass coupling as long as relative anchor point displacements could be shown to be insignificant. By rerunning some of the nonresonant positions using a floor response analysis and comparing the results to the previous coupled analysis, this was proved to be the case . Therefore, a more cost effective floor response spectrum analysis could be used for the remaining analysis without a compromise in accuracy.

This type of summation problem can be very difficult to detect. In this analysis, the authors were fortunate to have varied geometries to compare, which immediately provided a clue that a problem existed. Still, many hours of searching through computer printouts were required to pinpoint the exact nature of the problem and devise a solution. In analyses of fixed-geometry structures, the warning signs are not so easy to recognize and by using SRSS-10% summation the analyst may generate grossly conservative results.

In the subsequent analysis of the fuelling machine and supports attached to a lumped mass model of the reactor and reactor channel, the same problem occurred. In 1 of the 6 positions examined, unusually high loads appeared. An investigation showed that the fundamental fuelling machine bending mode was tuned to a fundamental reactor end-shield mode and the use of absolute summation on closely spaced modes caused erroneously high results. However, the occurrence of significant relative displacements and other coupled modes between the fuelling machine and support components and the reactor prevented further decoupling to circumvent the problem. Amongst the various response-spectrum modal-summation algorithms available in STARDYNE at that point in time, the SRSS-10% rule was the least conservative industry-recommended practice. It had become clear to the CGE authors that this method was overly conservative for a complex model where many closely spaced modes occurred.

Accepting these results would have resulted in extremely expensive design changes and the CGE authors elected to use a time history analysis and manual manipulation of the data to show that the SRSS-10% results were overly conservative and that major design changes were not required.

The dynamic model would require suppression of superfluous modes for existing summation techniques to produce realistic results. However, stress analysis proved the model to be too coarse to provide the necessary detail for components. The finely detailed beam element model resulted in accurate determination of the dynamic mode shapes but numerous superfluous modes were also generated (Of 66 modes generated in one run, only 12 were required to account for 95% of the response). This abundance contributed directly to the likelihood of difficulty with summation of closely spaced modes.

For the current analysis,it was concluded that an increase in detail was required to produce a model adequate for computerized stress analysis of most of the structure and a decrease in detail was required for dynamic analysis to retain the most significant modes and help circumvent the summation problems with closely spaced modes. These two contrasting ideals point to a common solution - substructuring. Most of the complexity in the model required for stress analysis is in components which contribute little to dynamic response. As such, substructuring would enable a complex frame to be condensed to only its most significant modes.

SUBSTRUCTURE TECHNIQUE

The substructure method of structural analysis is available as an option in some of the commercially distributed general-purpose finite-element programs. For instance, STARDYNE, ANSYS and NASTRAN offer this capability. In statics, the substructure formulation is mathematically exact. In dynamics, the method as implemented in the popular Guyan (4) approach, involves an approximation of inertia, damping and applied loading. The choice of a suitable program for the substructured seismic analysis of the fuelling machine and supports is governed by such factors as (a) the program's capability to accommodate substructuring in dynamics, (b) the authors' familiarity with the program, (c) the efficiency of eigenvalue analysis, (d) the variety of built-in modal summation techniques and (e) cost and user-friendliness. Factors (b)-(e) have tended to favor STARDYNE in the present case. In regard to factor (d), it is worth noting that STARDYNE now includes, as an option, the relatively new Complete Quadratic Combination (CQC) method (5), which reduces the conservatism characteristic of the more familiar SRSS-10% technique. Factor (a) appears, at first glance, to militate against the use of STARDYNE, inasmuch as the standard application of the substructuring option in the program lies in the realm of statics. However, the authors have chosen STARDYNE and have succeeded in dovetailing various features available in STARDYNE to form a viable framework for single-level, dynamic substructuring (6).

A flow diagram of the STARDYNE (non-standard) framework is shown in Figure 3. In each substructure, a set of Guyan (Master/Dynamic) degrees of freedom (DOF's) is chosen and the mass and stiffness matrices are condensed to these DOF's in a Forward Pass. In what is termed the Global Pass, the Guyan DOF's from all substructures are assembled into a Residual Structure, which may also have additional DOF's of its own. The Residual Structure is subjected to an eigenvalue analysis via the powerful Lanczos technique. The resulting frequencies and modal mass participation factors are accepted as correct for the structure. The eigenvectors are reformatted via a

Restart operation so as to be compatible with the next step. A Backward Pass is executed for each substructure for determining its expanded eigenvectors and associated stresses. These results are stored on file TAPE4 of the substructure. The vector headers in this file are then rewritten via a small FORTRAN routine so as to include the appropriate frequencies and participation factors. A Response Spectrum analysis may now be carried out via the DYNRE4 module of STARDYNE for any desired substructure and the Residual Structure, using the relevant TAPE4.

It is essential that the dynamic DOF's are chosen so as to yield adequate accuracy not only in the frequencies and modes but also in the participation factors. This is because the mass participation factors, which, in effect, determine the modal loading, have been evaluated on the basis that seismic action occurs on the mass matrix of the Residual Structure rather than on the original, unreduced structure. The operations of reformatting the eigenvectors of the Residual Structure and of editing the vector headers in substructure TAPE4-files are not standard. They would be obviated if STARDYNE were to provide for dynamic substructuring as a built-in option.

IMPLEMENTATION OF SUBSTRUCTURING

The design of the fuelling machine and supports consists of both large, simple structural components and smaller, intricate frame components. For this analysis, only the smaller, complex frames of the suspension and carriage assemblies were substructured in an effort to reduce manual stress analysis. Substructure models were constructed out of both plate elements and beam elements. Guyan DOF's were chosen to ensure proper mass distribution in the Residual mass matrix. In addition, all contact points between these frames were modelled and chosen as Guyan DOF's in order to provide accurate load transfer between frames. This resulted in 5 substructured frames attached to each fuelling machine bridge assembly. The fuelling machine bridge, itself, was not substructured but was modelled as a simple frame using beam elements and the master degrees of freedom representing the substructures were added to produce the Residual Structure. The Residual Structure and the five substructured frames are illustrated in Figure 2.

The use of substructuring resulted in the size of the Residual Structure being 1/4 of previous unsubstructured model. At the same time, the model represented all rolling and sliding connections between frames.

DETAILS OF ANALYSIS

The first step required before undertaking any analysis using computer codes is to verify the code's accuracy. In view of the approximation inherent in dynamic substructuring, the novel nature of the present application of STARDYNE and the cumbersome logistics of substructure file-handling it was deemed crucial to verify the procedure with a representative but simple model. To this end, a simple beam element model resembling the fuelling machine bridge and containing the key features that were to be retained after substructuring was analyzed using both substructured and unsubstructured techniques. The frequencies, participation factors and mode shapes were compared, especially to ensure that multidirectional modes were still represented and at the proper frequencies. The substructuring results correlated within 5% and it was concluded that the accuracy of the solution had not changed significantly by incorporating the substructure technique. In addition, by analyzing a sample model first, the authors had the opportunity to debug and streamline the tape and disc file control statements reducing the costs of job control errors during the real analysis. This preliminary sample analysis is recommended for anyone who chooses this method so as to become familiarized with the details of file handling.

The forward pass of the five substructured frames needed to be performed only once and was valid for all geometries, because the sliding and rolling joints which would change in moving the structure to various reactor channel positions were modelled as stiffness-matrix additions coupling boundary degrees of freedom in the global model.

The fuelling machine was moved on the bridge such that ten reactor channel positions were studied. The positions were chosen based upon the results of previous analyses with additional positions introduced to achieve a uniform spread of positions over the reactor face. To allow for stress analysis leading to seismic qualification of the fuelling machine and supports detached from the reactor, the isolated response of the structure in these ten positions was studied.

It was found that only four of the ten positions were necessary to compile an envelope load case covering the worst cases on all components of the system. This conclusion allowed the backward pass of the analysis to be bypassed on six of the cases resulting in significant financial savings. In an unsubstructured analysis, this would not have been possible as a complete set of nodal responses, loads, and stresses would have to have been calculated before this observation could have been made.

Using the four most significant positions, backward passes were made resulting in four sets of loads and stresses on each frame. This step was, as expected, the most expensive in the whole procedure. Contributing to this were the two nonstandard operations mentioned earlier, which comprised 13% of the overall cost of analysis. However, these extra costs were offset by the savings achieved by simplification of the dynamic model allowing insignificant positions to be deleted before the backward pass stage.

With the worst case loads determined for the fuelling machine bridge assembly detached from the reactor, the analysis turned to the attached configuration where a reactor model and fuel channel model were added to the global structure, along with a duplicate of the existing reactor area bridge structure on the opposite side of the reactor.

The same ten positions were examined and changes in the results from the "detached" cases were studied to determine the dynamic coupling behavior of the fuelling machine bridge, fuel channel and reactor. An unusual result emerged at one position where the amplitude of the fuelling machine vibration was dramatically higher than in the other nine cases but the response of the other components was nearly the same. Absolute summation of closely spaced modes was suspected as the cause. So, a second examination of this position was made using the CQC method and the results then compared favorably in the area of the fuelling machine and remained unchanged in other areas of the structure. Absolute summation was therefore confirmed again as the problem. The analysis proceeded with the search for the worst-case positions with results from nine cases derived from SRSS-10% summation and the remaining case employing CQC summation.

For the "attached" analysis, only 3 cases were required to compile a worst case envelope of the loads and as such only 3 backward passes were required.

Worst-case loads and stresses in the global model and each substructure were compiled for both the attached and detached configurations. These loads and stresses were added absolutely to static loads and stresses due to a 1g vertical acceleration. Two final tabulations of worst-case seismic-plus-static loads and stresses were made for use in the stress analysis of the various components.

With this more detailed presentation of loads and stresses throughout the assembly, more rapid and precise determination of highly stressed areas was possible allowing for action to be taken with minimal effect on the manufacturing schedule.

In addition, a reduction in conservatism resulted from a more realistic determination of response and from a better understanding of the behavior of sliding and pivoting joints.

Most important, however, was the avoidance of costly design changes that would have resulted from overly conservative simplifications present in similar analyses performed in earlier years.

CONCLUSIONS AND SUMMARY

The seismic analysis of the on-power fuel handling equipment is a formidable task. The use of a methodical approach to the examination of channel positions facilitated a slightly conservative compilation of worst-case loads, without extraordinary efforts in the examination of many noncritical channel positions.

The total computing cost of the substructuring technique in the seismic analysis of a 4x850 MWe fuelling machine on reactor was not significantly different from the expenditure in a previous unsubstructured analysis; however, much more detail was added in the substructure analysis leading to a more accurate calculation of loads and stresses for the seismic qualification of the system. The overall effect has been that unduly conservative results and costly design changes have been avoided. The CQC method of modal summation has also played an important role in this regard.

Thus the technique described in this work can be recommended for the seismic analysis of relatively complex models at reasonable cost and, for such models, in cases where there is a significant need to reduce the manual effort involved in stress analysis.

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ACKNOWLEDGMENT

The funding for this project was provided by Ontario Hydro as part of the engineering contract with Canadian General Electric Company for the design of nuclear fuel handling equipment for a 4x850 MWe CANDU power plant. The authors would like to thank Ontario Hydro for providing the necessary seismic response data and building structural models and Atomic Energy of Canada, Ltd. for providing the reactor structure model. The analysis would not have been possible without this cooperation.

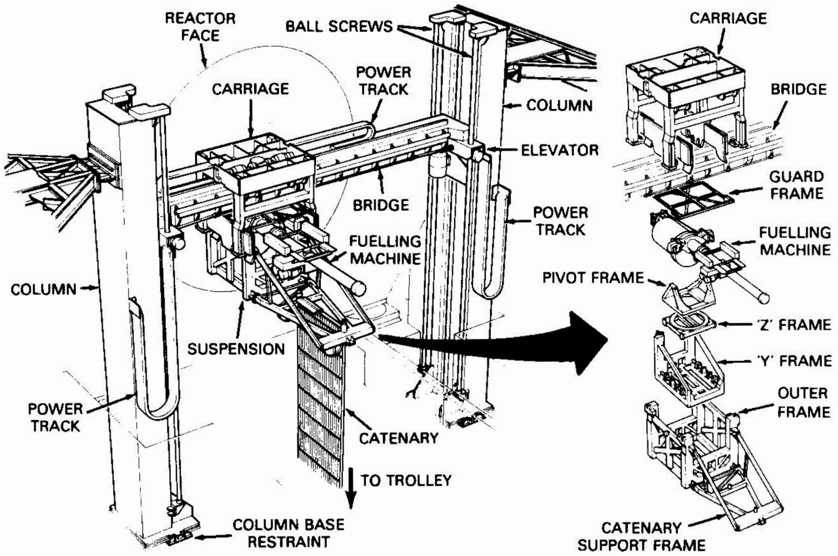


Figure 1) 4x850 MWe Fuelling Machine and Reactor Area Bridge Supports

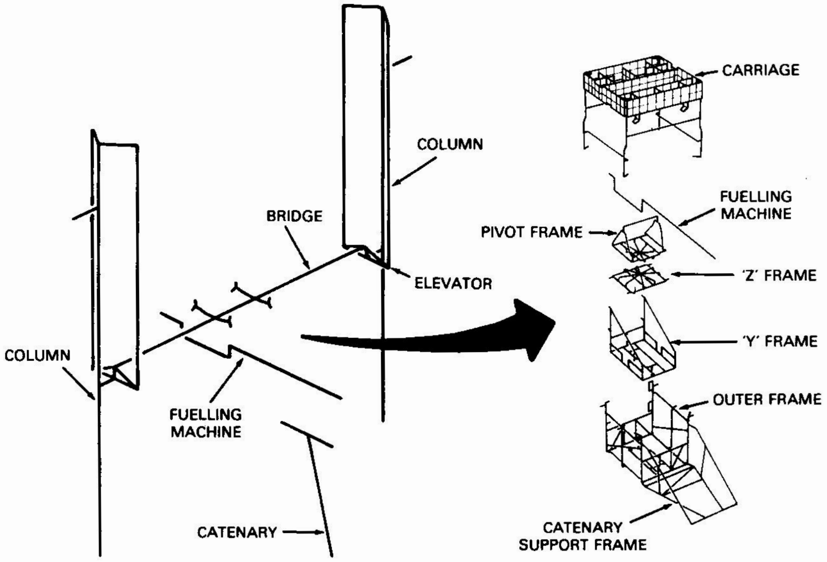
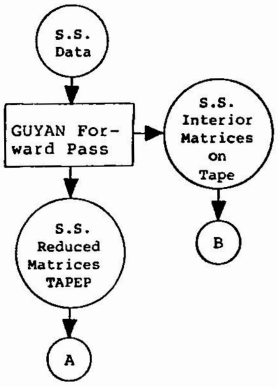
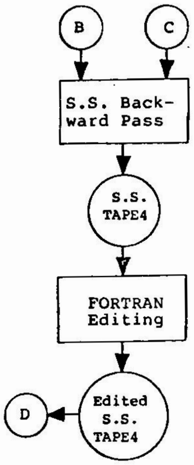


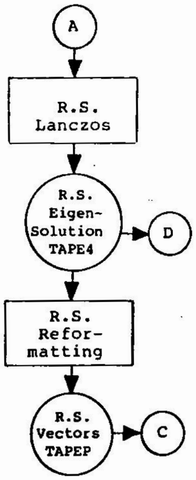
Figure 2) 4x850 MWe Fuelling Machine and Supports - Substructured Model



(i) Forward Pass (for each S.S.)



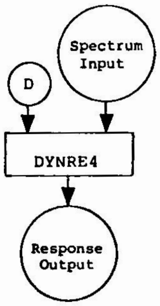
(iii) Backward Pass (for each S.S.)



(ii) Global Pass (for R.S.)

Note:

R.S.: Residual Structure
S.S.: Substructure



(iv) Response Analysis
(for R.S. & each S.S.)

Fig. 3 Substructure Analysis Flow in STARDYNE