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Effects of Aircraft Impact on a Seismically Isolated Reactor Building

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ABSTRACT

During the past decade, a lot of effort has been spent to develop strategies to mitigate the damaging effects of earthquakes. This work has been directed at both civil structures and nuclear facilities. A highly attractive strategy for nuclear facilities, especially for liquid metal reactor plants, is to use seismic isolation. Because the design of heavy metal reactors requires the use of a coolant that physically weighs a lot and the use of a thin-walled reactor vessel, it is difficult to meet seismic requirements. However by using seismic isolation, it is possible to decouple the reactor building's response from the strong ground motions.

Up until September 11, 2001, seismic isolation systems were designed to handle only the seismic threat. Threats from aircraft impact were usually not considered because nuclear power plant sites, for the most part, were chosen to be away from airports and, thus, outside of flight paths. Now with the possibility of a deliberate aircraft crash into a reactor building, existing and future seismic isolation systems must also be evaluated against this new threat.

This paper presents a preliminary study on the response of a reactor building impacted by commercial aircraft. The study evaluates the response of a representative seismically isolated reactor building subjected to separate impacts from either a Boeing 720 or a 747 aircraft. It is shown that for the representative seismically isolated reactor building studied, the isolation system response is favourable with a comfortable margin of safety.

KEY WORDS: Seismic Base Isolation, Earthquake, Aircraft Impact Response, Laminated Rubber Bearings, Nuclear Power Plants, Liquid Metal Reactors, Reactor Building

INTRODUCTION

The protection of nuclear and civil structures from the devastating effects of earthquakes has been the focus of intense research and development throughout the world. Seismic isolation is an effective means for reducing and even eliminating the devastating effects of earthquakes on people, equipment and structures. For over a decade, Argonne National Laboratory (ANL) has been involved in R&D activities [1] on the implementation of seismic isolation for nuclear power plants (NPPs). NPPs can be classified as low-to-medium rise structures, thus, ANL's research also applies to low-to-medium rise civil structures, such as, bridges, buildings less than ten stories, etc.

Seismic isolation systems have been deployed at several nuclear facilities. The nuclear power plant at Koeberg, South Africa uses a seismic isolation system that employs a combination of elastomer bearings and sliding pads. The NPP at Cruas, France uses only elastomer bearings and the spent fuel pools at La Hague, France uses neoprene pads as seismic isolators.

Plans to incorporate seismic isolation into future nuclear facilities include the DFBR, APWR and ALTFR plants in Japan and the EFR plant in the European Union. Several advanced reactor concepts have been selected for the next generation of reactors, the so-called Generation IV (Gen IV) reactors. The following designs have been proposed as part of the Generation IV program: STAR-LM (300-400 MWth) [2], ENHS (125 MWth), KALIMER (150-330 MWe) and S-PRISM (1000 MWth). Among the concepts selected were reactor designs that use liquid metal coolants such as sodium or lead bismuth. STAR-LM and ENHS use a lead-bismuth eutectic as the coolant, and KALIMER and S-PRISM use liquid sodium as the coolant. Because these reactors operate at lower pressures and higher temperatures than pressurized water reactors, thin-wall vessels are used to reduce thermal stresses. The thin-wall reactor vessel, which contains the coolant pool, would not perform well under earthquake loading. In order to survive the damaging effects from earthquakes, all liquid metal reactor designs currently plan to use seismic base isolation. In the United States the Secure, Transportable, Autonomous Reactor-Liquid Metal (STAR-LM) [3] reactor, the Advanced Fast Reactor (AFR300) and the PRISM [4] and Super PRISM reactors all employ base isolation to mitigate the devastating effects of earthquakes. In Korea, the KALIMER LMR reactor uses base isolation [5].

The method chosen for isolating advanced nuclear reactor plants is seismic base isolation. The main reason for this choice is that seismic isolation uses passive devices, which have been proven to be effective as shown by Coveney [6]. Base isolation provides protection to the structure and its contents, and, thus, functional operations can continue during the quake or be resumed shortly thereafter. With this design strategy, a seismic isolation device is placed between the ground and the structure. The isolators effectively decouple the structure from the strong earthquake motion. The importance of using a passive device cannot be over stressed. There is no dependence on people, power supplies, electronic controls/devices, or complex mechanical systems.

The 1994 Northridge California quake and the 1995 Kobe Japan quake have demonstrated the effectiveness of the use of elastomeric isolators for earthquake protection. The base-isolated University of Southern California University hospital had no structural damage or content damage and continued operation during and after the Northridge quake. An earthquake that registered 7.2 on the open-ended Richter scale occurred in Kobe Japan. Reports indicated that the seismically isolated West Japan Computer Center of the Ministry of Post and Tele-communications, which is a 6-story concrete building, survived the quake without damage to its structure or contents. The peak ground acceleration at the Center was 0.3 g, and the acceleration above the isolators was attenuated to 0.1 g. A five story concrete building, which was about one kilometer from the center, recorded a peak acceleration of 1.0 g at the roof level. The excellent performance of isolated structures during these two earthquakes provides *in-situ* proof of the effectiveness of seismic isolation for mitigating earthquake damage.

Research and development efforts at Argonne have covered a wide spectrum that includes technical specifications, elastomer specimen testing, scale-size bearing tests and *in-situ* bearing tests. Many investigations were done to find the material response characteristics of several elastomers by using small pads of the elastomer bonded to flat metal bars or cylindrical discs. The results of these tests have been reported periodically and are given in the following: Kulak and Hughes [7], Kulak [8], Hughes and Kulak [9], Kulak and Hughes [10], Kulak and Hughes [11], Kulak and Hughes [12] and Kulak [13]. One of the lessons learned from this research was that with proper attention to details isolators can be manufactured to meet the requirements of the nuclear industry and their regulators.

Up until September 11, 2001, seismic isolation systems were designed to handle only the seismic threat. Threats from aircraft impact were usually not considered, explicitly, because nuclear power plant sites, for the most part, were chosen to be away from airports and, thus, outside of flight paths. Now, unfortunately, with the possibility of a deliberate aircraft crash into a reactor building, existing and future seismic isolation systems must also be evaluated against this new threat. Since September 11, the U.S. nuclear industry and its regulators have been looking into the effects of a commercial jetliner crash into NPP building structures. Since Gen-IV designs are on the drawing board, so to speak, an opportunity exists to incorporate design features that would ensure that the Gen IV reactor building can sustain the damage from an aircraft crash. The same applies to the design of the seismic isolation system; it must be designed not to fail from aircraft-crash loading. The first step is to evaluate the response of a typical isolated reactor building to aircraft impact loading and that is the main focus of this paper.

There are several issues associated with an aircraft crash into NPP structures. For example, will the structure *per se* maintain its integrity? What are the effects from a potential fuel fire or explosion? What are the consequences of impact-induced vibrations on the primary and secondary system? This paper will not address any of these but will address the issue regarding the response of the isolation system to aircraft impact. The next section describes some of the key characteristics of the isolators that would be used in the representative seismic isolation system. The following section describes the first order approach used to evaluate the response of a representative isolated reactor building subjected to the impact from a commercial jetliner. The section after that presents the results from a preliminary evaluation of the response of an isolated reactor building to loading from an aircraft crash. The final section presents conclusions drawn from the numerical simulations and identifies areas for further research.

SEISMIC ISOLATION SYSTEM

As mentioned above, all of the Gen-IV reactor designs will use seismic isolation and most of them will employ laminated high damping rubber bearings as the isolator. To date, most of the designs are for two-dimensional seismic isolation, which only provides seismic protection in the horizontal direction. The European Unions' EFR and Japan's ALTFR, however, will use three-dimensional seismic isolation systems. Typical preliminary layouts for seismic isolation systems are shown in Figures 1 and 2. Figure 1 is a conceptual layout for the proposed STAR-LM reactor and

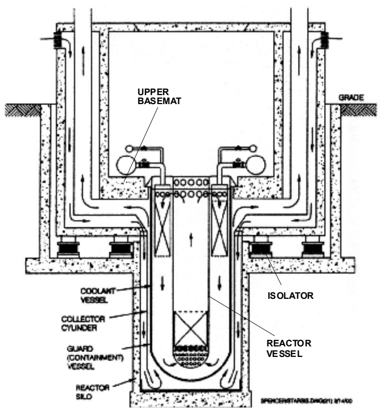

Figure 1. STAR-LM Reactor Layout.

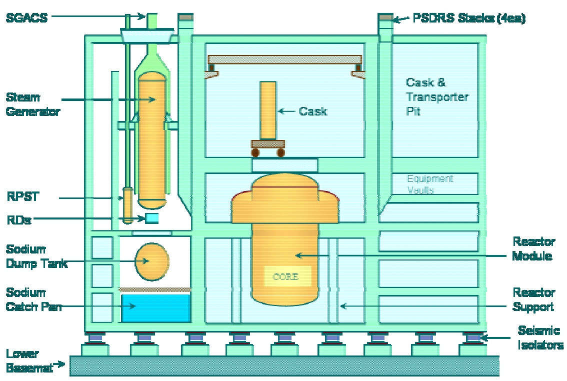

Figure 2. KALIMER Reactor Layout.

Figure 2 is for the KALIMER reactor. In both designs, it is seen that seismic isolation bearings are inserted between an upper and lower basemat. The lower basemat is resting on the ground and the upper basemat supports the superstructure. The earthquake motion is felt directly by the lower basemat, but the isolators reduce the horizontal forces so that the upper basemat is subjected to greatly reduced acceleration levels.

Figure 3 shows a representative laminated rubber bearing (LRB) that consists of alternating layers of steel shim plates and high damping natural rubber. The natural rubber contains nanometer dimension particulate fillers that provide damping of about 2-12%. The damping exhibited by these particulate filled natural rubbers is hysteretic, i.e., the damping is frequency independent over the large frequency range of interest. End plates are located at the top and bottom surfaces for mounting to the superstructure and lower basemat, respectively.

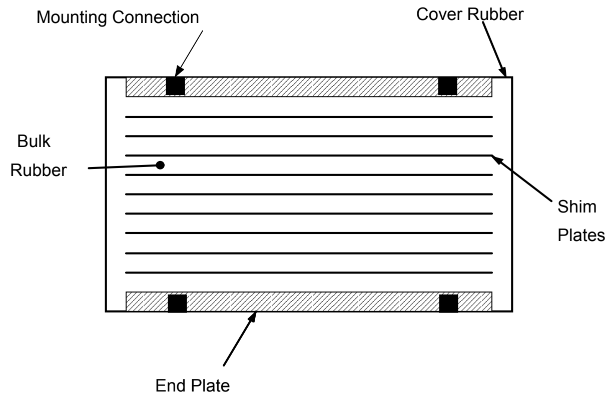

Figure 3. Steel Laminated High Damping Isolator.

Typical stress-strain curves in shear for a 1:8-scale LRB [5, 14] are shown in Figure 4. The three curves are the third cycle responses at shear strain levels of 100%, 200% and 300%. The 100% shear strain response, which is equivalent to the total rubber thickness of 34.8 mm, is seen to be fairly linear and to a first order can be modelled as linear viscoelastic. In contrast, the response at 300% is highly nonlinear with hardening behaviour that can preclude excessive displacement. It is noted that design shear strains range from 75-100%. Shear-compression test to failure of the 1:8-scale isolator are shown in Figures 5. For various loading rates and under a vertical pressure, failure of the isolator varies from 95 mm (273%) to 108 mm (310%). Isolation systems are typically designed to have a natural frequency in the range of 0.5 Hz to 1.0 Hz (i.e., 1-2 sec period), which is far below the resonant frequencies (4 -100 Hz) of the primary and secondary systems.

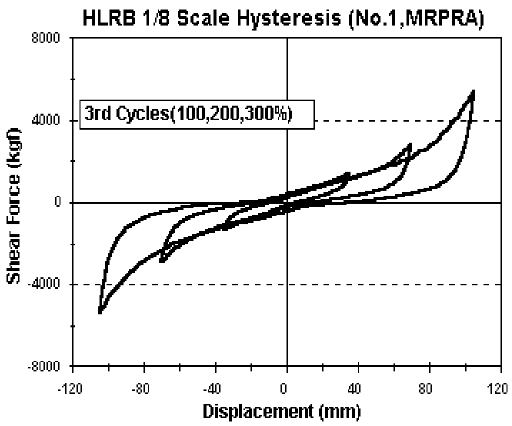

Figure 4. Stress-strain Response Curves.

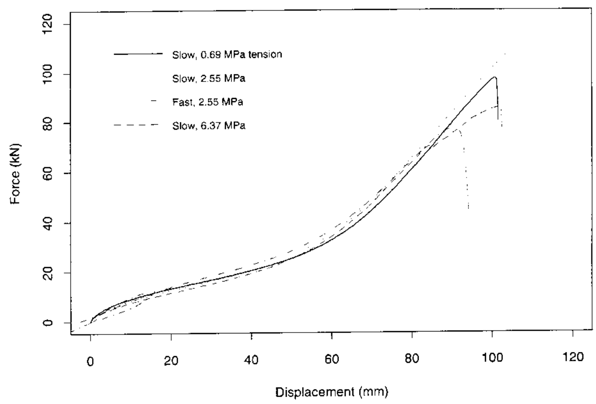

Figure 5. Shear-Compression Failure Curves.

NUMERICAL MODEL

In order to obtain a first order estimate for the response of a seismically isolated reactor building, a simple 1 degree-of-freedom model was chosen. For this approach, the reactor building is considered to be rigid, and it is assumed that steel laminated high damping rubber bearing (LRB) are used for the isolators. Figure 3 shows a representative LRB that consist of alternating layers of steel shim plates and high damping natural rubber. The natural rubber contains nanometer dimension particulate fillers that can provide damping up to 12%. End plates are located at the top and bottom surfaces for mounting to the superstructure and lower basemat, respectively.

The numerical model (Fig. 6) for a seismically isolated reactor building consists of a mass, M, representing the reactor building, a spring element representing the shear stiffness, K, of the LRB and a damping element representing the damping, C, of the LRB. The spring and damping elements are connected to the ground, G, which was assumed to be fixed. The isolator was assumed to be linear elastic with an equivalent viscous damping. The linear elastic assumption would be fairly valid provided the computed shear strains do not greatly exceed 100%. The use of equivalent viscous damping would also be justified provided that the system vibrates at the frequency at which the hysteretic damping was measured, and with a one degree-of-freedom system this is the case. The isolation frequency used in the analysis is 0.5 Hz and the equivalent damping coefficient for the isolation system is 12%.

The use of this first order model has the following implications: (1) the reactor building is rigid and, thus, cannot absorb any energy, which is conservative; (2) the effect of impact location, i.e., the vertical location of the impact, cannot be evaluated: (3) a potential overturning mode cannot be evaluated. This simple model, however, provides the following: insight into the expected range of the response and the time history, an estimate for the horizontal displacement and resulting shear strains of the isolator, and a sanity-check for future higher-order analyses.

The Riera approach [15] was used to obtain the loading histories on a reactor building that was impacted independently by a Boeing 720 and 727. The impact angle to the perpendicular of the vertical surface of the reactor building was taken to be 0 degrees, which produces the most conservative loading. Figure 7 shows the Riera loading function for a Boeing 747 travelling at 150 m/s. The maximum load of 330 MN occurred at 0.2 sec after impact and the loading duration was 0.4 sec. The Riera curve was further approximated by a triangular loading function (Fig. 7) for subsequent comparison of the numerical solution with the closed form analytical solution, which was not tractable with the Riera representation. The numerical results presented here were based on the triangular loading function. Note, the use of triangular loading is conservative since the area under the triangle is larger than the area under the Riera curve by 38%.

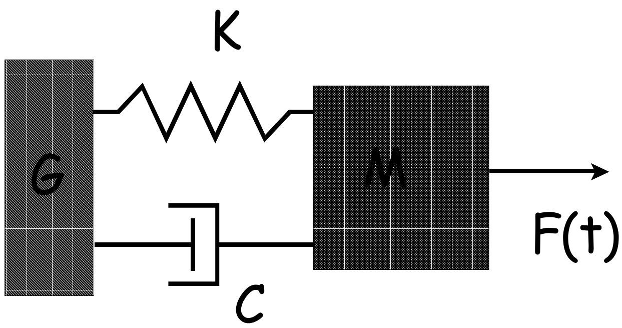

Figure 6. Single Degree of Freedom Model.

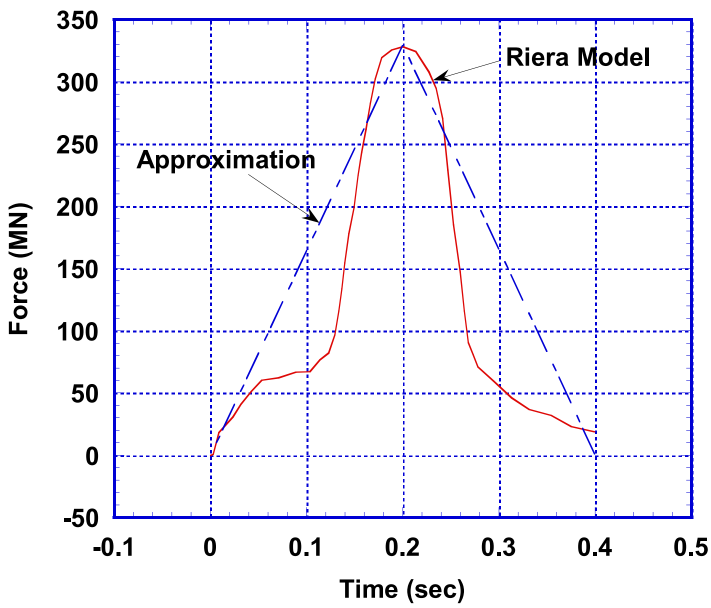

Figure 7. Impact Loading History from a Boeing 747.

RESULTS

The above model was exercised to study the response of a seismically isolated reactor building subjected to the impact of Boeing's 720 and 747 commercial aircraft. For the Boeing 720, the undamped case has a maximum displacement of 7.06 cm (25% shear strain) and, with 12% damping, the maximum displacement is 6.08 cm (22% shear strain). For the Boeing 747, the maximum displacement was 29.13 cm for the undamped case, which corresponds to a maximum shear strain of 105%, and for the damped case the maximum displacement was 25.09 cm (90% shear strain). It is noted that 100% shear strain of the full-scale isolator is 27.8 cm , which is equivalent to the total thickness of the rubber. For all cases, the peak displacement occurred at 0.64 sec, which was 0.24 sec after the end of the loading interval. These results are summarized in Table 1. Figure 8 shows the temporal displacement response at the top of the isolation system when impacted by a Boeing 747 travelling at 150 m/s. It is seen that 10 sec after impact the oscillations have been damped to small levels.

Table 1 Comparison of maximum aircraft impact responses at seismic isolation system for a representative nuclear power plant.

Impact response	B747-150m/s		B720-100m/s	
	0% damping	12% damping	0% damping	12% damping
Maximum displacement (m)	0.2913	0.2509	0.0706	0.0608
Maximum shear strain (%)	105	90	25	22

SUMMARY AND CONCLUSIONS

The aircraft impact responses of the seismic isolation system for a base isolated nuclear power plant when subjected to two commercial jetliners, Boeing 720 at the speed of 100m/s and a Boeing 747 at a speed of 150m/s, were calculated. A simple one degree-of-freedom model was developed for a representative reactor building and seismic isolation system. The isolators used were assumed to be steel laminated, high damping elastomeric bearings, which have been proven to be a viable technology. Parameters were chosen to represent the total mass of the reactor building as well as parameters to represent the seismic isolation system. These parameters were based on engineering judgement of existing systems. Numerical simulations were performed to determine the transient response of this system.

Based upon the parameters chosen to characterize the reactor building and isolation system, the following conclusions can be drawn from this initial study:

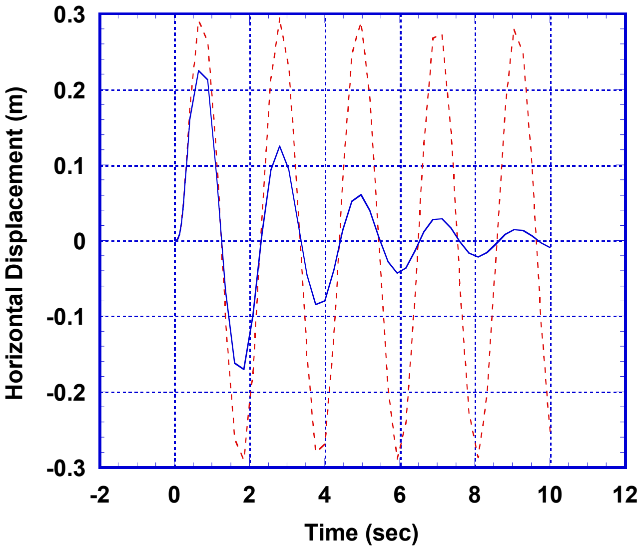

Figure 8. Displacement History of Isolation System

- The isolated reactor building can survive the impact from a commercial aircraft, such as a Boeing 720 at 100m/s or a Boeing 747 at 150 m/s;
- The maximum calculated horizontal displacement was 29 cm, which is equivalent to a shear strain of 105% and this is, in fact, nearly equal to the nominal design shear of 100% for earthquake design;
- There is a large margin to the failure shear-strain of the prototype isolator, which is about 300% (83 cm); and
- Damping of 12%, which is achievable with current elastomers, can reduce the peak displacement to 25 cm from 29 cm, which is a reduction of 14% of the undamped value.

Further studies of aircraft impact on seismically isolated nuclear power plants are needed to evaluate the following:

- The response to overturning moments by using a multi-degree-of-freedom model;
- The effects of impact location and angle;
- The response of a three-dimensional isolation system;
- The effects of a flexible reactor building; and
- The effects of grade level, up to and including underground reactor building.

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