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Effect of seismic isolation on the Tokamak in ITER

T. Tsunematsu [a,*], H. Namba [b], Y. Akutsu [a], Y. Ohkawa [a], A. Yagenji [a], M. Takeda [b], K. Yajima [b], Y. Nitta [b], K. Kobayashi [c], I. Maeda [c], Y. Takenaka [c]

[a] *Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Naka-machi, Ibaraki-ken 311-01, Japan*
[b] *Shimizu Corporation, Minato-ku, Tokyo 105-07, Japan*
[c] *Kajima Corporation, Minato-ku, Tokyo 107, Japan*

Abstract

The support structure of the International Thermonuclear Experimental Reactor (ITER) is suggested to have appropriate stiffness that accommodates both thermal distortion of the system and a maximum ground acceleration of 0.2 G (1 G = 9.8 m s^{-1}) due to earthquakes. For a site with earthquakes more severe than 0.2 G, the seismic isolation design is a possible candidate for keeping the seismic input low enough. The present design of ITER assumes that only the Tokamak pit portion is isolated, due to the whole building being very large and complex. In this study, dynamic analyses of the whole Tokamak building with a base-isolated Tokamak pit were carried out, and the effect of the isolation of the pit structure was evaluated. As a possible input level, a 0.4 G maximum ground acceleration was assumed. Particular attention was paid to the relative displacement between isolated and non-isolated portions, due to the smaller relative displacement being desirable for the design of pipes across the isolation gap. © 1998 Published by Elsevier Science S.A. All rights reserved.

1. Introduction

The ITER Tokamak consists of a superconducting magnet system and a vacuum vessel which contains in-vessel components such as blanket and divertor modules. The magnet system is cooled down to the superconducting temperature to provide a stiff magnetic field for plasma confinement and control. Temperature of the vacuum vessel varies from normal room temperature to 250°C. The support system in the Tokamak fusion reactor should be established with several major constraints: (1) to maintain a reasonable gap size (from several cm to several tens of cm) ranging from room temperature to the operating temperature; (2) to establish structural integrity against electro-magnetic loads due to plasma operation and disruptions; and (3) for seismic load. The support structure of the ITER Tokamak is designed for horizontal and vertical seismic loads with maximum ground acceleration of 0.2 G as well as for the dead weight and severe disruptions. The support structures are flexible to account for thermal loads as a consequence of the supercon-

* Corresponding author. Tel.: +81 29 2707477; fax: +81 29 2707368; e-mail: sekim@naka.jaeri.go.jp

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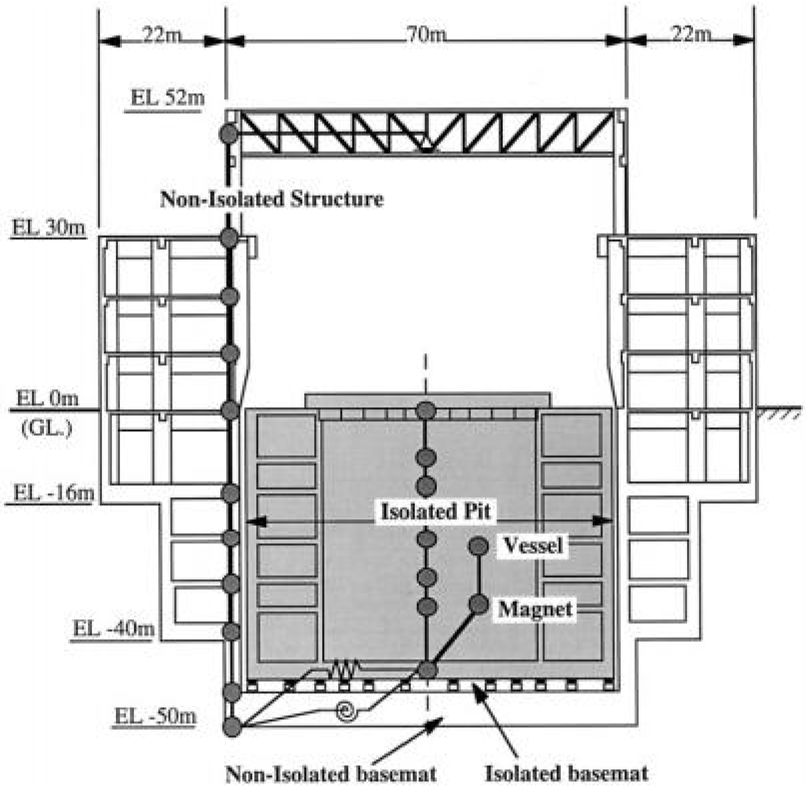

Fig. 1. Section of Tokamak Hall and analysis model.

ducting Tokamak. The analysis model of the ITER Tokamak is described by Tado et al. [1]. For more severe seismic conditions, an isolation system is required to ensure the structural constraints without a significant modification of the component design. Two major issues need to be resolved in order to ensure the integrity of the Tokamak support system by using the seismic isolation system: (1) to find an optimum frequency and load conditions of the isolation pads; and (2) to provide a non-isolated structure of the Tokamak building which contains the isolation part. In addition, the distortion of the connected pipes and electrical leads should be limited within a certain range (e.g. less than several 0.1 m) to ensure integrity of the support system. In this paper, models are proposed for dynamic analyses with resultant requirements to the isolation pads and the surrounding non-isolated structure of the Tokamak building. In the meantime, the design of the pipe system suggests that $\sim$0.15 m of a deviation is desirable [2].

2. Configuration of the Tokamak building

The Tokamak building has a complex structure with a box at the first floor and a cylinder below the second basement, where the outmost wall diameter is 94 m. Fig. 1 shows the section of the building in the east–west direction as well as the configuration of a mass-beam model which is discussed later. The pit portion, whose diameter is 64 m and is located in the underground center of the hall, is isolated. There is a gap of 1 m clearance in the horizontal direction between the isolated and non-isolated portion. The total weight of the isolated structure including the Tokamak components is $\sim$200000 tonf, and that of the non-isolated structure is $\sim$400000 tonf.

3. Soil conditions and design basis earthquake

The ground condition is assumed to be uniform rock, where the velocity of a shear wave is 500 m s^{-1} and the damping factor is 2%. As for the design basis earthquake, the maximum ground acceleration is set to be 0.4 G in the horizontal direction. The response spectrum of the earthquake was determined based on a Newmark-Hall spectrum [3]. The design basis response spectrum for 5% critical damping is shown in Fig. 2. An 'artificial' design basis earthquake for dynamic analysis was created for this study based on the spectrum [4].

4. Analysis models

A model of the Tokamak Hall for analyses in the east–west direction (X-direction from here on), that is composed of masses, beams and springs, is shown in Fig. 1. Isolators and the ground are modeled by spring elements with translational and rotational degrees of freedom. The characteristics of the spring that represent the ground were evaluated using an axisymmetric FEM analysis in order to evaluate the effect of soil-structure interaction (SSI) and the dominant round shape of the outer walls of the basement [5]. As for the Tokamak primary components, the magnet and the vacuum vessel are modeled as a concentrated mass. The period of the first vibration mode of the non-isolated structure in the east–west direction is 0.51 s, and that of Tokamak components is 0.65 s (1.5 Hz) [1].

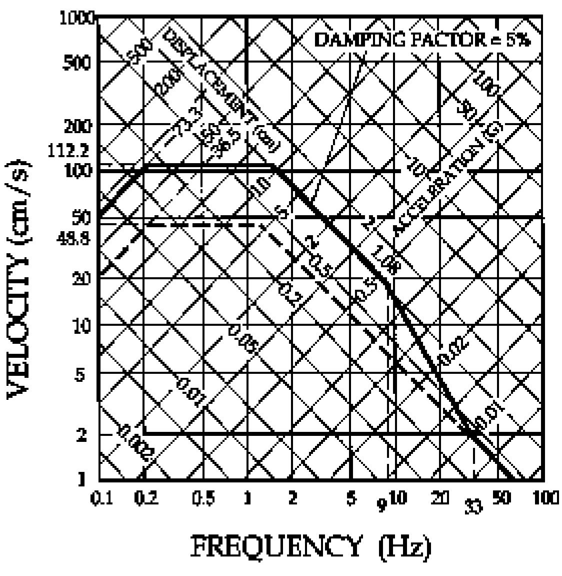

Fig. 2. Design basis earthquake (response spectrum $h = 5\%$).

5. Dynamic characteristics of isolators

Preliminary analyses were carried out in advance to find a set of isolation period and damping that keeps response acceleration of the isolated structure within an allowable range and that also makes relative displacement of the isolation layer as small as possible.

5.1. Parametric calculations with a 1-DOF model

A whole isolated portion including Tokamak components was modeled as one mass with one degree of freedom. The isolator layer is modeled by a non-linear spring with bi-linear hysteresis to represent a typical rubber bearing with lead core damper. Fig. 3 shows the hysteresis model. The design basis earthquake was directly used as input.

Parametric analyses were carried out using the following values.

Isolation period (second tangential stiffness)	$T_2 = 1.0$, 2.0, 3.0, 4.0 s
Damper yielding shear coefficient	$\beta = 0.02$, 0.05, 0.08

where: $T_2 = 2\pi\sqrt{W/K_2 \cdot g}$, K_2 is the second modulus of hysteresis and $\beta = Q_y/W$, Q_y is the shear force that causes lead damper to yield.

Non-linear dynamic analyses in the time domain were carried out. Fig. 4 shows the maximum response acceleration and the displacement of the isolated structure. The result shows that a parameter combination of $T_2 = 2.5$ s and $\beta = 0.05$ can reduce the maximum acceleration of the mass

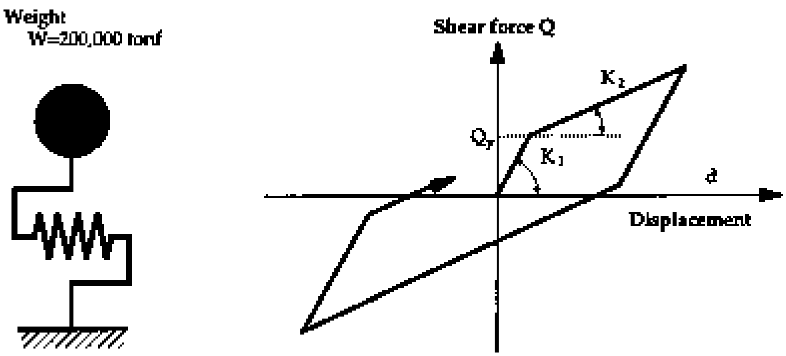

Fig. 3. Model of base-isolation and its hysteresis.

down to 0.2 G (202 Gal, 1 Gal $= 10^{-2}$ m s^{-1}) while the input is 0.4 G. This combination of parameters were then chosen for the following analysis with a stick model.

5.2. Response analysis with a stick model of the isolated portion (isolation period $T_2 = 2.5$ s)

An analysis with a stick model which represents the whole isolated portion and the Tokamak components was carried out to verify the previous analysis result with the 1-DOF model and to evaluate maximum acceleration of the Tokamak components. A non-linear spring with $T_2 = 2.5$ s and $\beta = 0.05$ was used for the isolation layer. This analysis provided the following result.

Maximum acceleration of isolated basemat	204 Gal
Maximum acceleration of Tokamak machine (vessel)	286 Gal
Maximum relative displacement at isolation layer	0.255 m

One may realize that the result of the previous 1-DOF model is equivalent to the response of the isolated basemat. As for the acceleration response of the Tokamak components, as mentioned in Section 1, the present design suggests that an allowable acceleration level is 0.2 G in terms of maximum ground acceleration. With the assumption that the Tokamak components are considered to be one mass, and if the Tokamak components are supported directly from the ground without isolation, then the response acceleration of the Tokamak components is ~ 500 Gal. This is clear if one sees Fig. 2 (0.4 G) scaling by a factor of 0.5, with such conditions that the natural frequency of the Tokamak components is 1.5 Hz and its damping is 5% (the present design is 4%). This means that the present design, which allows 0.2 G input, may accept a 500 Gal response of Tokamak components. Meanwhile, the maximum acceleration of the Tokamak Vessel, 286 Gal, is less than 500 Gal. Therefore, a higher response than 286 Gal can be accepted, so that one can make the isolation layer stiffer to get the relative displacement smaller. Subsequently, the following preliminary analysis with a full model including soil-structure interaction assumes a parameter combination of $T_2 = 2.0$ s and $\beta = 0.05$, which is stiffer.

5.3. Response analysis with a full model (isolation period $T_2 = 2.0$ s)

An analysis with a full model, including an axisymmetric ground FEM model, was carried out to include the effect of soil-structure interaction. A parameter combination of $T_2 = 2.0$ s and $\beta = 0.05$ was selected for this analysis as the axisymmetric FEM analysis of soil requires a linear analysis in the frequency domain, the non-linear parameter $\beta = 0.05$ was converted to an equivalent linear one (damping factor h) based on

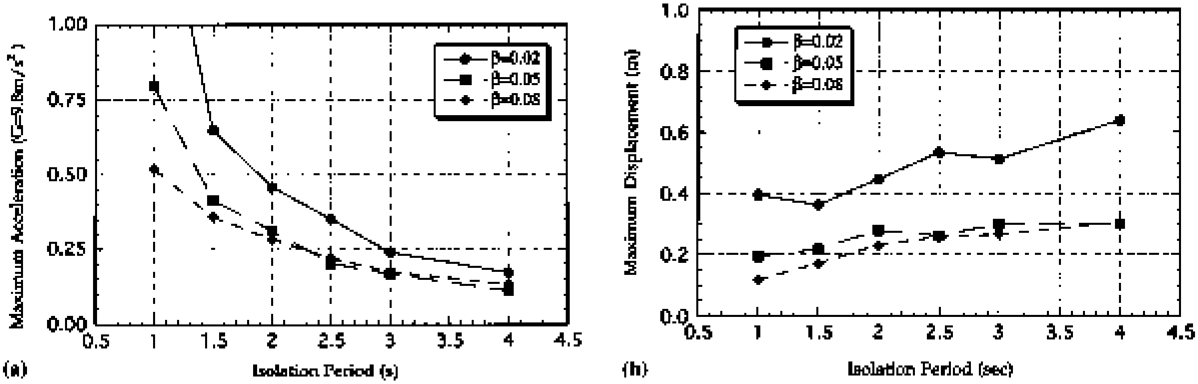

Fig. 4. Results of 1-DOF Model (response of isolated portion): (a) maximum response acceleration; results of 1-DOF Model (response of isolated portion); (b) maximum response displacement.

an area of a hysteresis loop (Fig. 3) obtained by the above-mentioned 1-DOF model. For this case, $\beta = 0.05$ subsequently turns out to be equivalent to $\sim h = 10\%$. The result of the full model analysis in a north–south direction (Y-direction from here on) was as follows. (Results in the X-direction were slightly smaller).

Maximum acceleration of isolated basemat	304 Gal
Maximum acceleration of vacuum vessel	303 Gal
Maximum relative displacement between isolated and non-isolated portions	0.252 m

The maximum acceleration of the isolated basemat (304 Gal) exceeds 0.2 G, however, the maximum acceleration of the Tokamak vessel (303 Gal) is still far less than the aforementioned 500 Gal. As the maximum acceleration of the Tokamak vessel (303 Gal) is not critical as yet, another stiffer parameter combination of $T_2 = 1.5$ s and $h = 10\%$ was selected for the final analysis in this study.

5.4. Dynamic analysis (isolation period $T_2 = 1.5$ s)

The combination of $T_2 = 1.5$ s and $h = 10\%$ was then chosen and a full model analysis was carried out. A summary of the maximum acceleration is listed in Table 1. All maximum values in Table 1 represent both X- and Y-directions. A coMParison of the response spectra of the design basis earthquake to that of the acceleration response of the non-isolated basemat and that of the isolated basemat is shown in Fig. 5. CoMParing the accelerations and response spectra of the design basis earthquake (0.4 G), non-isolated basemat (0.241 G) and isolated basemat (0.313 G), one may recognize that both SSI at the non-isolated basemat and base-isolation work as filters, which reduce higher frequency components where the frequency is higher than ~ 1.0 Hz ($T = 1.0$ s). In this study, the SSI effect is considerable, however, base-isolation still provide an improved and steadier contribution to the reduction of the response spectrum over a wide frequency range (higher than 1.0 Hz), as shown in Fig. 5. The present design of ITER assumes a concrete strength of $F_c = 29.4$ MPa. As the maximum shear stress in the non-isolated portion, which is 3.76 MPa, exceeds the desirable level of $F_c/10$, stiffening walls and frames may be required.

Table 1
List of maximum response accelerations

Location	Max. acceleration (Gal)
Non-isolated basemat	241
Isolated basemat	313
Vacuum vessel	388

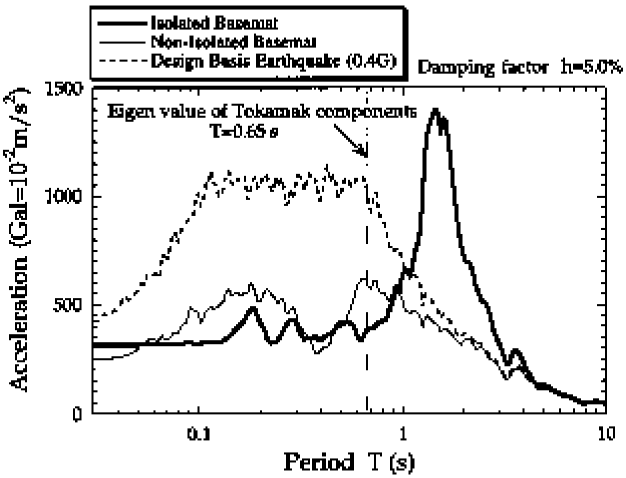

Fig. 5. CoMParison of response acceleration spectra.

6. Conclusion

The effect of base-isolation of the ITER Tokamak Hall was evaluated by dynamic analyses. A maximum ground acceleration of 0.4 G was assumed as input. Results from the analyses showed that base-isolation keeps the response of Tokamak components less than a reference case when they are not isolated and subject to a maximum ground acceleration of 0.2 G. However, even if a stiff isolator condition exists, such that the isolation period of 1.5 s is selected, the relative displacement between the isolated and the non-isolated portion is 0.196 m which exceeds a desirable value of 0.15 m. Therefore, the design of pipes across the isolation gap should accommodate a large deviation margin where the allowable limit may be 0.3 m in the present technology. From the view point of shear stress of the non-isolated structure, stiffening walls and frames may be required. Considering these findings, it is concluded that the ITER structure will remain feasible by means of base-isolation if it is placed on a site where the seismic hazard is twice as high as the assumption of the present design.

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