Seismic Tests on HTR-PM Reactor 1:3 Side Reflector Model

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ABSTRACT

The internals of HTR-PM, which consist of graphite/carbon bricks and metal components, exhibit nonlinear characters under seismic loads. In order to investigate the dynamic response of the core of HTR-PM, a seismic experiment of 1:3 scaled side reflector has been conducted at INET Tsinghua University. The graphite bricks and carbon bricks were connected by graphite dowels and keys with gaps between components. Metal components were designed to provide supports and constrains to the graphite internals. Three models which include lower-barrel without ceramic balls, lower-barrel with ceramic balls and whole model with ceramic balls were tested with random loads, OBE loads and SSE loads respectively. The test results, including modes, acceleration dynamic amplification factors, and displacement dynamic responses were obtained. According with safety standards, these experiments confirmed the integrity of the HTR-PM reactor core internals.

INTRODUCTION

HTR-PM (High Temperature Reactor-Pebble bed Modules) reactor core structure which is composed of graphite bricks, carbon bricks and keys/dowels, is recognized as multi-body structure. The graphite internals form the core cavity and the channels for the pebble balls, helium, control rods and absorber balls. This multi-body structure represent non-linear characteristic under seismic loads, because of the gaps between components. A seismic experiment was carried out to investigate the dynamic response of this structure.

Seismic designs were not introduced until the construction of AGR Heysham II nuclear plant, UK. The seismic criteria SSE and OBE were considered when the analytical program FLUNSH was employed, Allen (1989). Seismic tests aiming at investigating the integration of pebble-bed reactor core were performed, including 1:2 top reflector model, 1:3 side reflector model and 1:6 cylindrical model. These extensive experimental investigations confirmed the stability and safety of the HTR structure under seismic excitation, Theymann et al. (1989), although small rigid-body motions of side reflector brick were detected. A series of seismic tests were also conducted for VHTR, Ikushima et al. (1982), including 1:2 single column model, 1:2 region core model, 1:2 vertical 2D core model and 1:2 horizontal 2D core model. These models were utilized to investigate the dynamic behaviours and verify the analytical program GTOROTO. Column softening-hardening characters were observed, Ikushima et al. (1982).Recently, tests on a quarter scale model of AGR cores were commenced by University of Bristol, UK. The shaking table experimental program is to access the existing numerical analytical dynamic models (GCORE and SOLFEC), Dihoru et al. (2013).

An equivalent static force analytical method had been adopted to assess the integrity of HTR-10 test reactor graphite core structure. The single reflector column model for HTR-PM with various boundary conditions was tested on shaking table, Wang et al. (2010). Furthermore, basing on similarity laws, the double-layer graphite core structure model was researched under seismic excitations to reveal the dynamic response of 1:2 HTR-PM side reflector core structure, Sun et al. (2012).

This paper present the seismic tests on 1:3 HTR-PM core side-reflector model basing on similarity laws conducted in 2012. Random motion loads, seismic load including SSE&OBE loads were applied. The magnitude of random motion loads ranging from 0.1g to 0.2g. Thus acceleration data from detective spots were achieved and analysed.

SEISMIC TESTS TARGETS

These tests were conducted by China Academy of Building Research (CABR), aiming at:

(1) Achieving dynamic response of side reflector, including natural frequencies, modes of vibration, damping ratio, model under various seismic excitations.
(2) Investigating deformation, stiffness and displacement of graphite structure. Verifying the integrity and safety of graphite structure.
(3) Inspecting the stress and strain level of the keys/dowels and graphite components.
(4) Analysing the reliability of numerical model developed to investigate the dynamic response of side reflector model.

TEST MODEL AND LOAD CONDITIONS

Some simplification and modification of models were applied: (a) the models were 1:3 scaled, (b) notches were placed on the brick for the installation of acceleration sensors, (c) carbon bricks and graphite were the same in material, which is Chendu Tansu (NG-CT-01). The material properties are shown in table 1.

Table 1: Graphite material properties

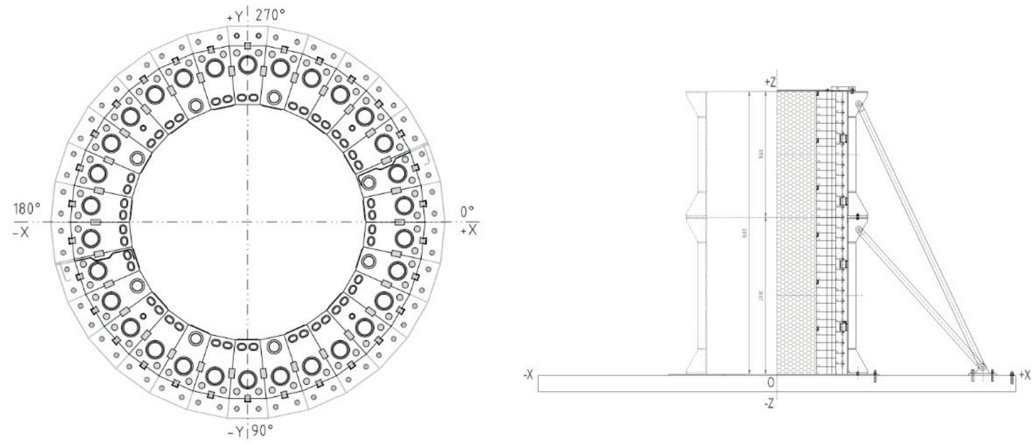
Dencity [kg/m^3]	1.85×10^3
Poison ratio	0.14
Young's modulus [GPa]	11.5
Friction ratio (graphite-graphite)	0.20
Friction ratio (graphite-metal)	0.15

The tests comprised of three conditions, shown in Table2.

Table 2: Test conditions

Condition	Model height [m]	Graphite layers	Carbon layers	Balls
1	2.0	20	15	Without balls
2	2.0	20	15	With balls
3	3.6	36	27	With balls

The model consists of graphite bricks, carbon bricks, graphite dowels/keys and metal components. Metal components include fasten belts, anti-distortion keys, barrels and metal supports. The complete cylindrical model was formed by 30 graphite bricks and 30 carbon bricks in horizontal section. Bricks piled up in vertical direction with 20 layers graphite bricks and 15 layers carbon bricks in condition 1-2, and with 36 layers graphite bricks and 20 layers carbon bricks in condition 3, shown in Figure 1. Upper layer bricks were connected with lower bricks via dowels. Graphite bricks and carbon bricks are connected by keys in the same way with tests conducted formerly, see Sun et al. (2012) and Lai et al. (2014). The steel barrel, with bricks built in, were installed on the base board. Anti-distortion keys were placed in the gap between carbon bricks and steel barrel to avoid rotation of the bricks assembly. The fasten belts were applied to prevent radial displacement of bricks. Ceramic ball scaled in size and density, filled the pebble bed formed by bricks, to simulate the fuel balls, shown in Figure 2.



(a) Horizontal section sketch (b) Vertical sketch of condition 3

Figure 1 Sketch of test model

Figure 2 Test model install on base board with ceramic balls

SEISMIC EXCITATIONS

The model was installed on the shaking table provided by CABR. The seismic excitations for each condition are:

(1) Random motion tests. On purpose to explore the natural frequencies, shape of vibration and damping ratio, the magnitude of excitations is 0.1g in each direction (X, Y and Z), and 0.2g in each horizontal direction (X and Y). Loading time lasted over 2min.

(2) Seismic excitations SSE OBE. To achieve dynamic response of the model, and investigate the ability to endure seismic loads.

(3) Random motion tests II. To explore the dynamic characteristic after seismic loads. To show the frequency and shape of vibration difference between before and after seismic loads.

SENSORS DISTRIBUTION

Acceleration sensors were mounted in notched graphite bricks, in which acceleration data can be achieved in three directions (radial, tangential and vertical). Detective spots located on the 12th, 18th, 24th, 30th, 36th layer. Five detective spots were mounted on each layer every 72° in circular direction. Note that, 2 additional detective spots were mounted on 6th layer. So, there were 12 detective spots mounted in condition 1-2, when only 20 layers graphite bricks were installed. And there were up to 27 detective spots mounted in condition 3.

FREQUENCIES

The frequency response showed similar results under X and Y excitations, due to symmetrical model layout. The results are shown in Table 3. Frequency decreased significantly after seismic excitations under condition 1 and condition 3. Frequency decreased slightly and increased after seismic excitations under condition2.

Table 3: Natural frequencies of the model

Condition	Random motion [g]	Frequency X [Hz]	Frequency Y [Hz]
1	0.10	20	18
	0.20	15	12
	0.20	5	6
2	0.10	15	13
	0.20	13	12
	0.20	14	13
3	0.10	15	14
	0.20	12	11
	0.20	9	10

DISSCUSION

Acceleration magnitude data achieved from 5 horizontal spots on 36th layer and 6 vertical spots in the 342° direction was selected and analysed. Under SSE excitation, horizontal acceleration frequency response is shown in Figure 3, vertical acceleration frequency response is shown in Figure 4. Significant incensement in acceleration magnitude is observed as detective spots' height increasing. Note that, due to the failure of the spot on 36th layer 342° , failure is not listed.

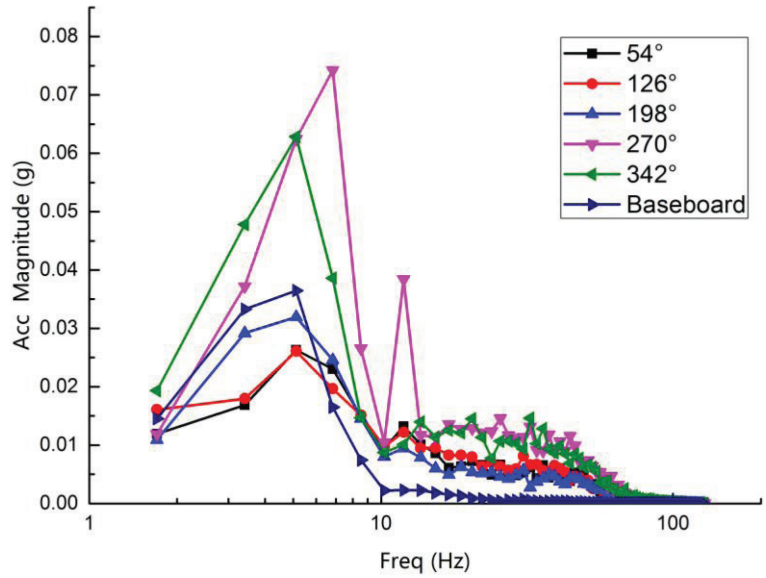


Figure 3: Acceleration frequency response on 36th layer

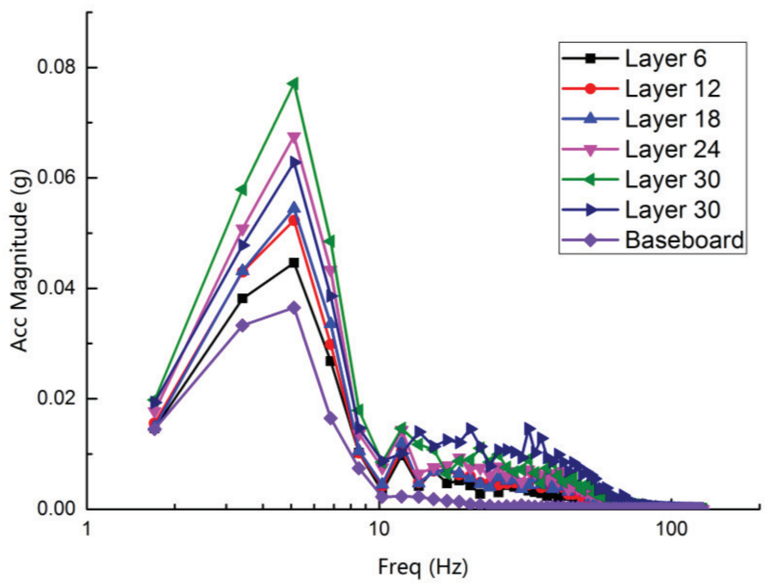


Figure 4: Vertical acceleration frequency response

Displacement this paper was obtained by integration of acceleration. The model exhibited low frequency feature, that magnitude peaks locate in low frequency area, and decrease rapidly as frequency increasing.

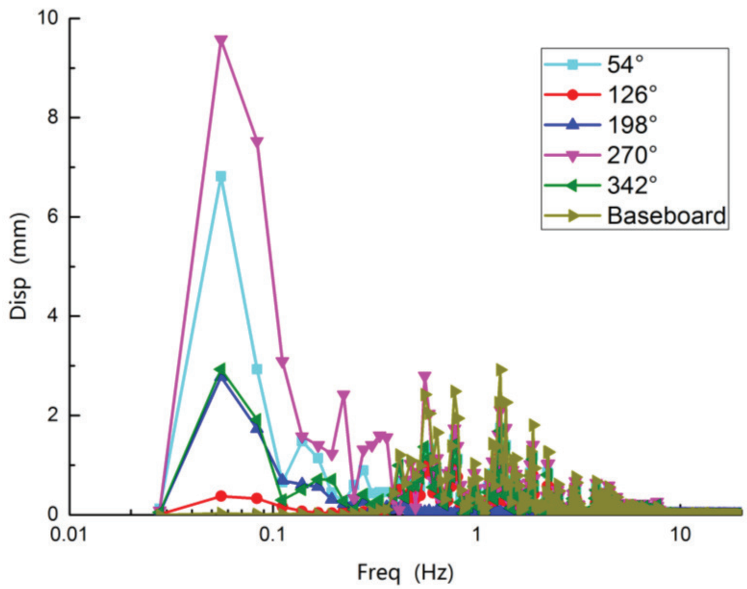


Figure 5: Displacement frequency response on 18th layer

CONCLUSIONS

The test achieved dynamic response of the model under various excitations. The natural frequencies decreased after the application of seismic loads. The stiffness the model decreased. Displacement and deformation of the model was analysed. Integrity and safety of graphite structure was confirmed.

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