Study on Shaking Table Test and Simulation Analysis of Graphite Dowel-Socket Structure

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SUMMRY:
In order to study the seismic behavior of graphite internals, a simplified dowel-socket column model which contains graphite bricks and graphite dowels was made. This graphite column model was test by shaking Table. The natural frequency and mode shapes of the model were gained by using sine wave sweep method and white noise sweep method. The model acceleration and deformation were also gained during Safe Shutdown Earthquake (SSE) load. According to the test model, a finite element model was build and calculated. Created by solid elements, this finite element model has contact properties which can simulate the contact behavior between different graphite internals. Modal results and dynamic response of FEM model were gained. The simulation analysis results and test results were compared. The results indicate that the FEM model is accurate in reflecting the dynamic characteristics of the real structure, and it will be the foundation of the future research work.

Keywords：Dowel-socket structure; Shaking table test; Dynamic response; Finite element method; Abaqus

1. GENERAL INTRODUCTIONS

The core structure of High Temperature gas-cooled Reactor (HTR) is mainly constructed with graphite internals, which does not only serve as reflector but also important structural components. The seismic behavior of the core structure is essential to keep the reactor’s safety functions. Those graphite internals, which can not be riveted or welded together like metallic internals, can only be connected together by key-keyway and dowel-socket components to form a relatively loose structure. Therefore, the dynamic analysis on the integrity of HTR core structure is very important.

2. TEST DESIGN AND INSTALLATION

2.1. Test Model Description

Because the real core structure of HTR is complex and contains hundreds of graphite internals, study object of this paper is a simplified dowel-socket graphite column model (Fig. 2.1.). The model consists of 20 bricks and 38 dowels which are made of graphite. The material parameters of graphite are shown in Table 2.1. The graphite internals sizes are shown in Figure 2.2. Graphite dowels are set into dowel holes on graphite brick, and then adjacent graphite bricks are connected by the graphite dowels (Fig. 2.3.). Finally all 20 graphite bricks are connected in the same way and the column model is installed (Fig. 2.3.).

2.2. Boundary Condition and Loading History

The graphite bricks are marked as brick 1, brick2…brick20 from bottom to top. The base of graphite column model (brick 1) is fixed on the shaking Table while the top of model is free without constraint.

Loading history include frequency sweep and SSE load. Frequency sweep is a method which can detect model dynamic characteristics while using SSE load can get model dynamic response.

The SSE waves are a special kind of artificial wave which is created by Testing Response Spectrum (TRS). TRS is created by iterative analysis base on the Required Response Spectrum (RRS). Three directions of RRS and TRS are shown in Fig. 2.5. The waves of SSE are shown in the Fig. 2.6.

Loading history of shaking table test is shown in Table 2.2.Because of the limited length of this paper, not all test loading histories are shown here.

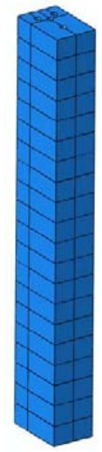


Figure 2.1. Column model

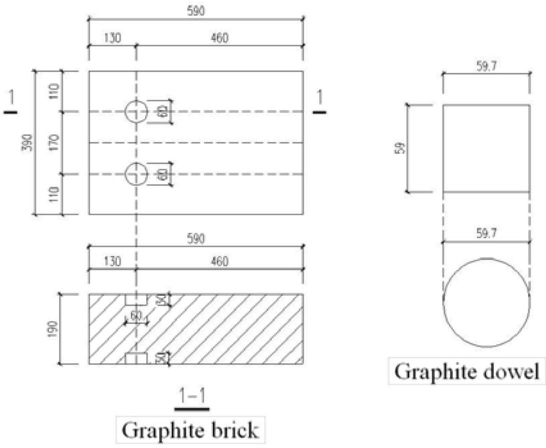


Figure 2.2 Sizes of bricks and socket

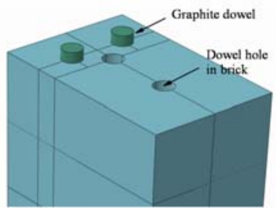


Figure 2.3 Schematic of installation

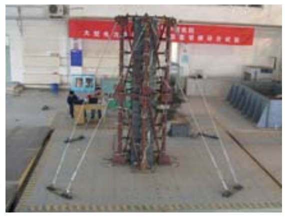
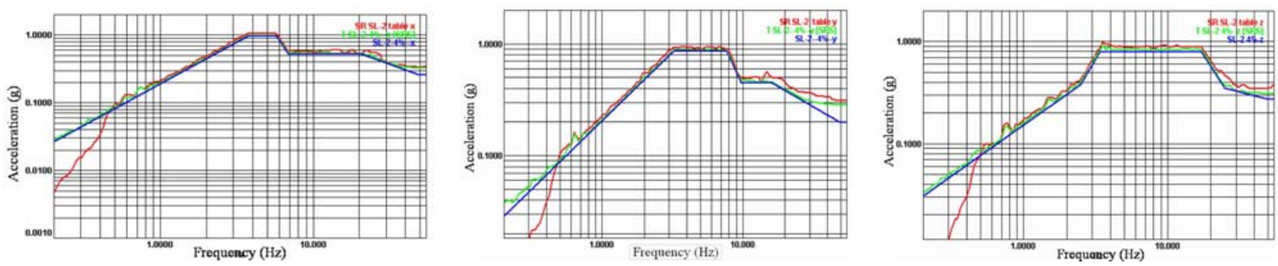


Figure 2.4 Aerial view of model

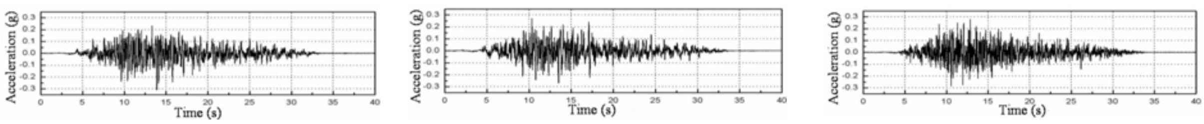
Table 2.1. Material parameters of graphite

Name of parameters	Unit	Value
Density	Kg/m^3	1850
Poisson's ratio	-	0.14
Modulus of elasticity	GPa	11.5
Compressive strength	MPa	80
Friction coefficient	-	0.20



(a) X direction (b) Y direction (c) Z direction

Figure 2.5. RRS (blue) and TRS (red) in three directions



(a) X direction (b) Y direction (c) Z direction

Figure 2.6. SSE waves in three directions

Table 2.2. Loading history of shaking table test

Test No.	Test load	Direction	Sweep peak / g	Test No.	Test load	Direction	Sweep peak / g
1.1	White noise	X	0.05	1.8	White noise	X	0.15
1.2	White noise	Y	0.05	1.9	White noise	Y	0.15
1.3	White noise	Z	0.05	1.10	White noise	X	0.20
1.4	Sine sweep	X	0.05	1.11	White noise	Y	0.20
1.5	Sine sweep	Y	0.05	1.12	SSE load	XYZ	-
1.6	White noise	Y	0.10	1.13	White noise	X	0.20
1.7	White noise	X	0.10	1.14	White noise	Y	0.20
				1.15	White noise	Z	0.20

2.3. Transducers Installation

As shown in Fig. 2.7. Test transducers include acceleration transducers, laser displacement meters and strain gauges. Acceleration transducers were set on the each graphite brick to measure the acceleration response. Laser displacement meters were set on the steel frame which was fixed around the graphite column to measure the displacement response. Strain gauges were set in groove of graphite bricks to measure the material strain. The details of transducers installation are shown in Table 2.3.

(a) Acceleration transducers (b) Laser displacement meter (c) Strain gauges in groove

Figure 2.7. Transducers installation

Table 2.3. Details of transducer installation

Transducer type	Transducer direction	Transducer locations
Acceleration transducers	X	brick1 - brick20
	Y	brick1 - brick20
	Z	brick9, brick19
Laser displacement meter	X	brick9, brick15
	Y	brick9, brick15
Strain gauges	-	brick5, brick16

3. TEST RESULTS AND ANALYSIS

3.1. Test phenomenon

During the SSE load, the graphite column model was shaken and graphite internals rattled against each other. After the shaking table test, slight residual deformation can be found between graphite bricks. The corner of graphite brick6 and brick7 were broken (Fig. 3.1.).

(a) graphite brick 6 (b) graphite brick 7

Figure 3.1. The corner of graphite brick was broken

3.2 Test results

3.2.1. Frequency and vibration mode

Base on the transducers data, the frequencies of graphite column model are shown in Fig. 3.2. Black line represents frequencies of X direction and red line represents Y direction. Because the model stiffness of X and Y direction are different, model frequency of X direction is larger than Y direction.

As discussed above, graphite column model consists of many graphite internals and these graphite internals are connected by dowel-socket style installation. The model can be defined as multi-body system. Model frequency is not a constant value but depended on the amplitude of table input. For example, the model frequency of X direction has been changed from 8.0 Hz (0.05g input) to 6.7 Hz (0.1g input).

The first vibration mode curves of graphite column model are shown in Fig. 3.3. The vibrating amplitude alone two directions have been described in curves. Graphite bricks which are in the top of model have bigger vibrating amplitude.

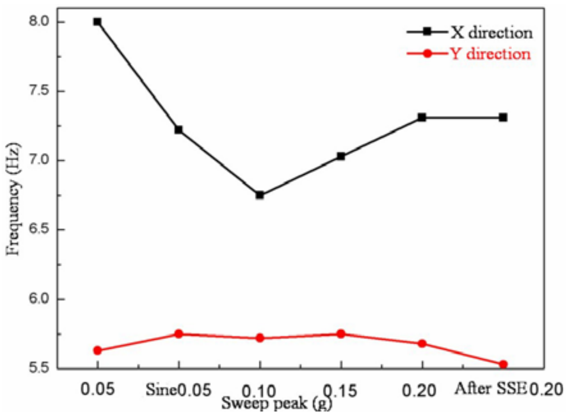
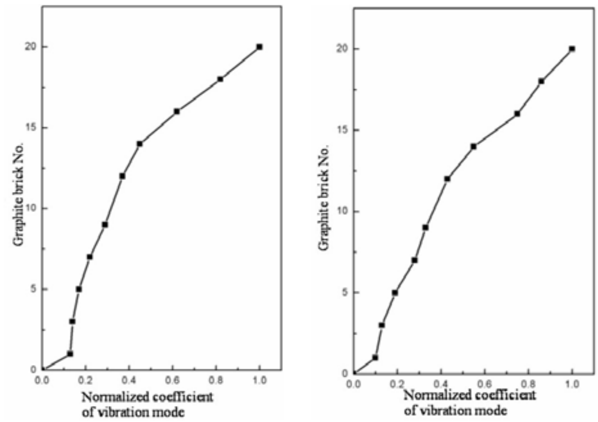


Figure 3.2. Frequency changes of model



(a) X direction (b) Y direction

Figure 3.3. First vibration mode curves

3.2.2. Comparison of sine sweep and white noise sweep results

In order to verify the accuracy of white noise sweep method, two different sweep methods were used in test. White noise sweep is the major research method and sine sweep is only used in test No. 1.4 and No. 1.5 as comparison (see Table 2.2.). The frequency results by using different sweep methods are shown in Table 3.1. From the table, some conclusions can be drawn as following.

1. As discussed above, frequency of graphite column model has been changed with different table input. This phenomenon can also be proved in Table 3.1.

2. When white noise sweep and sine sweep input are 0.05g, the frequency difference of both sweep method are not significant.

3. When 0.05g sine sweep at Y direction (test No. 1.5) was finished, 0.10g white sweep at the same direction (test No. 1.6) was tested. The results indicated that the frequency values of different sweep method are very close.

Table 3.1. Frequency results of different sweep method (Unit: Hz)

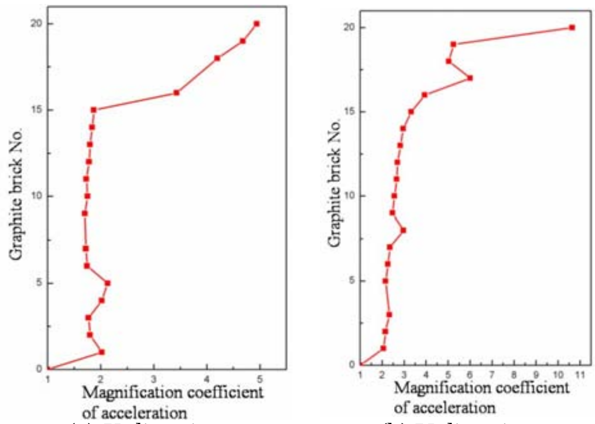
	0.05g white noise sweep	0.05g sine sweep	0.10g white sweep
X direction	8.00（Test No.1.1）	7.22（Test No.1.4）	6.75（Test No.1.7）
Y direction	5.63（Test No.1.2）	5.75（Test No.1.5）	5.72（Test No.1.6）

3.2.3. Dynamic response

Base on the transducer result of each graphite brick, the dynamic response of whole graphite column model can be described. Curves of model magnification coefficient acceleration are shown in Fig. 3.4. Curves of relative displacement between adjacent bricks are shown in Fig 3.5. From these curves, some conclusions can be drawn as following.

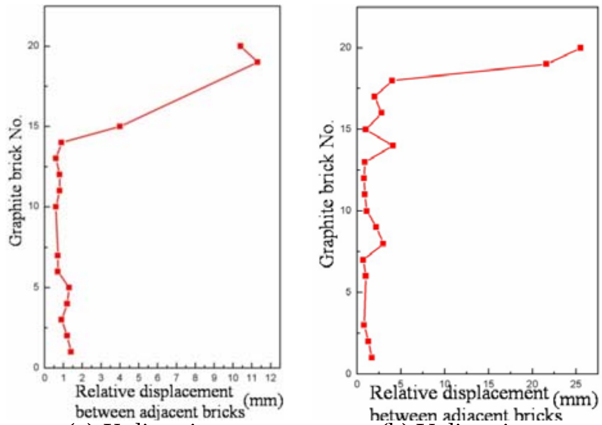
1. The curve shape of X and Y directions are very similar to each other, but the curve value in Y direction is larger than X direction. This indicates dynamic response in Y direction is more obvious than X.

2. Because the top of graphite column model was free without constraint, these bricks which are in top of the column have stronger dynamic response as shown in curves.



(a) X direction (b) Y direction

Figure 3.3. Model magnification coefficient



(a) X direction (b) Y direction

Figure 3.4. Relative displacement between bricks

4. FINITE ELEMENT MODEL AND SIMULATION ANALYSIS

4.1. Finite Element Model description

A finite element model of graphite column was build by Abaqus (Fig. 4.1. and Fig. 4.2.). Use solid elements to creating all graphite internals. These graphite internals are assembled in the same way of test model. Material properties are defined base on Table 2.1. Contact properties are also defined in order to simulate contact behavior between graphite internals.

Because graphite column model is multi-body system, and graphite internals rattled against each other during the test. Dynamic explicit algorithm is adopted for this situation.

The boundary condition and loading history of simulation model and test model are the same.

Figure 4.1. Finite element model

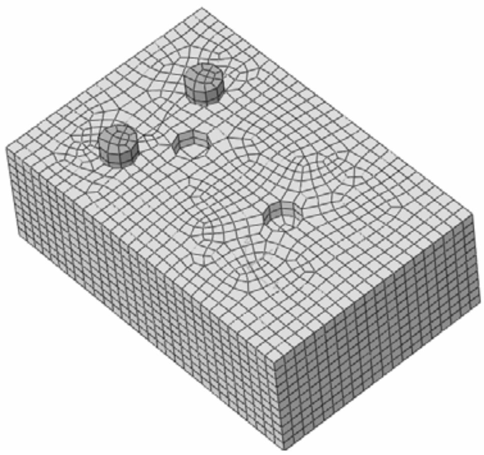


Figure 4.2. Model details

4.2. Dynamic Response

Because of the limited length of this paper, not all analysis results are shown here. Some field output results are shown below. Every graphite brick has different displacement value in X direction as shown in Fig. 4.3. Brick 2 to brick 20 have displacement in Z direction as shown in Fig. 4.4 Stress concentration area of graphite dowels are shown in Fig. 4.5.

Acceleration and relative displacement results are calculated and compared with the test results. The envelope curve of peak acceleration comparison is shown in Fig. 4.6. The envelope curve of relative displacement between graphite bricks is shown in Fig. 4.7. The curves indicate that simulation analysis results agree well with test value.

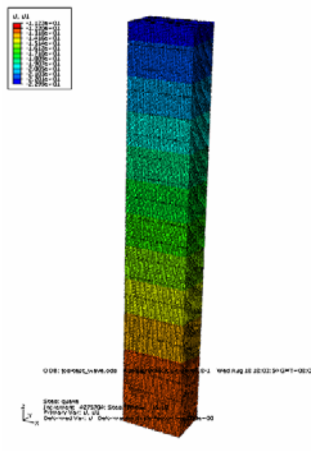


Figure 4.3. Displacement in X direction

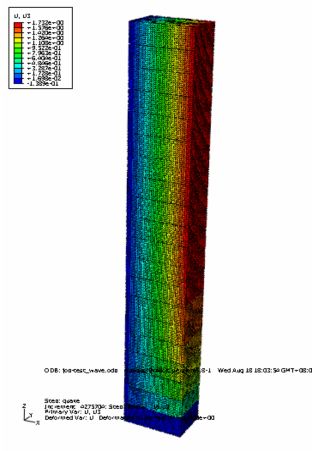


Figure 4.4. Displacement in Z direction

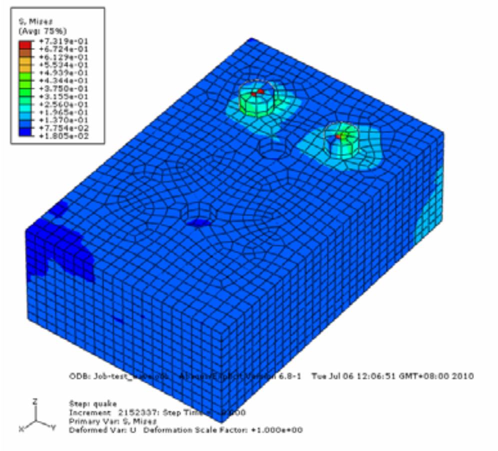


Figure 4.5. Stress distribution

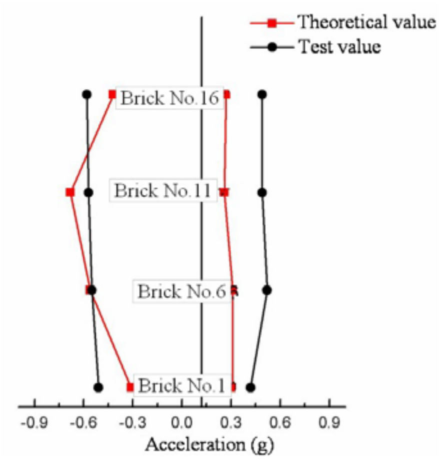


Figure 4.6. Envelope curve of acceleration

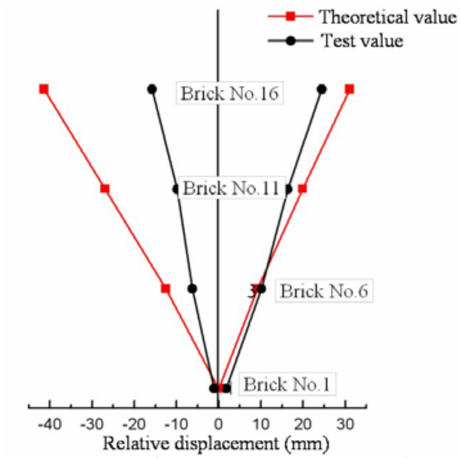


Figure 4.7. Envelope curve of relative displacement

4.3. Modal Analysis

Because graphite column is multi-body system, modal analysis method is different from traditional civil structure. Some simplification should be done before modal analysis. Graphite dowels are deleted in finite element model and replaced by connectors. The lateral stiffness of connector is the same as graphite dowel. This simplified model is assembled with connectors and doesn't include any contact surface (Fig. 4.8.).

Modal analysis results are shown in Fig. 4.9. and Table 4.1. Frequency results indicate that theoretical value of frequency is larger than test value. The reason of value differences depends on many factors. One reason is that the theoretical model is a simplified model; some mechanical properties such as friction coefficient aren't defined in model.

Table 4.1. Simulation analysis results of frequency (unit: Hz)

	Theoretical value			Test value
	First frequency	Second frequency	Third frequency	First frequency
X direction	6.2	19.3	34.4	4.8
Y direction	4.7	14.9	27.3	2.7

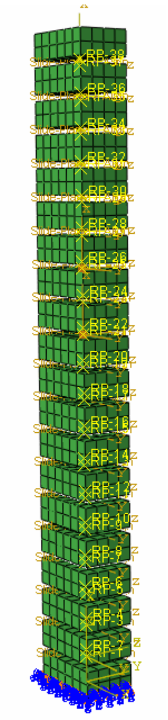
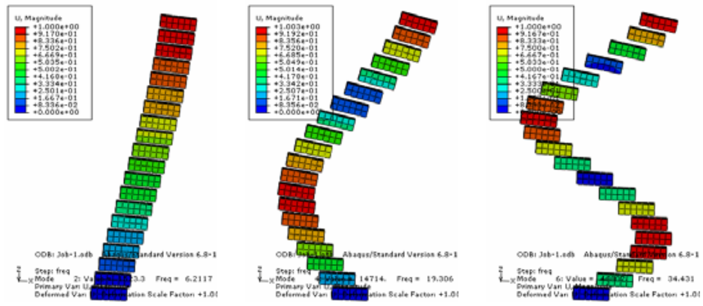
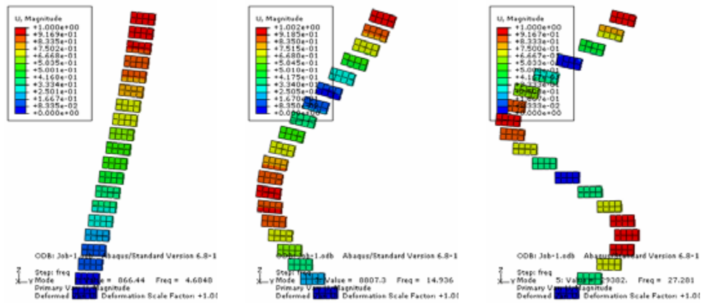


Figure 4.8. Simplified model



First mode Second mode Third mode

Figure 4.9. Vibration modes of X direction



First mode Second mode Third mode

Figure 4.10. Vibration mode of Y direction

5. CONLUSION

From the studies of presented in this paper, the following conclusions can be drawn:

1. Because graphite column model have contact problem, model dynamic characteristics (lateral stiffness and frequency) have changed during the shaking table test.

2. According to the comparison results of different sweep method, frequency values of sine sweep method and white noise sweep method are very close.

3. Base on the test data, some dynamic analyses are done. The results indicate that graphite bricks in top of the column have stronger acceleration response and relative displacement response.

4. A finite element model was build. Simulation analysis results and test results are compared. The results indicate that the finite element model is accurate in reflecting the dynamic characteristics of graphite column.

AKCNOWLEDGMENT
This work has been supported by the National S&T Major Project of China (Grant No. ZX06901).

REFERENCES

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