Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Full scale dynamic test of the 105-storey Ryugyong Hotel in Pyongyang

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ABSTRACT : A full scale test of the Ryugyong Hotel was carried out to evaluate the dynamic properties of the structure for two lateral perpendicular directions and torsion, applying both ambient and forced vibration test methods. Within the forced vibration test procedure two complete tests were performed: first applying the excitation force at the 94th floor and measuring the response along the vertical axis of the central core (considering the structure as a cantilever) and then, generating the force at 25th floor, at the edge of one of the wings, in direction orthogonal to it's longitudinal axis, and measuring the response along the wing - at every tenth floor (considering the structure as a 3D-system). The results presented in the paper were obtained by integration of the separate tests' results in a spatial presentation of the structure's dynamic properties.

1 INTRODUCTION

The Ryugyong Hotel in Pyongyang is an unique structure considering the combination of its: (1) size: 105 story- 320 m height and 550,000 tones mass; (2) shape: pyramidal-look elevation, three wing star in plan, (3) structural system: reinforced concrete bearing walls and (4) casting technology: high strength concrete.

The test presented in this paper is a part of a research project named: "Research study for evaluation of seismic resistance of The Ryugyong Hotel in Pyongyang" - which consists of the following experimental and analytical investigations:

1. Full scale - ambient and force vibration - tests of the building for definition of its dynamic properties;
2. Analysis and definition of seismic parameters of the building site;
3. Quasi-static tests of selected structural parts of the building (the typical wall-slab connection and the link between the wing and the central core) for definition of their strength and deformability characteristics;
4. Shaking table test of a reduced scale model - a test which should provide information on the dynamic behaviour of the entire building, subjected to both low (dynamic response in linear range - the design level) and high intensity earthquakes (response in non linear range - observation of the structure's behaviour at the stability limit);
5. Development of mathematical models for three dimensional both linear and nonlinear dynamic response analysis of the structure (using the results of the field and laboratory tests);
6. Installation of a system for monitoring the behaviour of the building during the earthquakes which may occur in future.

2 DESCRIPTION OF THE TESTED STRUCTURE

The Ryugyong Hotel is a complex consisted of three separated structures: (1) a central 105 storey tower, (2) three 25 floor additional buildings rising by each of the tower wings and (3) the ground floor part around the tower (Fig.1); built on a site area of 60 ha, on mainly new and weakly weathering sandstone.

The 105 storey tower is 321.3 m high (8x3.6 + 96x3.0 + 1x4.5 m) and it's floor area is 320,000 m^2. The tower consists of three wings, 56.4x18.9 m (in plan), around a central core - a cylinder with diameter 34.2 m. The wings rise vertically up to the 25th story, then taper up to the 81st floor (with a slope angle of 75.6^0), where they vanish, while the central core starts to taper towards the top, into a cone with the same slope (Figs 1 and 2).

The bearing wall spatial system is formed as a combination of (1) reinforced concrete circular walls of the central core, (2) both external and corridor walls of the wings (the wall ratio: at the wings 0.0149, in the core 0.172) and (3) reinforced concrete slabs.

Two different quality concretes were used in the construction: (1) the "M-450" concrete (f_c=40 MPa, E= 35,000 MPa) was built in the structural elements of the first 51 stories and (2) the "M-400" concrete (f_c=35 MPa, E= 33,000 MPA) for the remaining 53 stories. Two types of reinforcement were applied: (1) Type III - profiled $25Mn_2Si$ steel bar (yielding point σ_y=400 MPa, tensile strength f_t=600 MPa, ultimate point strain ε_u=14% and modulus of elasticity E= 210,000 MPa), and (2) Type I - circular St.3 steel bar, used as structural reinforcement, with no regard to calculations (σ_y=240 MPa, f_t = 380 MPa, ε_y=25%,

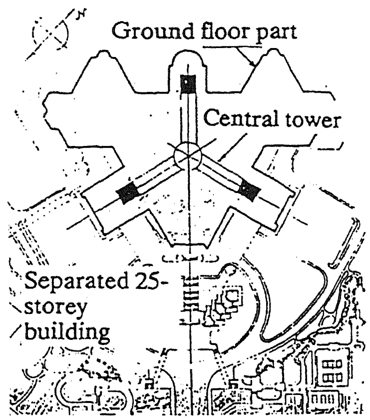

Figure 1. Plan of The Ryugyong Hotel

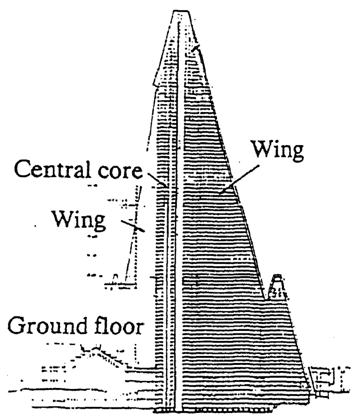

Figure 2. Elevation of the central tower

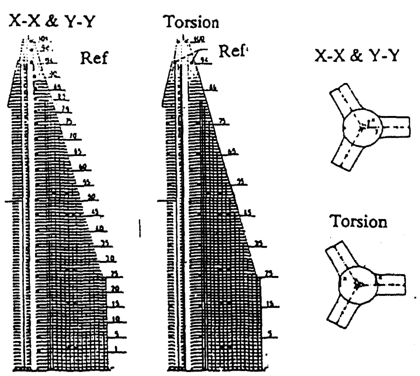

Figure 3. Ambient vibration test: instrumentation set-up

and E = 210,000 MPa). The total mass of the building after the completion of all works should be 559,770 t, the mass of the skeleton 461,300 t, while the mass of the structure in the testing stage was 490,282 t.

The object of the full scale test was only the central tower. In the period the test was carried out (April and May 1990), the skeletons of both central tower and additional (separated) 25 storey blocks were completed, while the ground floor part was under construction. These skeletons were completely built within a year, eleven months before the test. In the time of the test the plastering work on the skeleton was almost completed, while the attachment of thermo isolation to the external walls was about 90% finished. About 60% of the intermediary walls masonry was also completed, and 5 elevators as well as a crane at the top of the tower were in use. The construction work to be done after the test was: (1) assembly of the intermediary walls, (2) sticking of fixture and finishing elements and (3) equipment of the furniture and facilities.

3 AMBIENT VIBRATION TEST (AVT)

The definition of the natural frequencies of the structure was initial step of the procedure. The response spectra were recorded at several locations (at various levels) in order to detect as much natural frequencies as possible. Otherwise, some of the spectra peaks, and consequently the corresponding mode shapes could have been missed due to either a 'zero point' of particular mode at the considered level or the evidently influential mode coupling effects.

The results of these preliminary measurements (Table 1) have shown that:

1. All the modes significantly envolved in the response were concentrated in the frequency range 0.0-5.0 Hz (thus, the low-pass filter of the signal conditioner was adjusted at 30 Hz, while a 10 Hz low-pass filtering option was selected for the in-situ processing of the signals),

2. After 10-12 averages the spectra became steady. Thus, 200 s (16 sequences - 16x12.5 = 200 s) recording time - option was adopted for the in-situ processing and 10 minutes duration for the time histories recorded on tape;

3. The first three modes - at 0.5, 1.2 and 2.0 Hz - prevaileds in both X- and Y-direction response;

4. The third (2.40 Hz), the fourth (3.28 Hz) and the fifth (4.00 Hz) mode were predominant in the torsional vibration of the building.

The natural mode shapes of the structure were defined by simultaneous recording of the response at four locations - one sensor was used as referent, while the other three were travelling through the measuring locations (Figure 3).

The AVT results can be summarised in several general conclusions:

1. The first mode frequency in all the three directions was detected between 0.5 and 0.6 Hz, but due to the significant mode coupling effect the accurate value definition was impossible.

2. The second mode shape in both X (1.20 Hz) and

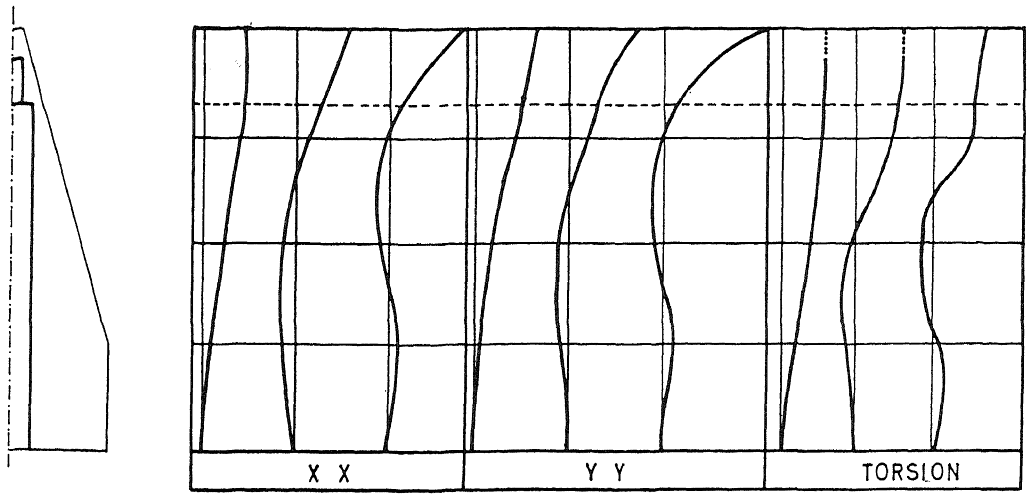

Figure 4. Ambient vibration test: vertical mode shapes

Table 1. Natural frequencies of the structure - defined in the ambient vibration test

Direction	Frequency (Hz)				
	1	2	3	4	5
X-X	0.50	1.20	2.00	2.64	3.44
Y-Y	0.56	1.28	2.08	2.88	4.00
Torsion	0.56	1.60	2.40	3.28	4.00

Y (1.28 Hz) direction had predominant participation in the response of the structure. The second torsional mode was not emphasized and its peak ocurred at various frequencies in the range between 1.40 and 1.60 Hz, hardly recognisable sometimes (due to very close strong lateral modes).

3. The third mode in both X (2.00 Hz) and Y (2.08 Hz) direction had also strong effect to the overall response. The third torsional mode was recorded at the frequency of 2.32 Hz.

4. It was evident that no final conclusion on the values of the higher lateral modes frequencies (in the range above 2.0 Hz) could be drawn. The main reason was that their participation in the response was very modest, while the range in which the fourth and the fifth mode had been expected overlapped with the range of the strong torsional resonances. The frequencies of 3.28 Hz and 4.00 Hz were adopted as 4th and 5th torsional modes, while for the higher modes the situation was same as for the remaining two directions.

After a careful analysis of all the acquired results the first three modes of vibration in each of the tested directions were evaluated (Fig. 4). The major problem in the evaluation of the higher modes was that their phase angles were completely unrecognizable in the phase spectra. Although possible, the evaluation of mode shapes based only on information on their amplitudes, never gives reliable results (especially for the frequently- phase- changing higher modes). However, the higher modes occurred in the frequency range in which the force generators employed in the FVT were far more efficient.

4 FORCED VIBRATION TEST (FVT)

In FVT the force should be applied at the top of the building - where zero point of a mode shape never occurs. But, in this case the last 10 floors were very flexible and it was evident that the force could not be transmitted to the lower part of the building. Thus, the 94th floor was chosen in the tests for definition of the central core mode shapes (FVT-94) as a level well connected to the rest of the structure and - according to the AVT results - as a level with no zero point for the first three modes of vibration in each of the tested directions. The 25th floor was selected for application of excitation force in the tests for definition of the wing natural frequencies and mode shapes (FVT-25).

The locations at which the response was measured (measuring points) were selected according to the test objectives - to provide detailed three dimensional picture of the building's dynamic properties, compatible with the presumed mathematical model for dynamic response analysis. The AVT results had also indicated that at least 21modes of vibration might be excited within the range from 0.5 to 9.0 Hz. Therefore, the vertical mode shapes of the central part were observed at every fifth floor to provide information on all the phase variations, which in case of the higher modes may occur within few levels (it means that some of the higher modes could have been missed if every tenth

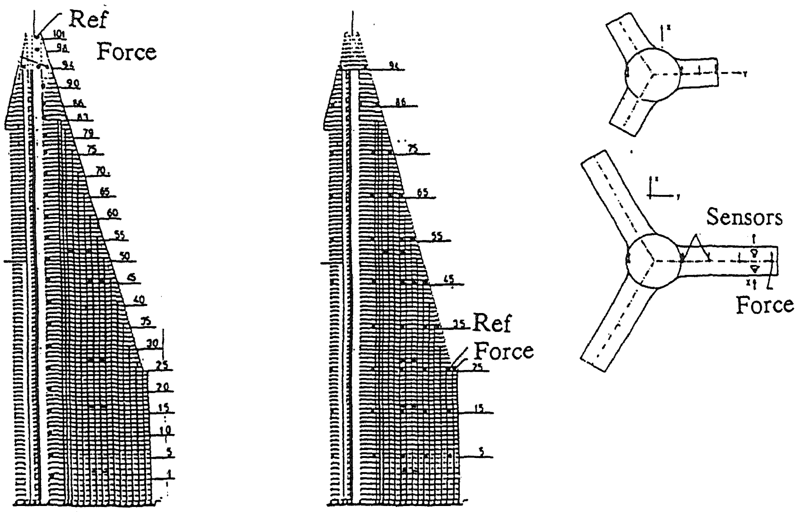

Figure 5. Forced vibration test set-up

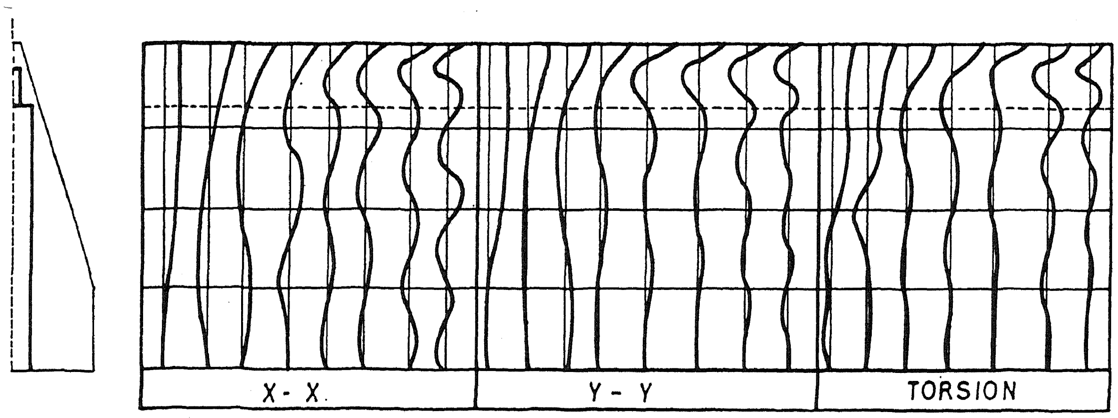

Figure 6. Final results : vertical mode shapes

floor was monitored). In the investigation of the wing mode shapes five locations along the wing were chosen for the lower floors (this number was reduced at the higher levels where the wings are shorter), in order to record the horizontal shape associated with the corresponding vertical mode of vibration. The distribution of the measuring points in all the single tests performed during the FVT procedure (a total of 61 single test) is presented in Fig 5.

4.1 Forced vibration test with force acting at 94th floor (FVT-94)

In the FVT-94-FRC tests as much as 14 to 16 resonant frequencies were detected in each of the test directions, in the considered range (0.0 - 8.0 Hz). Some of them had appeared as interference from another direction, but in some cases - particularly in the range between 2.5 and 5.0 Hz - the mode coupling effects were so strong that it was impossible to distinguish to which mode each of the detected frequency belonged. Thus, they have been evaluated in the tests for definition of the mode shapes.

The measurement of the mode shapes (MS test) was performed in series of single tests, each of them consisting of successive test sequences in which the excitation force was adjusted at one of the frequencies indicated in the (previously defined) FRC and the response of the structure was simultaneously measured at both the referent and each of the remaining five measuring points. After each single test all the acquired results were processed and the corresponding parts of all the considered vertical modes were plotted. The procedure was repeated for all test directions and vertical shapes were defined at all indicated frequencies (Figure 6).

Horizontal mode shapes were also measured at

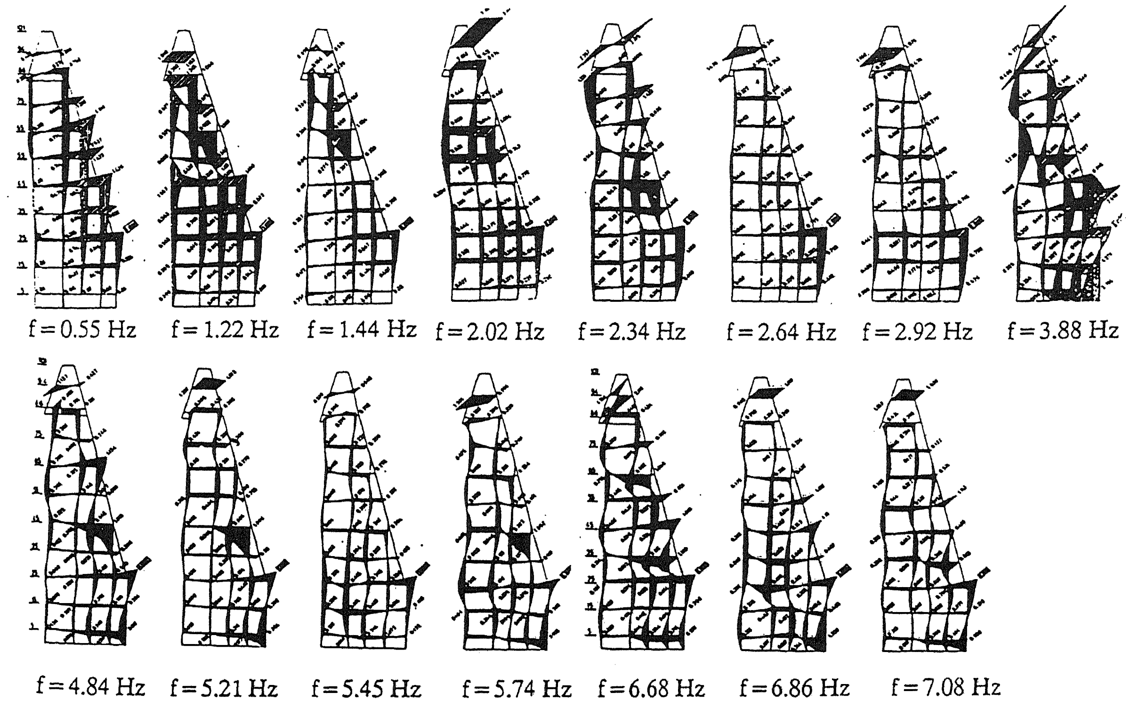

Figure 7. Wing mode shapes of vibration

selected floor levels: 75, 50, 25. The results of these tests had to provide the necessary link between the central core and the wing measurements for integration of the test results into three dimensional mode shapes.

4.2 Forced vibration test with force acting at 25th floor (FVT-25)

The FVT-25 was performed as a complete forced vibration procedure with excitation force acting only in one direction - normal to the longitudinal axis of the wing :

1. A set of FRC tests, in which the response was measured simultaneously in three locations at 25th floor (including the referent point) and in a location at 94th floor (the one used as referent in the previous tests) and
2. A series of MS tests in which the measuring points were distributed along the wing's longitudinal axis, including two locations at the edges of the central core, at every 10th floor .

Due to the significantly higher level of response to torsion, the FRC obtained in the FVT-25 were very usefull for final evaluation of the natural frequencies of torsional vibration, uncoupling them from the lateral vibration resonances.

The mode shapes evaluated in the FVT-25 are a part of the three dimensional picture of the buildings' dynamic properties. They were also used for assignment of the detected natural frequencies to the corresponding mode shapes i.e. for distinguishing the torsional mode shapes from those of the remaining two test directions. In this test the floor rotations were measured in several points within the floor levels and the generated torsional force was considerably higher than the force applied from the narrow (and distant) 94th floor. Observing the wing shapes (Figures 7 nad 8), the first 7 torsional modes (at 0.56, 1.44, 2.34, 3.88, 4.84, 5.46 and 6.68 Hz; respectively) can be easily separated from the lateral vibration shapes.

The natural frequencies of the first eight modes in each of the tested directions, as well as the corresponding damping ratios, are specified in Table 2.

5 CONCLUSSIONS

An extensive field test study of the dynamic properties of The Ryugyong Hotel was performed using the ambient and forced vibration test methodology. A detailed spatial picture of the building's natural mode shapes of vibration was obtained. In the study the structure was considered both as a cantilever and as a spatial structural system.

1. The comparison between the test results and the dynamic properties obtained in the design showed a very good agreement. It proved that although simplified, the mathematical model used for the design of the building gave acceptable results, even for structural systems of this size and type.
2. The full scale test results can be used as a basis