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# Shaking table test of 1/40 scale model of 105-storey Ryugyong Hotel

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ABSTRACT: To predict the earthquake response of the 105-storey reinforced concrete shear wall building (Ryugyong Hotel, Pyongyang, DPR Korea), a model in scale 1/40 was tested on the shaking table at the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology, Skopje, Republic of Macedonia. The model was designed following the principles of true replica modelling using heavy plaster mixture with sand as a material for model construction. The model was 8.03 m high with a total mass of 14.6 t. By simulating various intensity earthquakes (from 0.05 g to 0.90 g) the linear and nonlinear behaviour of the model was investigated up to the final collapse. It was predicted that for the design level of the ground motion on the site of 0.2 g, the building would have an elastic response without any cracks, while for the maximum expected earthquake intensity (0.35 g), initial cracks in the wings between the 50th - 70th floor will occur due to bending. The nonlinear failure mechanism develops for a ground motion higher than 0.45 g. The general conclusion was that both the design and construction procedure applied to this Hotel were correctly performed.

## 1. INTRODUCTION

The dynamic behaviour of highrise buildings exposed to earthquake motions is a very important problem, particularly in the case of specially shaped structures as it is the Ryngyong Hotel building. Made by reinforced concrete shear walls and monolithic floor slabs, with a total height of 321.3 m (105 stories) and a total mass of 470 000 t, it represents a really unique structure in world scale. Considering these facts, within the scope of the scientific cooperation between the Institute of Design and Construction Paek Du San, from Pyongyang, DPR Korea, and the Institute of Earthquake Engineering and Engineering Seismology, Skopje, Macedonia,, a scientific research project was accomplished within the period of 1989-1992. The project consisted of four phases: (1) Full-scale testing of the constructed building applying forced and ambient vibration methods (1990); (2) Quasi-static testing of vital structural elements and assemblage (1990-1991); (3) Investigation of seismic parameters on the site (1990-1991); and (4) Shaking table test of 1/40 scale model (1991).

## 2. DESIGN AND CONSTRUCTION OF THE MODEL

Considering the geometry and the mass of the prototype building and the capacity of the shaking table at IZIIS Dynamic Testing Laboratory in Skopje, a model in scale 1/40 was adopted as the most convenient one. Calculation of the model parameters have been performed following the principles of similitude between the model and prototype based on the Buckingham's theorem. For proper simulation of the inertial as well as the gravity forces, a combination of the true replica and artificial mass simulation modelling technique has been applied. Table 1 shows the proportion between the prototype and model parameters for the considered geometrical scale of 1/40.

Based on the scaling factors given in Table 1., numerical values of modeling parameters are given in Table 2.

The model itself is built of heavy plaster mixture with sand in order to obtain reduced modulus of elasticity. Matching the scale ratio $E_r$ = 1/40, it is achieved 1/20 as the lowest one, because of the casting problem if 1/40 mixture is applied. So, the requirement for proper simulation of inertial and gravity forces is fulfilled by an additional mass equal to the model mass. The model geometry is shown in Fig. 1. The height of the model is 8.03 m and its total mass is 14.6 tons (7.2 ton self mass + 7.4 additional mass). The total number of stories is 22, each of them representing 5 stories of the prototype, with walls

Table 1. Similitude requirement for 1/40 scale model.

| Parameters of similitude | Required scaling factors | Achieved scaling factors |
|---|---|---|
| Length ($l_r$) | $l_r = 1/40$ | 1/40 |
| Time ($t_r$). | $l_r^{1/2} = (1/40)^{1/2}$ | $(1/40)^{1/2}$ |
| Frequency ($\omega_r$) | $l_r^{-1/2} = (40)^{1/2}$ | $40^{1/2}$ |
| Gravitational acceleration ($g_r$) | 1 | 1 |
| Acceleration ($a_r$) | 1 | 1 |
| Mass density ($\rho_r$) | $E_r/l_r = 1$ | 2.0 |
| Strain ($\varepsilon_r$) | 1 | 1 |
| Stress ($\sigma_r$) | $E_r = 1/40$ | 1/20 |
| Modulus of elasticity ($E_r$) | $E_r = 1/40$ | 1/20 |
| Cross-sections ($A_r$) | $l_r^2 = (1/40)^2$ | $(1/40)^2$ |
| Specific stiffness $(E/\rho)_r$ | $l_r = 1/40$ | 1/40 |
| Moment of inertia ($I_r$) | $l_r^4 = (1/40)^4$ | $(1/40)^4$ |
| Force ($F_r$) | $E_r l_r^2 = (1/40)^3$ | $2(1/40)^3$ |
| Energy $(FN)_r$ | $E_r l_r^3 = (1/40)^4$ | $2(1/40)^4$ |

Table. 2. Prototype/model parameters

| Parameters | Prototype | Model |
|---|---|---|
| Height | 321.3 m | 8.03 m |
| Number of storeys | 105 | 22 |
| Total mass | 470 000 t | 14.6 t |
| Construction material | concrete | heavy plaster mixture with sand |
| Compression strength | $\sigma_c = 40$ MPa | $\sigma_c = 2.0$ MPa |
| Modulus of elasticity | E=35000 MPa | E=1750 MPa |
| Material density | $\rho = 2.5 t/m^3$ | $\rho = 2.4 t/m^3$ |

cross-section area and moment of inertia corresponding to the average values of the representative prototype levels. The minimum

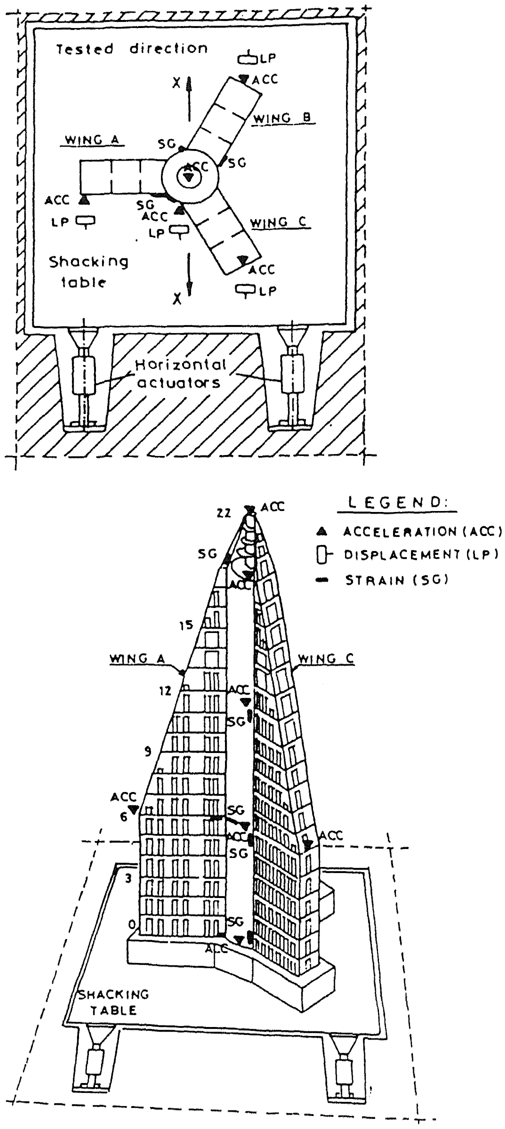


Figure 1. Disposition of the 1/40 scale model with instrumentation set-up.

thickness of the walls and floor slabs is 3 cm. Reinforcement is performed by 10/10 mm mesh with thickness of the wires of 1.0 mm. To build the model a special casting form is applied. The model is built for one month, while the minimum curing time was two months.

## 3. TESTING EQUIPMENT AND INSTRUMENTATION SET-UP

The tests were performed on two-componental seismic shaking table located at the Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering

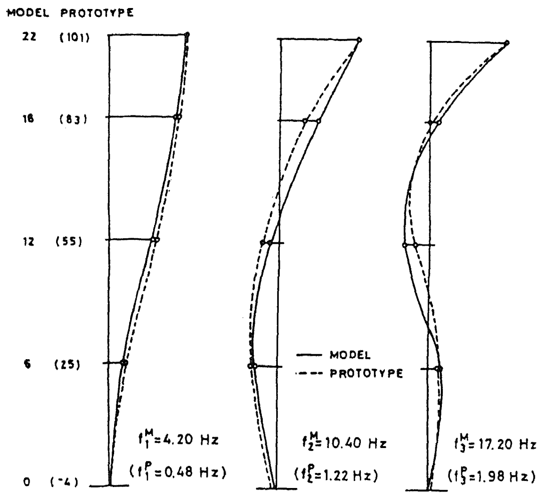


Figure 2. Comparative presentation of prototype and model mode shapes in x-x direction.

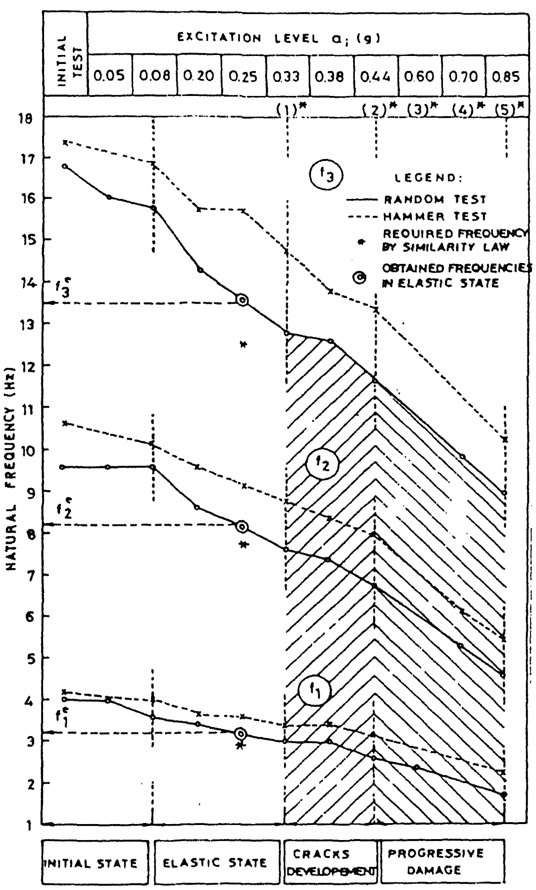


Figure 3. Frequency decay of the model during earthquake excitation tests.

Seismology, Skopje, Macedonia. The size of the shaking table is 5.0/5.0 m, with self mass of 30 tons and carrying model mass of 40 tons. The working frequency range is from 0-50 Hz, max. displacement in horizontal direction ±12.5 cm and in vertical direction ±6.5 cm. It is a programmable shaking table for various types of excitations such as: harmonic, triangle, square, random or earthquake motion. The model response was monitored by a 32 channels high-speed data acquisition system consisting of 9 accelerometers, 8 displacement transducers and 15 strain gauges, providing the information about floor accelerations, storey drifts, wing deformations and strain distribution at selected points. Fig. 1 shows the instrumentation set-up of the model.

## 4. TESTING METHODS

During test performance, two kinds of tests have been applied: dynamic properties test and seismic response test.

### 4.1. Dynamic properties test

The dynamic properties tests have been carried out for several times: before the seismic excitation for definition of initial dynamic characteristics of the model (initial stiffness, damping, mode shapes, natural frequencies) and after each series of tests as an indication of the stiffness degradation. The dynamic properties of the model have been checked by different methods: by means of small electrodynamic actuator, placed on the top of the model (exciting the model to harmonic motion within frequency range of 0-30 Hz); by means of shaking table (random excitation test) and hammer tests.

### 4.2. Seismic response tests

The seismic response test have been performed by excitation of the typical earthquake acceleration time histories (synthetic) that correspond to the expected earthquakes at the site conditions. At the beginning, a set of low intensity test was applied to investigate the linear response of the model. The next set of single test was carried out with the intensity level near to design level (about 0.2 g) at which the cracks have not been expected. To provoke nonlinear behaviour and cracks occurrence, a series of moderate and high intensity (0.3-0.9 g) has been applied in the last phase of the testing.

Table 3. Prototype/model frequencies estimation in x-x direction

| Num. of freq. | Proto-type freq. (Hz) | Reguired model fr. (Hz) | Initial mod. fr. by FVT (Hz) | Initial mod. fr. by sh. table (Hz) | Model fr. in elastic range (Hz) | Model fr. at first crack state (Hz) | Model fr. after final tests (Hz) |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| f1 | 0.48 | 3.03 | 4.20 | 4.00 | 3.20* | 3.00 | 1.8 |
| f2 | 1.22 | 7.71 | 10.40 | 9.60 | 8.20* | 7.50 | 4.6 |
| f3 | 1.98 | 12.50 | 17.20 | 18.80 | 13.50* | 12.60 | 9.1 |

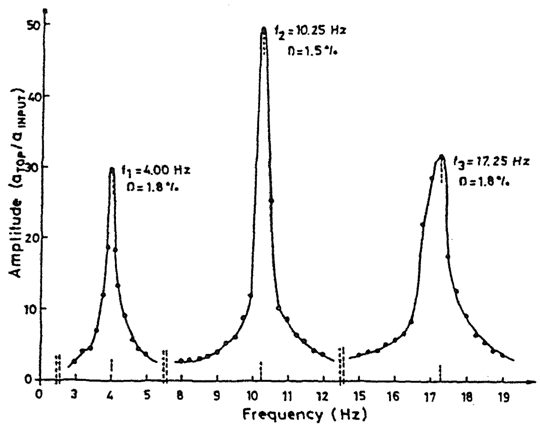


Figure 4. Frequency response curves of the model for the first three modes obtained by harmonic excitation on shaking table.

## 5. TEST RESULTS

Based on the acquired data and observation response features, initial dynamic characteristics of the model, the critical points and stress concentration locations, as well as stiffness degradation failure mechanism and safety factor were defined.

### 5.1. Dynamic characteristics of the model

To verify the similarity of the model with the prototype, i.e., the accuracy of the modelling approach, a comparative presentation of the first three mode shapes is given in Fig. 2. The full line represents the mode shapes of the model obtained from the forced vibration test performed by a small actuator placed on the top of the model, while the dotted line, the mode shapes of the prototype obtained from the full scale test. Table 3 shows the frequency estimation of the model for different levels of excitation force. Fig. 3 shows the frequencies decay during the seismic excitation test. It can be concluded that the initial state dynamic characteristics are higher than the required ones, which is reasonable considering the relatively low level of excitation. The values given in Table 3, column (5) (assigned by an asterisk) could be considered as representative and comparable with the required values, column (2), for the linear elastic state of the model behaviour. They are about 7% higher than the required ones, which seems to be an acceptable difference. The damping capacity for linear elastic state, is defined from the frequency response curves shown in Fig. 4. The damping ratios vary from 1.5 - 1.8%, which is very close to the prototype values for corresponding modes (1.30-1.70%). Summarizing the discussion about the dynamic characteristics of the model, it is concluded that it could be assumed as a representative enough to reproduce the prototype behaviour.

### 5.2. Seismic response

After the initial dynamic characteristics estimation, the seismic excitation tests have been performed. Two important issues defined the testing programme. The first one was related to the design criteria of the prototype. Namely, the Ryugyong Hotel is designed based on the consideration that under peak ground acceleration up to 0.25 g it will behave in elastic range. The model behaviour should confirm this assumption. The second issue was related to the safety factor and failure mechanism, as well as stress concentration during strong earthquake motion. To simulate the realistic seismic conditions, a particular study of site seismic parameters has been performed within the project. Thus, based on the historical and existing seismological data about past earthquakes at a small, moderate and long distance from the hotel site, three synthetic and two real earthquakes have been evaluated. To satisfy the similarity law, all selected earthquake time histories have been comprised by a time scaling factor $\sqrt{1/40}$. Table 4 shows the testing programme of the seismic response tests. Five earthquakes were simulated with peak acceleration lower than 0.11 g. Synthetic 1, which represents maximum expected far distant earthquakes produced the most intensive response of the model, but without any damage. Three earthquakes of less than 0.2 g have been run as moderate intensity earthquakes which are expected at the hotel site. Synthetic 2 earthquake produced the most intensive response, but it caused no damage. For the design level of 0.25 g,, two earthquakes were excited as a local type. Synthetic 3 produced the higher response without any damage. The first crack state

Table 4. Response parameters of the model under seismic excitation

| Input acc. level | Test No. | Earthquake | Input acc. (g) | Max. response | | | |
|---|---|---|---|---|---|---|---|
| | | | | Acc.(g) (level22) | Displ.(mm) (level22) | Strain (μstr) | Measuring point |
| ≤0.10g | 21 | Synthetic 1 | 0.10 | 0.55 | 6.1 | 88.0 | Lev.ø |
| | 22 | Synthetic 2 | 0.08 | 0.47 | 3.1 | 62.0 | " |
| | 23 | Synthetic 3 | 0.08 | 0.50 | 3.8 | 50.0 | " |
| | 33 | Mexico 1985 | 0.06 | 0.23 | 3.0 | 50.0 | " |
| | 25 | Montenegro 1979 (Ulcinj-Albatros) | 0.08 | 0.40 | 3.5 | 78.0 | " |
| ≤0.2g | 38 | Synthetic 2 | 0.19 | 1.20 | 13.3 | 127.0 | " |
| | 39 | Synthetic 3 | 0.19 | 0.92 | 9.2 | 101.0 | " |
| | 40 | Montenegro ULALB | 0.19 | 0.85 | 10.0 | 122.0 | " |
| ≤0.25g | 44 | Synthetic 3 | 0.24 | 1.29 | 14.5 | 132.0 | " |
| | 45 | Montenegro ULALB | 0.25 | 1.00 | 13.0 | 143.0 | " |
| ≤0.40g | 49 | Synthetic 3 (1)* | 0.33 | 1.43 | 18.7 | 164.0 | " |
| | 53 | Montenegro ULALB | 0.33 | 1.50 | 22.5 | 168.7 | Lev. 18 |
| | 52 | Synthetic 3 | 0.38 | 1.46 | 22.0 | 180.0 | Lev. 18 |
| | 56 | Montenegro | 0.39 | 2.18 | 24.4 | 134.0 | Lev. ø |
| >0.40g | 55 | Synthetic 3 (2)* | 0.44 | 1.75 | 29.1 | 180.0 | " |
| | 58 | Synthetic 3 | 0.53 | 2.37 | 38.3 | 208.3 | " |
| | 60 | Synthetic 3 (3)* | 0.60 | 2.48 | 50.0 | 213.5 | " |
| | 62 | Synthetic 3 (4)* | 0.70 | 2.72 | 63.5 | 238.4 | " |
| | 64 | Synthetic 3 (5)* | 0.85 | 3.81 | 75.4 | 442.2 | Lev. 12 |

(1)* First cracks (wing "C" - level 15, wing "B" - level 12)
(2)* Development of horizontal cracks (wing "B" - level 12, wing "C" - level 11, 16, 17, 18)
(3)* Serious damage - horizontal and diagonal cracks (wing "C" - level 11, wing "B" - level 11).
(4)* Cracks in the central core (level 12)
(5)* Collapsing state

(1)* appeared during synthetic 3 excitation with 0.33 g peak acceleration. Similar effects were obtained at 0.38 g of synthetic 3 which was the maximum expected earthquake at the Hotel site. After these tests, small horizontal cracks occurred in wing "B" at level 12 and wing "C" at level 15. Progressive crack development (2)* occurred after synthetic 3 excitation with 0.44 g peak acceleration (wing "B", level 12 and wing "C", levels 11, 16, 17, 18). Serious damage of wings "B" and "C" occurred under synthetic 3 earthquake (0.6 g), assigned as state (3)*. Crack in the central core (level 12) occurred after 0.7 g intensity of synthetic 3 earthquake (state (4)*). After 0.85 g,, the failure of the model was very close at level 12. Summarizing the crack development, it could be pointed out that crack propagation starts at wings "B" and "C" within levels 12 and 15, as horizontal cracks due to bending, within 0.33-0.38 g. At higher intensity levels, horizontal cracks at the wings, as well as significant cracks at the top part of the model occurred. The heavy damage state occurred within the range of 0.70-0.85 g input acceleration level. Fig. 5 shows the time history and Fourier amplitude spectrum of synthetic 3 earthquake.

The maximum relative displacements of the model after different earthquake intensity

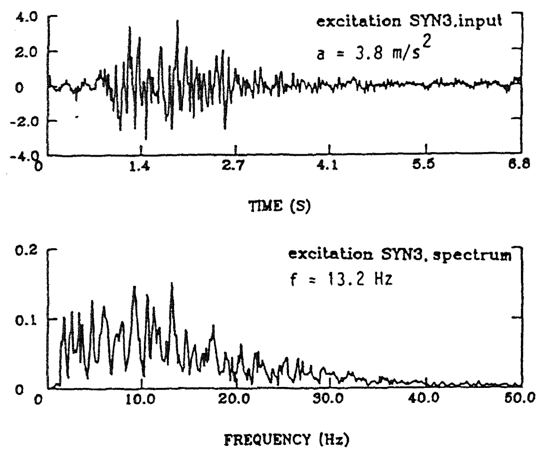


Figure 5. Time history of acceleration and Fourier amplitude spectrum of synthetic earthquake SYN3 (max. acceleration 0.38g).

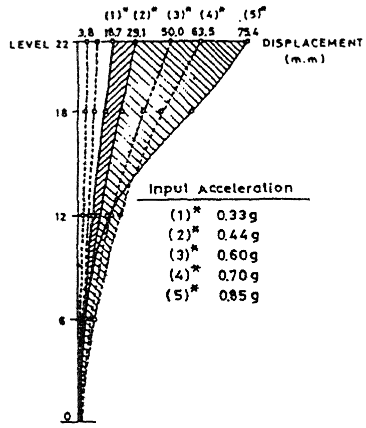


Figure 6. Comparative presentation of maximum relative displacements of the model recorded for different earthquake excitation levels of SYN3.

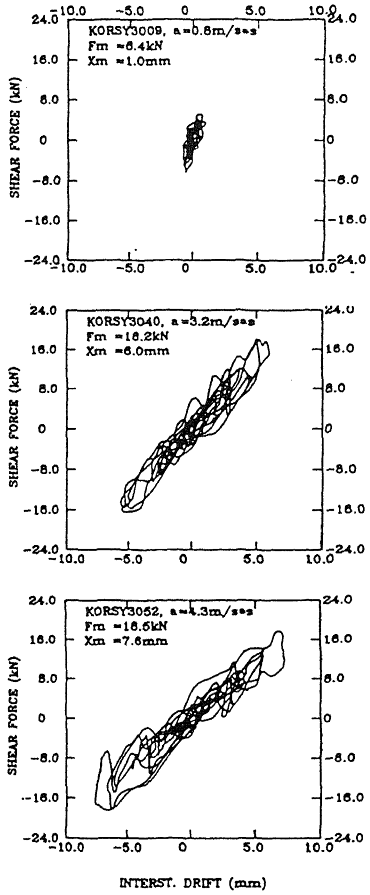


Figure 7. Shear force - interstorey drift relationships at level 12, central corre, for different earthquake intensities.

of synthetic 3 earthquake are shown in Fig.6.

Fig. 7 shows the shear force-interstory drift relationships at the critical level 12 of the model for different earthquake intensity.

Damage distribution is presented in Fig.8.

## 6. CONCLUSIONS

- The shaking table test of a 1/40 scale model representing the 105 storey Ryugyong Hotel in Pyongyong, DPR Korea, was successfully carried out. Constructed according to the true replica modelling principles, it has provided fairly realistic simulation of both the linear and nonlinear behaviour of the prototype.
- For the earthquake level of 0.25 g (higher than the design level of 0.20 g), the model response was within the linear range and no damage was observed.
- At the maximum expected intensity level for the site of 0.35 g, initial cracks were recorded at wings "B" and "C" (diagonally positioned in respect to the earthquake excitation direction).
- Intensive nonlinear response of the model was observed within the earthquake intensity of 0.44 g - 0.70 g.
- If the input acceleration level of 0.44 g is considered as a serious damage state, and 0.20 g as a design level, a safety factor of 2.20 could be predicted.
- The damage mechanism shows development of cracks at the wings, first, and at the central core, after that. So, in case of strong earthquakes, the first damage to the Hotel is expected to occur at the wings,

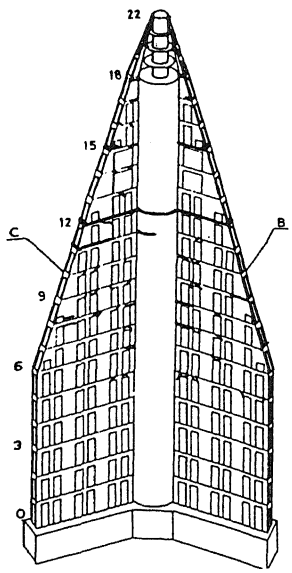


Figure 8. Damage distribution on the model after the tests accomplishment.

between the 50th and 70th floor, but for an earthquake intensity as high as almost twice the designed level.

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