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DYNAMIC TESTING OF FULL-SCALE 11-STORY RC BUILDING AND ITS 3-STORY STRUCTURAL PART: COMPARISON OF THE RESULTS AND SEISMIC RESISTANCE ESTIMATION

I. Iskhakov and Y. Ribakov

Dept. of Civil Engineering, Ariel University Center of Samaria, Ariel. Israel
Email: yizhak@ariel.ac.il, ribakov@ariel.ac.il

ABSTRACT :

Dynamic testing of full-scale RC buildings is one of the final stages in investigation of new structural schemes for seismic zones. It is required in order to verify the real seismic resistance of the building. However, this method is rather seldom used because it is time- and cost consuming procedure, and it may yield nonlinear deformations, damage in structural elements and the whole building. The damage may be so strong that after such tests it will be impossible to retrofit the building for its further using. Hence it is impossible to test each new real multistory RC building. Dynamic testing of a relatively small part of the building (having the same structural scheme) is one of the possible ways for solution of the above described problem. But the reliability of the experimental results, obtained for the structural part, should be verified (at least one time) by comparison to those from dynamic tests of a full-scale building. This paper deals with impulse testing of a 3-story structural part and comparison of the results to those of dynamic vibration testing of the full-scale 11-story RC building. It should be mentioned that there are almost always certain differences between the full scale structure and its structural part. In our case the real building was able to withstand dynamic loads in two horizontal directions, while the structural part was a plane frame. The full-scale building was subjected to dynamic loading using a vibration machine and the structural part was tested by applying an impulse force. Additionally, the framed system of the real structure had braces in one direction and shear walls in the other one, while the structural part had a frame system (without braces and shear walls). However, the height of the structural part was significantly lower compared to the full-scale building, so the stiffness parameters of both structures were of the same order. It was shown that, if the dynamic parameters of both structures are rather close, it is possible to obtain the seismic loads, acting on the real building, using the impulse forces, applied to the structural part. This approach may be successfully used for estimation of seismic resistance of real buildings designed for a given seismic zone.

KEYWORDS: dynamic testing, full-scale building, structural part, estimation of seismic resistance, base isolation

1. INTRODUCTION

New reinforced concrete (RC) structures are generally designed according to code requirements for the seismic zone, in which they are constructed. In principle, the seismic resistance of a designed building can be estimated by carrying out full-scale tests, but that is obviously uneconomical. Another way is to test a scale model of the structure. De Matteis et al. (2007) studied the dynamic features of the Fossanova Cathedral by experimental (ambient vibration) and numerical (FEM models) analyses. One of the aims of this study was evaluating the seismic behavior and vulnerability of the "gothic cathedral".

An alternative approach is to subject a full-scale part of an unfinished building to testing under vibration, or impulse loading. This approach can provide valuable information about the dynamic parameters of buildings – information that can be used to calibrate theoretical models, develop modeling techniques, and verify theoretically predicted damage. Dynamical testing of full-scale parts of buildings yields information about the real dynamical parameters of the whole system, such as natural vibration periods, vibration modes and damping ratios (Iskhakov and Ribakov, 2005). One of the advantages of this approach is that it makes it possible to estimate nonlinear structural behavior of a full scale building.

Fajfar and Godec (1982) obtained periods and free vibration mode shapes using numerical analysis and full-scale tests on three actual multistory RC buildings (20-, 12- and 10-story). They have reported that the dynamical characteristics, obtained from the free vibration tests for a 20-story shear wall building, agreed with a mathematical model. As shown by the experimental results for a large-panel 10-story building, good correlation of the results depended upon allowance being made for the flexibility of the floor slabs in their plane (the 10-story structure could be treated as a fragment of the 20-story one). The third building was a 12-story frame structure with infill walls. The influence of these walls was included in the theoretical model. The 12-story structure too could be treated as a full-scale fragment of the 20-story frame.

Kaminosono et al. (1982) tested a full-scale seven-story RC structure. The objectives of this study were obtaining the behavior of the structure, comparing the test results with analytical dynamic response analysis, and developing seismic-resistant design methods. The experimental study consisted of vibration, static loading and pseudo-dynamic tests. During the last test the structure was damaged. In order to perform further tests, the damaged seven-storey structure has been repaired and nonstructural elements were installed (Okamoto et al., 1983). It has been shown, that the repairs restore the stiffness and the strength of the structure. The seismic-resistance of nonstructural elements was verified in further pseudo-dynamic tests. Based on the obtained experimental results, a method for retrofitting of similar existing structures, damaged by earthquakes, can be developed. Certain contribution to experimental investigations of full-scale structures has been made by Bae and Suzuki (1999), Negro and Molina (2001), Paultre et al. (2002) and others.

By testing a full-scale part of a building under construction, it is possible to determine its nonlinear dynamical parameters. The finished building may be expected to have the same parameters. However, the ultimate aim is to minimize the inelastic response of the building. This may be done, for example, by implementing a base isolation system with characteristics chosen so that the whole system (building and base isolation) will have the required dynamical parameters.

In the study reported below, a full-scale fixed-base three-story structure – a part of an 11-story RC building under construction – was investigated experimentally and its nonlinear response was determined. Based on the results obtained, a base isolation system was designed using the proposed approach.

2. MOTIVATION AND AIMS FOR DYNAMIC TESTING STRUCTURAL PARTS OF MULTISTORY BUILDINGS

Dynamic testing of full-scale RC buildings is one of the final stages in investigation of new structural schemes for seismic zones. It allows verification of building's real seismic resistance. But this method is rather seldom used because it is time and cost consuming procedure, and it may yield nonlinear deformations, damage in structural elements and the whole building. Sometimes, after full-scale dynamic testing the damage may be so strong that after the tests it will be impossible to retrofit the building for its further using. Hence it is impossible to test each new multistory building.

Results of structural part dynamic testing can be used for prognosis of damage progress in full-scale buildings. It allows preventing of nonlinear deformations, cracking and estimation of buildings ability to withstand seismic loads. The proposed method may be also used for evaluation of seismic resistance of multistory buildings for using them in seismic zones with higher PGA than that, for which they were designed. It can be also used to study behavior of structural elements joints under strong dynamic loading.

Dynamic testing of a structural part of the building is one of the possible ways for solving this problem. Testing a structural part avoids a complicated process of full-scale buildings dynamic scaling, aimed to reduce the dimensions of the tested structure. This work is aimed at verification of such method by comparing the results obtained by testing a structural part to those of a full-scale building. For this reason a full-scale 11-story building and its 3-story structural part were tested. Additionally, effectiveness of using base isolation systems, designed for structural part, in full-scale building was examined.

3. PROGRAM OF FULL-SCALE BUILDING EXPERIMENTAL INVESTIGATION

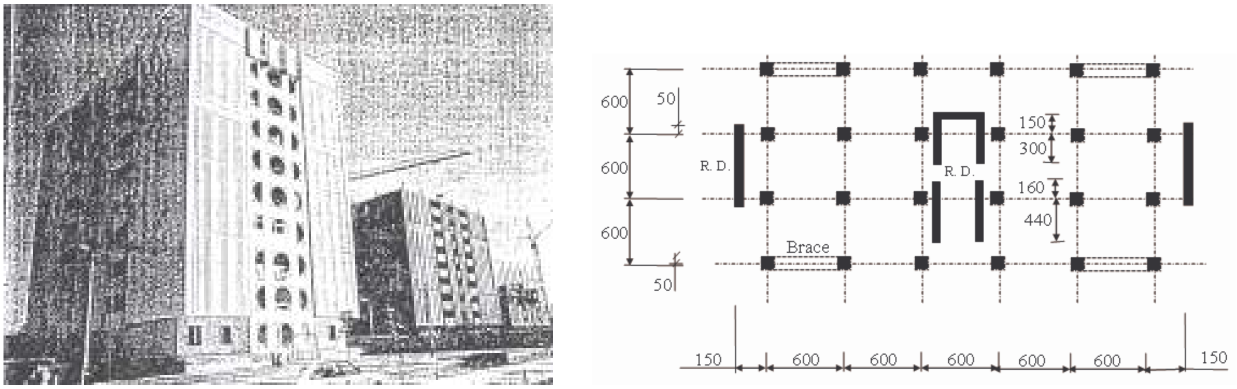
As it was mentioned above, a new typical building, designed for seismic regions, should be tested before it is recommended for a region with known seismic activity. This paper is focused on full scale testing of an RC 11-story building and its 3-story part. The experimental program was aimed at structural dynamic behavior examination of such type of buildings for seismic zones with PGA 0.1 g, 0.15 g and 0.3 g. An idea of using dynamic parameters of a structural part for design of the building was also examined. An additional problem was selecting the structural part so that its dynamic behavior would be close to that of the real structure (at least, according to the dominant vibration mode). For such multistory buildings (in our case for the 11-story building) contribution of the first three modes is usually more than 90% of the total dynamic response. In this case, according to the requirements of the modern seismic codes (Eurocode 8, 1993, IC 413, 1998), influence of higher modes can be neglected in the design procedure. Based on this assumption, a 3-story structural part of the 11-story building was selected. Moreover, the structural scheme of the building and of its part to be tested should be the same at least in one horizontal direction. The main structural joints, foundations and the soil conditions of the building and of its structural part should be also identical. In order to obtain similar logarithmic decrements for the building and for its structural part free vibration tests are used. It is logically to expect that if all the above mentioned conditions are fulfilled, the dynamic behavior of both structures will be similar and yield analogous structural damages.

Testing a structural part allows a unique possibility to investigate the influence of live loads on building's dynamic parameters by applying additional gravitation (static) loading. Carrying out similar tests on full-scale buildings is very difficult, but the effect of this loading can be taken into account for design of real multistory buildings. It is shown that based on the results, obtained from testing the structural part, recommendations, regarding suitability of the building for a seismic zone with known seismic activity, can be formulated.

4. MAIN EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Three-Story Structural Part

The tests were carried out on a three-story part of an 11-story pre-cast RC building under construction, as shown in Figure 1 (Iskhakov and Ribakov, 2000, 2005). The building had a beamless frame structure. The building part consisted of two columns (each three floors high) and three slabs (Figure 2).



(a) (b)

Figure 1 The 11-story building: (a) general view, (b) typical floor plan

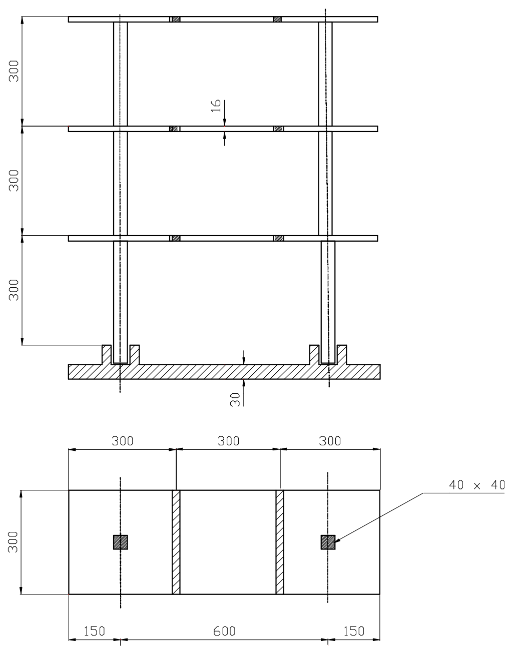


Figure 2 Structural scheme of tested part

Dynamic loads in the form of impulses were applied to the column-slab joint at the roof level in the plane of the frame. The impulse was provided, when required, by instantaneous application of the load by means of a guy cable (Figure 3). The impulse tests were carried out in steps. In the first step, recording of the micro-seismic vibration of the frame was followed by impulse tests under forces of 30 and 70 kN and application of a vertical static load of 3.84 kN/m^2 at the slabs. In the second step, the statically-loaded frame was subjected to impulse forces of 30, 70 and 106 kN. The peak horizontal roof displacements of the frame were 45, 110 and 175 mm, respectively. In the third step, the statically loaded frame was subjected to forces of 34, 77 and 110 kN. In the last case, the peak horizontal roof displacement was 200 mm. Cracks developed in the slabs under the 77 kN load and in the columns under the 110 kN load.

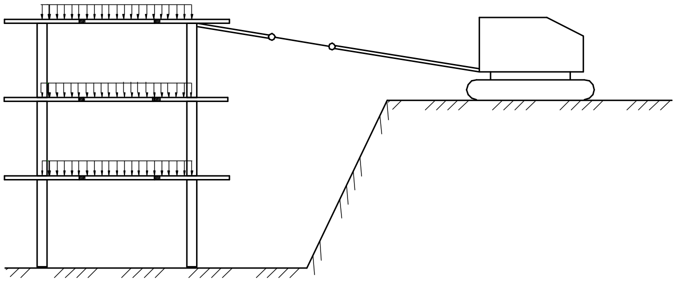


Figure 3 Application of impulse to building part

Damping ratio of the first vibration mode was determined using a logarithmic decrement. The experimentally obtained damping was used for further analysis of the structure (instead of the 5% value proposed by the theoretical dynamics). The micro-seismic records revealed three modes of vibration with the following periods: $T_1 = 0.6$ s, $T_2 = 0.16$ s, $T_3 = 0.06$ s. The following periods were recorded under 30 kN: $T_1 = 0.8$ s, $T_2 = 0.16$ s. On transition from 30 to 70 kN, the periods of the first and second modes increased by 20%. The third mode was recorded with a period 0.11 s. In the last step of the impulse tests under 77 kN, the periods were $T_1 = 1.35$ s and $T_2 = 0.3$ s (Figure 4). The natural periods of the frame are clearly seen to depend on the impulse load, which indicates that nonlinear vibrations have developed. This is particularly evident for the first vibration mode under the increased impulse load intensity.

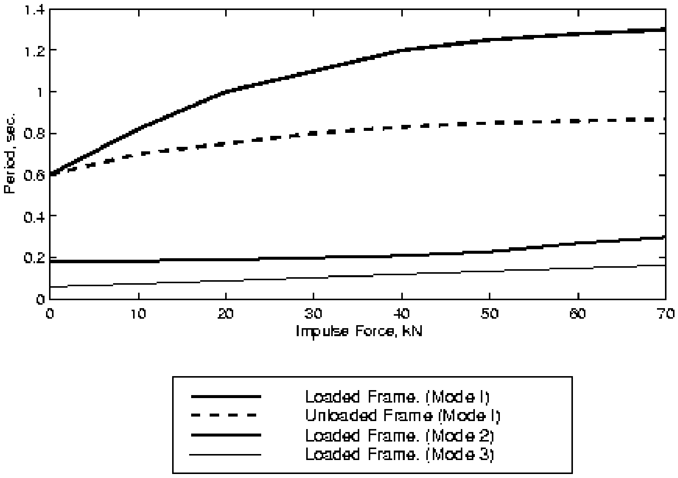


Figure 4 Experimentally obtained vibration periods

Figure 5 shows the experimentally obtained relation between the maximum amplitude of horizontal displacement of the frame and the intensity of the applied dynamical loads, which ranged from 30 to 110 kN. It should be noted that nonlinear vibration occurred when the impulse load was 70 kN or higher (see Figure 4). The roof accelerations were also recorded. Under the 70 kN load, the acceleration of the fragment was 0.35 g, which is equivalent to a strong earthquake. Thus, under impulse forces ranging between 70 and 110 kN, the frame behaved as a geometrically and physically nonlinear system. The damping ratio of the frame was 0.1 and its maximum velocity 20 cm/s.

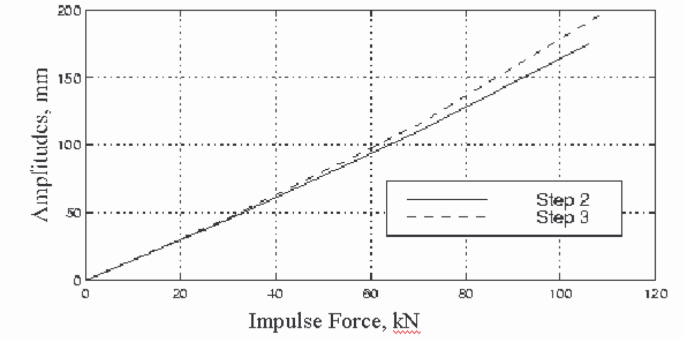


Figure 5. Experimentally obtained vibration amplitudes

4.2. 11-Story Full-Scale Building

The full-scale structure has been submitted to dynamic loads in order to determine experimentally the building's dynamic parameters under micro-seismic oscillations and vibration resonance actions. The tests were also aimed at verification of dynamic parameters of the building, obtained from impulse testing of a structural 3-story part. An additional aim was to analyze the pre-cast building's state and its joints behavior, the diaphragms and braces influence on the dynamic response and to determine the building's dynamic reserves in the linear and nonlinear stages.

The vibration was achieved using a machine consisting of five blocks, actuated by two electric motors, working simultaneously. This machine was installed at the center of the upper floor on a horizontal steel frame, connected to the slab by 12 mm steel bars at 40 cm spacing. The frame consisted of 140 mm height horizontal steel I-section beams and a 7 cm concrete layer between the beams. For recording of the building's dynamic parameters 11 accelerometers were used. Before the tests the accelerometers were verified on a vibration table. After the test the building was inspected and all damages were described and documented (Iskhakov and Ribakov, 2000).

Before the vibration test, the natural vibration periods of the building were determined applying a 1×1×1.5 m concrete block impact at the upper floor. The tests were carried out in phases. In each phase, the unbalanced masses of the vibration machine were increased corresponding to the required equivalent PGA. After each phase the building and its joints were inspected, including cracks development, damages caused to structural elements, etc. At the end of the tests the natural vibration periods of the building in the transverse and longitudinal directions were determined again, using the same concrete block impact.

According to the experimental results, the initial values of building's dominant natural vibration periods were 0.585 s in the transverse direction and 0.615 s in the longitudinal one, respectively. In the first phase the unbalanced mass was 1440 kg and the obtained oscillation period 0.65 s. The building's peak upper floor displacement was 4.5 mm. After the first phase the unbalanced mass was increased to 2720 kg, 3240 kg and 3280 kg (Iskhakov and Ribakov, 2000). The maximum dominant mode natural vibration period obtained in the tests was 0.72 s in the transverse direction. Its final value (obtained from the impact test performed after the experiments) was 0.70 s. The increase in the transverse direction natural vibration period from 0.585 s to 0.72 s shows, that some of the structure's rigidity was lost due to cracking and local damages.

5. BASE ISOLATION SYSTEM FOR STRUCTURAL PART AND ITS EFFECTIVENESS FOR A FULL-SCALE BUILDING

The increase in the natural vibration periods obtained from the test of a 3-story structural part was unambiguous evidence of nonlinear deformations in the frame. To reduce the nonlinear behavior, a base isolation system

(BIS) was implemented. The system was designed so that the displacement of the roof relative to the first story column bottom would be less than or equal to that of the fixed-base structure (as obtained in the tests). It was also expected to reduce the energy dissipated in the structural elements during their nonlinear behavior. Numerical simulation of the structural part with base isolation showed that the behavior of the isolated structure was linear and excluded its cracking (Iskhakov and Ribakov, 2005).

The results of the numerical analysis and the corresponding experimental data are given in Figure 6. The experiments showed that as the impulse load was increased, the displacements increased nonlinearly. The disagreement between these data and the theoretically obtained results was less than 10%. The BIS afforded a reduction in inter-story drifts without increasing roof displacement. It reduced the nonlinearity of the deformation, thereby lowering the risk of damage and failure of the elements.

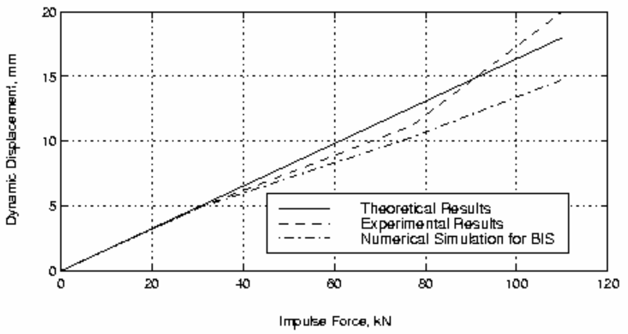


Figure 6 Dynamic displacements of 3-story structural part

The goal of base isolation of the real 11-story building was to keep the structural peak response to earthquakes with PGA of 0.3g similar to that of a fixed-base structure under the vibration loads with PGA of 0.15g (measured experimentally). Based on parametric study, performed by the authors (Iskhakov and Ribakov, 2000), it was concluded, that for the structure the above mentioned aim is successfully achieved by using a BIS with a natural vibration period of 1.4 s. This vibration period corresponds to that of a 3-story structural part with addition of gravitation loading (Iskhakov and Ribakov, 2005). The response of the structure to three selected earthquakes scaled to PGA of 0.3g has been obtained for the following study cases: 1) a fixed base structure; 2) a base isolated structure with natural vibration period of 1.4 s. The peak response of the structure is presented in Table 5.1.

Table 5.1 Peak response of the structure (base isolated / fixed base)

Seismic motion	Roof displacement (relative to the first-story columns base), cm	Base shear, kN
El-Centro	0.7 / 2.52	3690 / 6770
Eilat	0.13 / 2.39	3700 / 6310
Kobe	0.13 / 2.17	3650 / 7020

It was shown by the authors (Iskhakov and Ribakov, 2000) that using the BIS with the proposed natural vibration period yields reduction of the maximal displacements by 44 – 72 %. The base shear forces for these cases are also significantly reduced. Hence, the base isolation system, selected according to structural dynamic parameters obtained from experimental investigation of a 3-story structural part with addition of gravitation loading, efficiently works in a full-scale 11-story building.

6. CONCLUSIONS

Dynamic testing of a relatively small part of the building, having the same structural scheme, is one of the possible ways for experimental investigation of real buildings seismic behavior. Reliability of the experimental results, obtained for the structural part, was verified by comparison to those from dynamic tests of a full-scale building. Impulse testing of a 3-story structural part was carried out and the results were compared to those of dynamic vibration testing of the full-scale 11-story RC building using a vibration machine.

It was shown that, if the dynamic parameters of both structures are rather close, it is possible to obtain the seismic loads, acting on the real building, using the impulse forces, applied to the structural part. This approach may be successfully used for estimation of seismic resistance of real buildings designed for a given seismic zone.

Effectiveness of a base isolation, designed using the results of structural part impulse testing, for a full-scale building was examined. Using the BIS with the proposed natural vibration period yields significant reduction of the maximal displacements and base shear forces. It was proved that the base isolation system, selected according to structural dynamic parameters, obtained from experimental investigation of a 3-story structural part with addition of gravitation loading, is effective for the full-scale 11-story building.

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