Experimental and Numerical Investigation of an 11-story Reinforced Concrete Building's Nonlinear Dynamic Behavior

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Abstract
A structural scheme of a typical precast multistory RC building incorporating flat-slab and braced frame systems is presented. The building has been designed for seismic zones. First its dynamic parameters have been determined experimentally. Than the structure has been subjected to resonance vibration and impulse loads in order to yield cracking and other damage in the load-bearing elements and their joints. The obtained experimental results have been interpreted from the seismic-resistance viewpoint. The dynamic parameters and the structural elements damage nature for that building were the main subject of the experiments. Further theoretical investigation has been focused on examining the response of the building to real earthquakes. The experimentally obtained building response to vibration loading and the numerically calculated structural behavior under real earthquakes have been compared. It was concluded, that the building satisfies the seismic code requirements for zones with peak ground accelerations (PGA) less than 0.3g. In order to adapt the building to seismic zones with higher PGA without any changes in the load-bearing elements and their joints, it was proposed to use a base isolation system. Numerical simulation show, that the base isolated building represents safe response to real earthquake records with PGA equal to 0.3g. Hence the structure can be recommended for seismic zones with that PGA.

Keywords: experimental investigation, nonlinear dynamic behavior, RC building, full-scale testing.

Introduction

Generally, new reinforced concrete (RC) structures are designed according to code requirements for seismic zones, in which they planned to be constructed. The seismic zones are mainly characterized by peak ground acceleration (PGA). In surtain cases civil structures are designed as typical ones for a given seismic zone. If the same structures are constructed in seismic zones with higher PGA, the design is improper. In this case two solutions are available: the first one is full re-design of the building, and another one is using the existing project with additional system, adapting the building to the current seismic zone by changing its dynamic parameters (such as base isolation system). If the second way is selected, it is logically to investigate the existing building's dynamic parameters and their dependence on the increasing dynamic loading.

A most common way for investigating that parameters is testing of full-scale structures or their fragments under vibration, shock or shaking table loading. Full-scale dynamic tests provide valuable information on the characteristics of buildings that can be used to calibrate theoretical models, to develop modelling techniques, and to verify theoretically predicted damages. These tests usually provide the most complete information about the dynamic properties of a structure.

Kaminosono et al. (1982) tested a full-scale seven-story reinforced concrete 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 tested structure was 21.75 m in height and had a 272 sq m floor area, it consisted of three three-bay frames, parallel to the loading direction, and four two-bay frames, perpendicular to the loading direction. The middle frame, parallel to the loading direction, had a shear wall in the central bay from the first to the seventh story. The experimental study consisted of vibration, static loading and pseudo-dynamic tests. During the pseudo-dynamic tests the structure was damaged.

In order to perform further tests, the damaged seven-storey structure has been repared 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 were verified in further pseudodynamic tests. Based on the obtained experimental results, a method for retrofitting of similar existing structures, damaged by earthquakes, can be developed.

Fajfar and Godec (1982) compared mathematically obtained periods and free vibration mode shapes with the results of full-scale tests carried out on three actual multistory reinforced concrete buildings. Each of the buildings was represented by a number of models. It was reported, that the dynamic characteristics, obtained from the free vibration tests of a 20-story shear wall building, correspond to those of a pseudo 3D mathematical model. The experimental results for a large-panel 10-story building have shown, that for a good results correlation the flexibility of its floor slabs in their plane should be taken into account. The third building was a 12-story frame structure with infill walls. The influence these walls has been included in the theoretical model. Only moderate agreement between numerical and experimental results in the last case was reported.

Negro et al (1995) conducted pseudodynamic tests on a full-scale four-story reinforced concrete building designed to Eurocodes 2 and 8. The building was 10 m long by 10 m wide and 12.5 m high. It was designed as a high ductility class structure for a PGA of 0.3 g. A first test was conducted on the bare frame without infills. A second experimental program was conducted to study the influence of masonry infill panels on the behavior of the frame. The test was then repeated on the structure without infills at the first story, to create a soft-story effect. The experimentally obtained structural behavior was compared with that predicted theoretically by simplified approaches.

Certain contribution to experimental investigations of full-scale structures have been made by Bae and Suzuki (1999), Negro and Molina (2001), Paultre et al. (2002) and others.

This paper deals with a study, performed on a typical full-scale 11-storey precast flat-slab RC building. Initially the dynamic parameters of the building have been obtained experimentally. The dynamic loads, applied to the structure in the test, had a PGA like the seismic ones for the region, in which the building was designed. These loads were produced using a vibration machine. The measured response was then compared to the analytically obtained one in order to develop recommendations on using this structure in seismic zones with higher PGA. With this aim, a base isolation system was proposed for implementation. Numerical results demonstrated the effectiveness of the proposed approach.

The construction scheme and the structural system

The general view of the investigated building is given in Figure 1a. The bearing precast RC structure consists of columns with 6 m spacing in plan in both directions and beamless slabs (Fig. 1b). The columns are two or three story precast units with small unconcreted parts in the zones of column-slab connection, and have a cross section of 40×40 cm. The typical slab has a 16 cm thickness and consists of three precast units – overcolumn, between columns and middle plates.

The overcolumn precast plate has a square hole for its connection to the column. The shear studs along the plate's perimeter are aimed to provide the horisontal stiffness of the flat-slab and to avoid horizontal displacements of one precast plate relative to another. The space between the overcolumn plates is filled by the between column units.

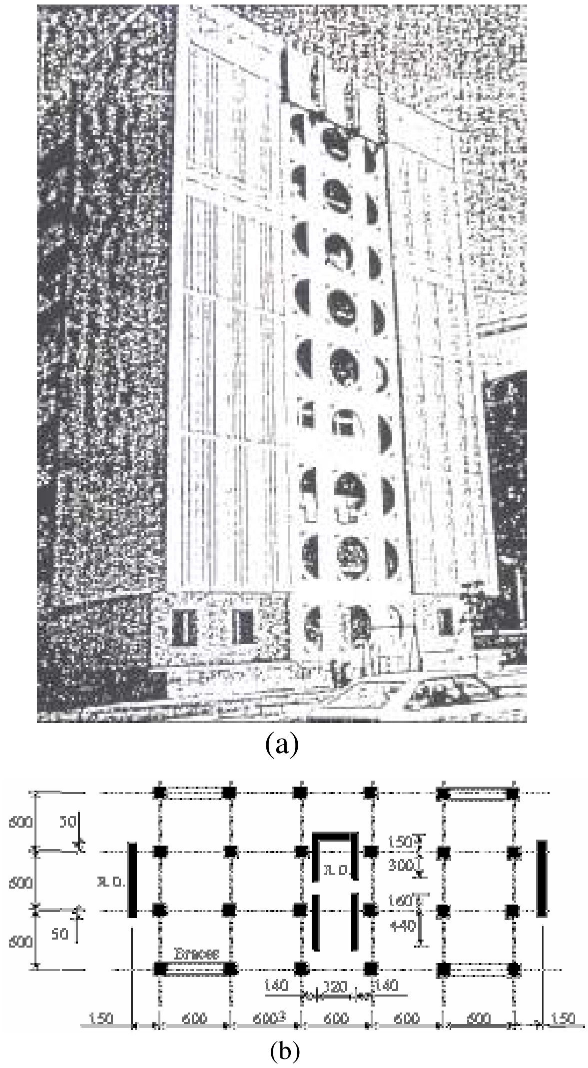


Figure 1: The investigated building: (a) general view, (b) typical floor plan.

The structural frames, consisting of columns and slabs, are designed to carry the vertical loads. In order to carry the horizontal loads, appropriate stiffness in both (longitudional and transverse) directions are mainly provided by braces and rigid diaphragms, resprctively. The diaphragms thickness is 16 cm and the braces have the same breadth, like the columns (see Figure 1b). This construction scheme includes non-bearing precast marginal wall panels suspended on columns.

The vibration tests

The above described full-scale structure has been submitted to dynamic loads in order to determine experimentally the building's dynamic parameters under microseismic oscillations and vibration resonance actions. The tests were aimed also to analyse the precast 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 PGA of the experimentally applied to the structure vibration loads has been selected according to the code requirements to the seismic zone, in which the building was constructed. The vibration was achieved using a machine consisting of five blocks, actuated by two electric motors, working simultaneously (Figure 2). 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.

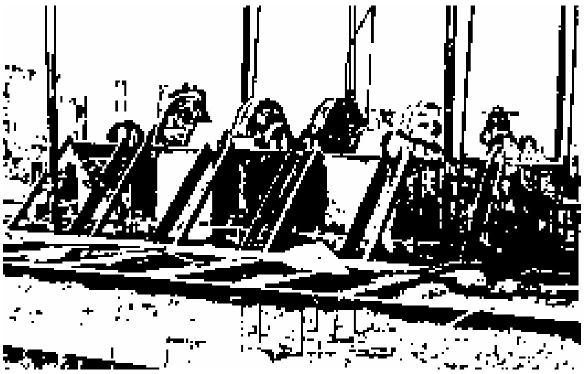


Figure 2. General view of the vibration machine and a steel-concrete connection frame

For recording of the building's dynamic parameters 11 accelerometers were used. Before the tests the accelerometers were verified on a vibration table. Additionally, after the test the building was inspected and all faults were described and documented.

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 fases. In each fase, the unbalanced masses of the vibration machine were increased corresponding to the required equivalent PGA. After each fase the building and its joints were inspected, including crackes 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.

Tests results and their interpretation from the building's seismic-resistance viewpoint

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 fase 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 fase the unbalanced mass was increased to 2720 kg, 3240 kg and 3280 kg. Table 1 shows the experimental values of the peak horizontal displacements due to the resonanse vibration forces equivalent to PGA = 0.15g; the equivalent seismic forces, and the shear forces at all floor levels.

Table 1. Peak structural response

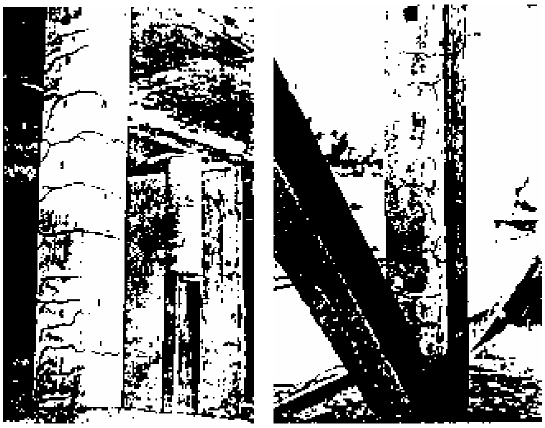
Floor	Displ., cm	Equivalent seismic forces, kN	Shear forces, kN
11	1.29	472	540
10	1.19	487	980
9	1.10	507	1140
8	0.93	492	1530
7	0.58	437	2370
6	0.40	405	2520
5	0.31	392	2980
4	0.27	367	3220
3	0.25	251	3325
2	0.20	207	3360
1	0.11	103	3400

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.

Figure 3 shows local damages and cracks in bearing structural elements. The cracks appeared, at the following locations: in the columns due to the effect of bending and torsion moments (Figure 3a); in the inside rigid walls due to diagonal tensile stresses (Figure 3b). The local damages were indicated at the columns-braces joints (Figure 4).

Theoretical investigation of the structure and comparison with the experimental results

In order to study the influence of real earthquakes on the structural seismic response, further numerical investigation was carried out. The following three seismic excitations were used as input in the analysis: El-Centro, U.S.A (1940), Eilat, Israel (1995), Kobe, Japan (1995). These excitations were scaled to a PGA of 0.1g, 0.15g, and 0.3g. An initial damping ratio of 2% was assumed for the first vibration mode of the structure. The analysis was carried out using routines written in MATLAB (MATLAB, 1993).



(a)

(b)

Figure 3. Cracks and local failures: (a) in columns; (b) in an inside rigid wall

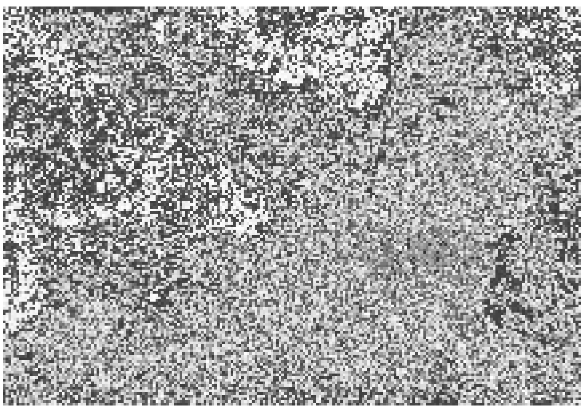


Figure 4. Local damages at the columns-braces joints

Peak upper floor displacements and base shear forces (BS) of the structure under the above-specified earthquakes with different PGA are given in Table 2.

Table 2. Peak structural responses to scaled earthquakes

PGA	0.3g		0.15g		0.1g	
	Displ., cm	BS. kN	Displ., cm	BS. kN	Displ., cm	BS. kN
El-Centro	2.52	6770	1.26	3390	0.84	2250
Eilat	2.39	6310	1.20	3160	0.80	2100
Kobe	2.17	7020	1.08	3510	0.72	2340

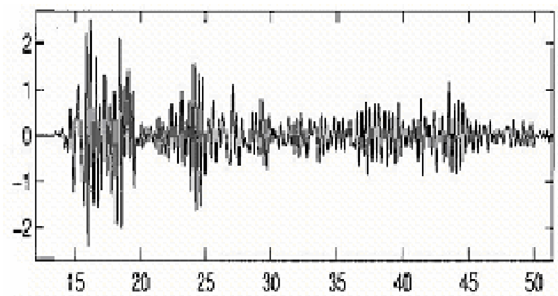
The numerical simulation shows that the experimental structural response (see Table 1) is close enough to that of the analytically obtained behavior under the selected real earthquakes scaled to PGA of 0.15g (see Table 2). In order to construct the building in zones with higher seismic level, it was proposed to use a base isolation system (BIS), for example, a sliding isolation system (Al-Hussaini et al., 1994).

The goal of the BIS implementation is to keep the structural peak response to earthquakes with PGA of 0.3g close to that of a fixed-base structure to the vibration loads with PGA of 0.15g (measured experimentally). Based on an addiitional parametric study, performed in this work, it was concluded, that for the investigated structure the above mentioned aim is successfully achieved by using a BIS with a natural vibration period of 1.4 s.

The response of the investigated structure to the selected earthquakes scaled to PGA of 0.3g has been obtaned for the following study cases:

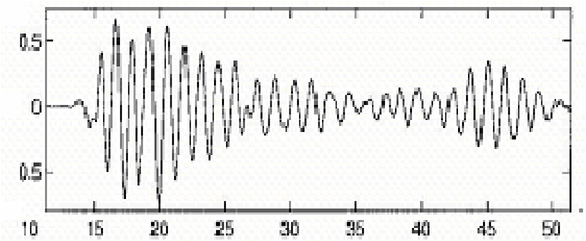
- a fixed base structure;
- a base isolated structure with natural vibration period of 1.4 s.

The peak response of the base - isolated structure is presented in Table 3. Upper floor displacement and acceleration time histories of the structure under the El Centro earthquake for both study cases are given in figures 5,6 ,7 and 8. Similar results were obtained for other earthquake records.



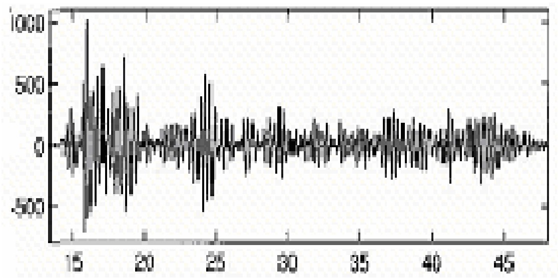
Time, s

Figure 5. Upper floor displacement time history of the fixed-based structure, cm



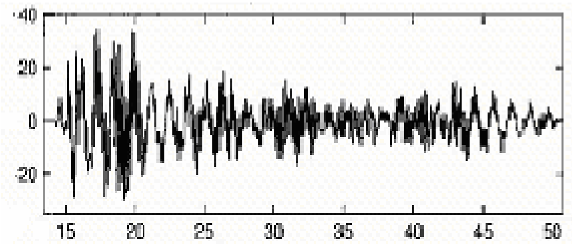
Time, s

Figure 6. Upper floor displacement time history of the base-isolated structure (relative to the first floor column bottom level), cm



Time, s

Figure 7. Upper floor acceleration time history of the fixed-based structure, cm/s^2



Time, s

Figure 8. Upper floor acceleration time history of the base-isolated structure (relative to the first floor column bottom level), cm/s^2

Table 3. Peak response of the base - isolated structure

Seismic motion	Roof displacement (relative to the first-story columns base), cm	BS, kN
El-Centro	0.7	3690
Eilat	0.13	3700
Kobe	0.13	3650

The numerical analysis shows, that using the BIS with the proposed natural vibration period enables to reduce the maximal displacements by 44 – 72 %. It also yields significant reduction in floor accelerations. The peak displacements of the base isolated structure to the earthquakes, scaled to PGA of 0.3g, are lower compared to that under the experimentally obtained values for vibration load with PGA of 0.15g. The base shear forces for these two cases remained almost without changes.

Conclusions

A full-scale 11-storey precast flat-slab RC building has been investigated experimentally and theoretically. Based on the literature review, it is one of the highest full-scale multistory buildings, subjected to vibration tests with an adequate magnitude, equivalent to a seismic excitation with PGA = 0.15g. The performed tests show, that the building has a safe response to these vibration loads, however some structural elements were damaged and cracks opening was obtained.

The idea of constructing a structure in seismic zones with higher seismic activity compared to that, for which it has been designed (0.15 g), was examined. For this reason, it was proposed to use a base isolation system (BIS) for this building, when it will be constructed in higher seismisity zones (0.3 g). In order to select the vibration period of a base isolated structure, a parametric study has been performed. It has shown, that increasing the natural vibration period of the building from 0.72 s to 1.4 s (about twice), adapts it to seismic zones with higher seismicity (PGA of 0.3 g instead of 0.15 g) and keeps its response in the same limits.

The experimentally obtained dynamic parameters of the building were close to the analytical ones. The measured response of the fixed-base building was compared to the analytically obtained structural behavior in order to develop recommendations for using this structure in seismic zones with higher PGA. Numerical results demonstrated the effectiveness of the proposed approach.

According to the analytical results, implementation of BIS significantly improves the structural response to stronger earthquakes. Thus, the base isolated structure can be recommended for seismic zones with PGA from 0.15 to 0.3g.

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