IN-SITU DYNAMIC TESTING AND MODELING OF A SIX-STORY PRECAST CONCRETE BUILDING

Ozan Cem Celik

ABSTRACT

Limited use of precast concrete structural systems in seismic regions due to their poor performances in the past earthquakes and lack of state-of-the-art design guidelines at the time led to two major research projects on the seismic design and performance of precast concrete buildings, PRESSS and SAFECAST, in the last three decades. These projects helped developing design guidelines for precast structural systems in the United States, Japan and Europe. To complement the findings of these projects, system identification of existing precast concrete buildings is required. This paper presents a sequence of forced and ambient vibration tests performed on a six-story precast concrete frame building and the finite element model of the building. To the best of the author’s knowledge, such vibration tests were not previously reported for precast concrete frames. Structural system dynamic properties are identified for the first three translational modes along each axis of the building and for the first three torsional modes. The identified natural frequencies and mode shapes are similar in both tests, whereas damping capacities are higher in general in the forced vibration test, consistent with the previous studies. Subsequent finite element analysis of the building is successful in reproducing the in-situ dynamic properties.

Keywords: Dynamic Properties; Dynamic Tests; Field Tests; Identification; Precast Concrete

1. INTRODUCTION

Precast concrete structural systems are superior to their cast-in-place counterparts due to their higher quality, quick erection at the site, less formwork and labor need, and reduced construction time and cost. On the contrary, precast structural systems have found limited use particularly in seismic regions due to their poor performances in the past earthquakes and the lack of state-of-the-art design guidelines at the time (Priestley 1991, Park 1995, Celik and Sritharan 2004, Xue and Yang 2010, Negro et al. 2013). To address the issues in seismic performance and design of precast concrete buildings, two major research projects, which were also supported by the precast industry, were undertaken in the last three decades. Within the scope of the joint United States-Japan PRESSS (Priestley 1991) and European SAFECAST (Toniolo 2012a) projects, cyclic and dynamic tests on several reduced- and full-scale subassemblages (Priestley 1996, Toniolo 2012b) and pseudodynamic tests on a five-story 3/5-scale and a three-story full-scale building model (Nakaki et al. 1999, Priestley et al. 1999, Negro et al. 2013, Bournas et al. 2013) were performed to examine the connection and overall system behavior. These projects helped developing design guidelines for precast structural systems (Ghosh and Hawkins 2003, Negro and Toniolo 2012). Next step requires identification of in-situ structural system dynamic properties of full-scale precast concrete buildings, which are essential in understanding their behavior when subjected to earthquake, wind, blast, and other dynamic excitations and needed in their design for such hazards. This paper identifies the natural vibration periods (frequencies), modal damping capacities, and vibration mode shapes of a six-story precast concrete frame building from its forced and ambient vibration tests, and compares these in-situ dynamic properties (except damping) with those from the three-dimensional linear elastic finite element structural model of the building. To the best of the author’s knowledge, such vibration tests were not previously reported for precast concrete frames.

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2. TEST BUILDING

The test building is a six-story precast concrete frame building, which is in use as a student dormitory at Hacettepe University in Ankara, Turkey (see Figure 1). It is 20.2 m tall and 53.2 × 15.8 m in plan (see Figure 2). The typical floor-to-floor height is 3.10 m, whereas the height of the ground floor is 4.65 m. It has seven bays along its long axis and three bays along its short axis. The building is separated from an identical building along its long axis by a bay that houses the stairs to both buildings. All precast columns are 600 × 600 mm and beams are 600 × 500 mm except the 400 × 500 mm interior beams along the short axis. Concrete grade is C35; i.e., the characteristic compressive strength is 35 MPa (Turkish Standards Institute 2000). Slabs are composed of 150 mm thick hollow-core panels laid out along the short axis with 70 mm in-situ topping. Beam-column joints are moment connections; beams were welded at the bottom with in-situ topping at the top. Base columns were placed in 1.2 m deep pockets linked with peripheral walls, all on a 0.7 m thick mat foundation. Nonstructural elements were not in place at the time of the forced and ambient vibration tests.
3. IN-SITU DYNAMIC TESTING

3.1 Instrumentation Scheme

In forced vibration testing, the building was excited by a fifth-floor-level (one floor below the roof) vibration generator (cf. Figure 2) with a known sinusoidal force (in kN) along its short and long axes, respectively:

\[ p(t) = 0.24f^2 \sin 2\pi ft \]  

where \( f \) is the excitation frequency (in Hz) and \( t \) is the time (in s). Sweeping the frequency of the vibration generator from 0.5 to 9.5 Hz, structural vibrations were continuously recorded by a dense network of 22 uniaxial accelerometers deployed throughout the building. In between each increment of frequency, typically 30 s were allowed for the transient response to damp out and the subsequent steady-state response to be captured. Each floor was instrumented typically by three horizontal accelerometers, two parallel along the excitation direction and the third in the perpendicular direction (cf. Figure 2), to record the translational as well as torsional responses. The first two floors and the roof floor were instrumented by two horizontal accelerometers parallel along the excitation direction. The rigid floor diaphragm assumption was verified by a third parallel accelerometer on the fifth floor (cf. Figure 2). Possible rocking responses were monitored by vertical accelerometers placed at three corners of the ground floor. Accelerations from all 22 accelerometers were recorded by two six-channel digital recorders at 100 samples per second in two setups for each excitation direction (see Table 1). Fifth-floor accelerometers that are along the excitation direction were used as reference accelerometers. Detailed information on the vibration generator, accelerometers, and data acquisition systems can be found in Celik (2015).

Table 1. Accelerometer locations and directions.

<table>
<thead>
<tr>
<th>Acc. #</th>
<th>Floor #</th>
<th>Short Axis Excitation</th>
<th>Long Axis Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R</td>
<td>A12 +y •</td>
<td>D17 +x •</td>
</tr>
<tr>
<td>2</td>
<td>R</td>
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<td>A17 +x •</td>
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<tr>
<td>4</td>
<td>5</td>
<td>A14A +y •</td>
<td>IB17 +x •</td>
</tr>
<tr>
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<td>5</td>
<td>A17 +y •</td>
<td>A17 +x •</td>
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<tr>
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<td>5</td>
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<td>A12 +y •</td>
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<td>A17 +y •</td>
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<td>A17 +y •</td>
<td>A17 +x •</td>
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<td>A17 +y •</td>
<td>A17 +x •</td>
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<td>G</td>
<td>A12 +y •</td>
<td>A12 +y •</td>
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<td>A17 +z •</td>
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<tr>
<td>22</td>
<td>G</td>
<td>D17 +z •</td>
<td>D17 +z •</td>
</tr>
</tbody>
</table>
3.2 Forced Vibration Responses

Upon digital signal processing of the records with the use of the analytic signal (Santamarina and Fratta 2005), an application of the Hilbert transform, steady-state acceleration response amplitudes were extracted at each operated frequency during the frequency sweep. Figure 3 shows the acceleration-frequency response curves (for a constant-amplitude sinusoidal force) for the excitations along the short and long axes of the building.

3.3 Ambient Vibration Responses

In ambient vibration testing, the building is assumed to be excited by a white noise random process. Ambient vibrations were recorded for at least 30 minutes following each forced vibration test setup with the same configuration of accelerometers (see Section 3.1). Figure 4 shows the Fourier amplitude spectra of the ambient accelerations (Santamarina and Fratta 2005, Kaya and Safak 2015).

4. FINITE ELEMENT MODELING

The 3-D linear elastic finite element structural model of the building (see Figure 5) was developed using SAP2000 (Computers and Structures 2016) based on the centerline dimensions. The height of the ground floor was taken as 4.5 m and the other floors as 3.1 m. Frame elements were used in modeling the columns and beams. Beam heights included the hollow core slab and the topping. The moment of inertia of the beams was assumed as two times that of the beam webs. Slabs were assumed rigid in their own plane and rigid diaphragms were defined at all floors. Beam-column joints were modeled as rigid joints and fixed supports were defined. The modulus of elasticity for grade C35 concrete was taken as 33,000
MPa (Turkish Standards Institute 2000) and its unit weight as 24 kN/m$^3$. The self weight of the hollow core slab and the topping was incorporated in the structural model as 4.0 kN/m$^3$. There were no nonstructural elements in place at the time of the tests, which could have contributed to the mass and stiffness of the building.

Figure 4. Fourier amplitude spectra of the ambient accelerations

Figure 5. 3-D finite element structural model
5. SYSTEM IDENTIFICATION

5.1 Natural Frequencies

In forced vibration testing, the natural frequencies of the building are essentially equal to the resonant frequencies in the acceleration-frequency response curves (cf. Figure 3; Rea et al. 1968, Chopra 1995, Celik et al. 2015). Table 2 presents the natural frequencies for the first two translational modes along each of the short and long axes of the building and for the first two torsional modes.

In ambient vibration testing, the frequencies at which the Fourier amplitudes of the accelerations (cf. Figure 4) attain their peak values are essentially the natural frequencies of the building (Safak and Cakti 2014). They are presented in Table 2 for the first three translational and torsional modes. Note that advanced system identification algorithms do exist for ambient vibration testing (Ljung 1999). System identification of this building using frequency domain decomposition methods (Brincker et al. 2001a, 2001b) can be found in Celik (2017).

In finite element modeling, the natural frequencies are determined from the eigenvalue analysis of the structural model. They are presented in Table 2 for the first three translational and torsional modes.

5.2 Damping Capacities

The half-power bandwidth method (Rea et al. 1968, Chopra 1995) was used to determine the damping capacities associated with the identified modes in both forced and ambient forced vibration testing, as presented in Table 3.

5.3 Mode Shapes

Mode shapes were determined from the recorded accelerations at resonant frequencies in forced vibration testing and from the Fourier amplitudes of the recorded accelerations at identified frequencies in ambient vibration testing. Figure 6 shows the mode shapes that were determined from the eigenvalue analysis of the structural model in finite element modeling.
CONCLUSION

Forced and ambient vibration tests were performed on a six-story precast concrete frame building. To the best of the author’s knowledge, these in-situ dynamic tests are the first to be performed on existing precast concrete frames. Dynamic properties of the precast structural system were identified from the forced vibration testing using well-established methods in the structural dynamics area (Rea et al. 1968, Chopra 1995, Celik et al. 2015) and from the ambient vibration testing using simple algorithms that rely on only Fourier transforms and band-pass filters (Safak and Cakti 2014). Natural frequencies, damping capacities, and mode shapes were identified for the first three translational modes along each of the short and long axes of the building and for the first three torsional modes. The identified natural frequencies and mode shapes were similar; however, the damping capacities identified from forced vibration testing were higher in general, consistent with previous studies. Natural frequencies determined from the linear elastic finite element structural model of the building developed subsequently were in close agreement with those identified from the in-situ dynamic tests.

6. CONCLUSIONS

Forced and ambient vibration tests were performed on a six-story precast concrete frame building. To the best of the author’s knowledge, these in-situ dynamic tests are the first to be performed on existing precast concrete frames. Dynamic properties of the precast structural system were identified from the forced vibration testing using well-established methods in the structural dynamics area (Rea et al. 1968, Chopra 1995, Celik et al. 2015) and from the ambient vibration testing using simple algorithms that rely on only Fourier transforms and band-pass filters (Safak and Cakti 2014). Natural frequencies, damping capacities, and mode shapes were identified for the first three translational modes along each of the short and long axes of the building and for the first three torsional modes. The identified natural frequencies and mode shapes were similar; however, the damping capacities identified from forced vibration testing were higher in general, consistent with previous studies. Natural frequencies determined from the linear elastic finite element structural model of the building developed subsequently were in close agreement with those identified from the in-situ dynamic tests.
7. ACKNOWLEDGMENTS

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8. REFERENCES


