CENTRIFUGE TESTING OF COMBINED FRAME-WALL-FOUNDATION STRUCTURAL SYSTEMS

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ABSTRACT

Numerous existing low-ductility reinforced-concrete (R/C) buildings are commonly retrofit with an additional shear wall to withstand seismically generated lateral forces. To investigate the seismic performance of combined frame-wall systems, an idealized two-story two bay planar R/C frame with an attached shear wall was designed using conventional practice. Resting on medium-dense sand, shallow footings are used to support the structure, with strip footings beneath the shear wall and square footings beneath individual columns. Modeled after the idealized structure, two 1/20th scale steel models were constructed and tested in the centrifuge at UC Davis. In a first attempt to incorporate structural nonlinearity into a centrifuge model, beam nonlinearity is accounted for using replaceable ductile fuses at the beam-ends. The structure-foundation system then incorporates both structural nonlinearity and foundation nonlinearity through rocking, sliding, and settling of the footings. Preliminary data analysis shows that these frame-wall systems have highly asymmetric hysteretic loops due to the asymmetry of the lateral force resisting system. In addition, results indicate substantial energy dissipation may be obtained through both the plastic deformations at the beam ends and below the foundations.

Introduction

The seismic performance of dual frame-wall system is influenced by the flexibility of the underlying foundation as well as that of the frame components (beam-column joints). However, conventional design practice generally does not take into account the flexibility of the underlying foundation; nor does it consider the design of the frame and wall as a whole system. Although mobilization of the bearing capacity below the footing(s) will result in nonlinear soil interface behavior that will dissipate energy, excessive demands at the foundation level may result in bearing failure within the soil. Nonetheless, this dissipation of energy may beneficially reduce

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structural demands imposed on the soil-structure system. To account for this dissipation of energy in performance based earthquake engineering, several issues must be considered. First, unfortunately, the rocking motion can result in excessive permanent settlement. Second, the nature of the redistribution of demands within the structural system must be considered. The second issue is particularly important for combined structural systems, where rocking of the foundation below one system may induce large demands at the interface between them due to their difference in stiffness. The more flexible moment frame will have a lower stiffness than the very rigid shear wall.

In the first significant recognition of the utility of the rocking foundation and structure, Housner (1963) studies the behavior of a rigid block which is excited by a rocking motion. He concludes that energy dissipation of the block depends on the amplitude and frequency of the rocking motion. Subsequent experimental studies have substantiated the beneficial energy dissipating features of rocking foundation systems (Barlett 1976; Wiessing 1979; Negro et. al. 1998). Recent work at UC Davis has considered an idealized shallow foundation (strip footing) supporting a shear wall structure and tested models of the same on the UC Davis centrifuge. Experiments by Rosebrook and Kutter (2001), denoted herein as the KRR series, and by Gajan et. al. (2003), denoted herein as the SSG series, have examined a range of footing sizes, static vertical factors of safety, and both clay and sand soil types. Shallow foundation models were subjected to static and dynamic pushes (pure compression, lateral displacement cyclic loading, and base excitation). Analysis of KRR and SSG experimental data and subsequent analytical modeling (Gajan et. al. 2005; Harden 2003) show the energy dissipation available from the rocking shallow foundation.

With the benefits of the isolated footing response in mind, experiments described in this paper now consider combined structure-foundation systems modeled after realistic building structures. To characterize the seismic performance of combined frame-wall systems, an R/C two-story two bay moderate ductility frame and shear wall building was designed using current design methods. Two 1/20th scale models were constructed and tested on the geotechnical centrifuge at UC Davis. Although much work has been conducted on centrifuge-scale nonlinear soil modeling prior to this research, little work has been conducted to evaluate centrifuge-scale nonlinear structural modeling. Incorporating structural nonlinearity, beams used replaceable ductile fuses at the beam-ends. The structure-foundation system then incorporated both structural nonlinearity from the fuses and foundation nonlinearity through rocking, sliding, and settling. The following sections describe the experimental program and present testing results.

**Experimental Program**

**Geotechnical Centrifuge at UC Davis**

The frame-wall foundation structure was designed to fit within a 1.76 × 0.9 meter (5.77 × 2.95 feet) rigid soil container mountable on the UC Davis centrifuge. This soil box was attached to the centrifuge’s 9 meter (29.5 feet) arm and, for these tests, was spun to create a gravitational field of 20g’s applied to the model. According to scaling laws, a specimen subjected to 20g’s is dimensionally twenty times larger than its size at 1 g. Most importantly, stresses scale 1:1 from model to prototype. 1:1 scaling of stress is especially valuable for geotechnical engineering
because soil properties are very sensitive to confining stress. However, the principles of centrifuge modeling can also be easily applied to structures, and it is valuable for problems that involve nonlinear soil-structure interaction. The centrifuge allows modeling of prototype soil stresses and, thus, captures the strength and deformation characteristics of the soil. Additional description of the centrifuge and information of governing scaling laws may be found in Kutter (1997).

**Design of Frame-Wall-Foundation Hypothetical Prototype for Centrifuge Models**

Before designing the centrifuge model, a hypothetical prototype consisting of a two-story, two-bay planar R/C frame with an attached shear wall was designed using conventional seismic design per FEMA 356 guidelines (FEMA 2000). Design gravity loads were selected assuming a surface load of 1.3 kPa (27 psf) acting over 4.6 meters (15 feet) tributary width. Prototype frame dimensions of 9.53 × 7.62 meters (31.3 × 25.0 feet) (height × width) were selected, and a shearwall of 9.53 × 2.54 meters (31.3 × 8.3 feet) was selected. Member stiffness was tuned to achieve a target fundamental period of T_n=0.5 seconds under flexible foundation conditions.

Shallow footings were used to support the structure, with strip footings beneath the shear wall and square footings beneath individual columns. The factors of safety presented in Table 1 are based on actual load (or moment) capacities determined experimentally for the different footings divided by either the gravity load or gravity and seismic load cases. Shallow footings were embedded no more than 0.14 m (5.5 inches) (prototype units) in medium-dense dry sand (Dr=80%). The reinforced concrete frame was designed per ductile seismic design as specified in the ACI 318-02 (2002). Concrete in the beams and columns were designed to account for confinement due to transverse hoops. Confinement strengths were calculated by using theoretical expressions relating the confinement to fluid pressure analogies.

<table>
<thead>
<tr>
<th>Loading Case</th>
<th>Strip Footing</th>
<th>Int. Sq. Footing</th>
<th>Ext.Sq. Footing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FSv</td>
<td>FSs</td>
<td>FSo</td>
</tr>
<tr>
<td>Gravity</td>
<td>8.1</td>
<td>53.3</td>
<td>131.7</td>
</tr>
<tr>
<td>Gravity + Seismic</td>
<td>8.7</td>
<td>2.9</td>
<td>6.5</td>
</tr>
<tr>
<td>Governing FS's</td>
<td>8.1</td>
<td>2.9</td>
<td>6.5</td>
</tr>
</tbody>
</table>

To evaluate the response of the designed frame-wall-foundation system, an OpenSEES (2005) model was constructed. Flexibility of the underlying soil foundation was modeled using nonlinear spring elements to incorporate radiation damping effects and allow the structure to rock, slide, and/or settle in the soil. Parameters for defining the constitutive relation that describe the nonlinear soil-foundation springs (bearing capacity, stiffness, etc.) were from KRR and SSG tests. Columns were modeled using nonlinear beam column elements, which capture the spread of plasticity along the length of the member. Beams were designed to yield with design level seismic forces through forced hinges at the ends of typical beam-column joints. The finite element representation of the beams used a “beam with hinges” concept, whereby the middle of
the element remained elastic, and plasticity was localized at ends of the element. The plastic hinge behavior was later mimicked by custom-designed steel fuses in the centrifuge model.

The idealized prototype building was reduced to 20g model-scale and suitable materials for fabrication of the model were chosen. Model scale frame-wall structural and foundation elements were made from steel and aluminum. Due to the workability of steel, the frame elements were constructed from steel (Figure 1). The steel beams and columns were fabricated from one-inch square hollow steel tubing. The existing aluminum shear wall and strip footing from previous KRR and SSG test series were used. Lead mass blocks were used to simulate the remaining dead load of the structure. Moment transferring bolted connections attached all fuse-beam-column and frame-to-shear-wall connections (Figure 1c). The modularity of the connections and pieces enabled the model to be assembled into the original two-story two bay configuration (Figure 1b) and also a modified two-story one bay configuration (Figure 1a). The modified one bay model was tested first, as its instrumentation was simpler and thus cleaner to post-process. After scaling to 20g’s, overall dimensions of the one bay model were 0.51 × 0.51 meters (20 × 20 inches); dimensions of the two bay were 0.51 × 0.89 meters (20 × 35 inches). Each model was tested in a different station within the soil box (Figure 2).

![Experimental structural model](image)

Unique to this centrifuge model series were designed yielding beam joints to allow structural nonlinearity and, thus, energy dissipation from the frame members. The final fuse design for these forced hinges consisted of a circular cross-section with strategically placed drilled holes. This fuse design yielded a desirable moment-curvature response and had sufficient room for wiring and installing quarter-inch strain gages in a full-bridge configuration. Fuses were fabricated from 19 mm (3/4 inch) diameter 16 gage hollow circular steel tubing and
instrumented with high-elongation strain gages (Figure 1c).

![Schematic plan view (units in mm)](image1)

![Two bay model in centrifuge soil box](image2)

Figure 2. Testing configuration for frame-wall-foundation structure model

**Instrumentation**

Instrumentation for the structure was arranged to capture local load distributions of shear, moment, and axial forces; global and local displacements; and lateral, vertical, and out-of-plane accelerations (Figure 3). The structure was slightly embedded in a 4 meter (13 feet) layer of dry Nevada sand (prototype units), which was instrumented with embedded accelerometers. The one bay structure had approximately forty instruments attached while the two bay had approximately sixty instruments attached. Fuses were instrumented with strain gages in a full-bridge configuration to measure changes in strain. Fuse moments were then based on calibration tests conducted at UC Irvine. Vertical linear potentiometers were placed across the width of each footing and used to calculate settlements and rotations. Laterally placed linear potentiometers measured sliding of individual footings.

![Instrumentation of frame-wall-foundation model (model units in mm)](image3)

Figure 3. Instrumentation of frame-wall-foundation model (model units in mm)

**Fuse Calibration**

Calibration of ductile fuses at UC Irvine consisted of testing four fuses under slow cyclic loading. For each test, an individual fuse was bolted into a lever-arm assembly that was attached securely to the loading apparatus (Figure 4a). The fuse was then cyclically moment loaded three complete times to designated displacements of: below yielding, at yielding, and beyond yielding.
A Romberg-Osgood equation was fitted to the recorded moment-rotation data. An example analytical moment-rotation response compared to the experimental moment is shown in Figure 4b. The average value of the parameters from the Romberg-Osgood fit were then used to calculate an analytical moment from recorded strain data for the centrifuge experiments.

Test Series

While at 20g’s, both models were tested under a variety of loading conditions. Both were subjected to separate series of static lateral pushes and dynamic base input shakes; only the two bay model was excited by a Loma Prieta earthquake motion recorded in Santa Cruz. Table 2 summarizes the test series conducted with the average maximum displacement of the push tests and the peak-to-peak base acceleration of the dynamic shakes. Static pushes were input as inertial-based loading at the upper floor level through a hydraulic actuator; dynamic shakes were input at the base of the soil layer through the UC Davis shake table. All loading was applied in plane with the frame-wall-foundation models.

Table 2. One and two bay tests. HSC (horizontal slow cyclic), D (dynamic) (Prototype units) (25.4 mm = 1 inch)

<table>
<thead>
<tr>
<th>Name</th>
<th>Ave Max Disp/Drift Ratio (%)</th>
<th>Name</th>
<th>Base acc (g)</th>
<th>Name</th>
<th>Ave Max Disp/Drift Ratio (%)</th>
<th>Name</th>
<th>Base acc (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSC1</td>
<td>19 mm / 0.20 %</td>
<td>D1</td>
<td>0.09 g</td>
<td>HSC9</td>
<td>9 mm / 0.09 %</td>
<td>D5</td>
<td>0.08 g</td>
</tr>
<tr>
<td>HSC2</td>
<td>17 mm / 0.18 %</td>
<td>D2</td>
<td>0.20 g</td>
<td>HSC10</td>
<td>17 mm / 0.18 %</td>
<td>D6</td>
<td>0.14 g</td>
</tr>
<tr>
<td>HSC3</td>
<td>12 mm / 0.13 %</td>
<td>D3</td>
<td>0.65 g</td>
<td>HSC11</td>
<td>26 mm / 0.27 %</td>
<td>D7</td>
<td>0.65 g</td>
</tr>
<tr>
<td>HSC4</td>
<td>28 mm / 0.29 %</td>
<td>D4</td>
<td>0.93 g</td>
<td>HSC12</td>
<td>15 mm / 0.16 %</td>
<td>D8</td>
<td>0.96 g</td>
</tr>
<tr>
<td>HSC5</td>
<td>55 mm / 0.58 %</td>
<td>HSC13</td>
<td>31 mm / 0.33 %</td>
<td>D9 (gm)</td>
<td>0.85 g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSC6</td>
<td>116 mm / 1.22 %</td>
<td>HSC14</td>
<td>59 mm / 0.62 %</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSC7</td>
<td>240 mm / 2.52 %</td>
<td>HSC15</td>
<td>116 mm / 1.22 %</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSC8</td>
<td>396 mm / 4.16 %</td>
<td>HSC16</td>
<td>238 mm / 2.50 %</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--</td>
<td>--</td>
<td>HSC17</td>
<td>398 mm / 4.18 %</td>
<td>--</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Experimental Results
**Force-Displacement Response**

Inspection of the global force and absolute displacement of both models reveals hysteretic energy dissipation through sliding and rocking. In Figure 5, tests D3 and HSC4 are for the one bay structure; tests D7 and HSC11 are for the two bay structure. Dynamic tests D3 and D7 show non-symmetrical stiffness as the structure rocks and slides; much more sliding of the one bay structure is observed as compared to the two bay structure. This may be in part due to the larger aspect ratio of the one bay; the stouter two bay model is less slender. Permanent sliding displacement of the one bay structure is approximately 170 mm (6.7 inches), compared with 100 mm (3.9 inches) for the two bay structure. Permanent sliding of the structure was towards the frame side, which is softer than the shearwall side. Test HSC11 also slides in the frame direction and does not return to its starting location. Test HSC4 does not show as much permanent sliding, possibly due to the magnitude and chronology of the test. Test HSC4 occurred after the dynamic one bay tests, during which the majority of the compaction and sliding of the soil may have already occurred.

![Figure 5. Example force vs. displacement for one bay and two bay model. (Prototype units)](image)

**Footing Response**

Examination of the footing response for test D7 (Figure 6) and test HSC 14 (Figure 7) shows energy dissipation occurring in the strip and square footings. These two bay tests indicate that the strip footing tends to dissipate more energy than either the interior or exterior square footings. Settlement from test D7 and test HSC 14 is relatively symmetric about the middle square footing as the structure rocks but non-symmetric for the strip footing and the exterior square footing. In test D7, the soil is settling fairly symmetrically underneath the footings as the model slides. More significantly, settlement and compaction of the soil for the strip footing and exterior square footing occur on the outer edges of the model as it rocks. Note that these data are not shown beginning with zero moment or rotation, due to the cumulative load and deformation from the previous test series.

The moment capacities of the strip footing and exterior square footing are greater than the moment capacities (square footing capacity = 0.325 MN-m; strip footing capacity = 0.700 MN-m) from isolated footings tests at constant axial load of previous experiments SSG03 and JMT01. Inspection of moment to axial force plots in Figures 6 and 7 shows redistribution of the vertical loads as the structure rocks; this changing vertical load will affect the moment capacity. Increased moment capacity is associated with momentary large axial load on the footing.
Fuse Response

Examination of the fuses for test HSC4 for the one bay and HSC11 for the two bay

Figure 6. Test D7: Footing Response of two bay model (Prototype units)

Figure 7. Test HSC 14: Footing Response of two bay model (Prototype units)
model shows energy dissipation in the fuses. These horizontal slow cyclic tests have an average maximum displacement of 28 mm (1.1 inches) and 26 mm (1.02 inches) in prototype units or 0.3% total drift. Analytical moment calculation shows that the fuse at the lower-story exterior column location (denoted by an arrow in Figures 1a-b) does not behave in the same manner for each test. At this location, the fuse in the two bay undergoes more relative rotation and thus dissipates more energy than the fuse in the one bay. The amount of energy dissipated by fuse 2 in the one bay is approximately 20% of the amount dissipated by the same fuse in the two bay model (Figure 8).

Figure 8. Moment-rotation behavior of fuse 2. (Prototype units)

Conclusions

In this paper, which focuses on combined soil-structure systems, the effectiveness of the commonly adopted retrofit strategy of adding a shear wall to a reinforced concrete frame is studied through centrifuge testing. Two 20g model frame-wall-foundation structures were tested on a centrifuge. Models were supported on strip and square footings and embedded in dry medium dense Nevada sand. Loading sequences included dynamic base excitation and slow cyclic inertial-based loading. Data analysis of the centrifuge experiments indicates these frame-wall systems have highly asymmetric hysteretic loops due to the asymmetry of the lateral force resisting system; in this case, the shear wall is in an unsymmetrical position on one end of the building. For footings with a fairly large factor of safety against collapse due to vertical loads, the moment capacity of the footing increases as the vertical load on the footing increases. Thus footings at the edge of the building that are subject to cyclic axial load will behave differently from footings near the center of the frame, where axial loads may be almost constant. Analysis of the centrifuge data shows that significant system-level energy dissipation occurs in the model during both pseudo-static and dynamic loading. Fuse calibration from the UC Irvine experimental data shows energy dissipation through moment-rotation of the beam hinges. The centrifuge tests reported here are among the first model scale experiments that have included reasonably accurate simulations of building nonlinearity coupled with foundation nonlinearity. The load paths followed by the individual foundations of the building are quite unsymmetrical -- comparatively different load paths from those followed in individual idealized footing tests. It is envisioned that this work will fill a critical gap in characterizing the system level ductility of dual lateral resisting systems, where soil structure interaction is considered.

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