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AN INERTIAL FORCE-LIMITING FLOOR ANCHORAGE SYSTEM FOR LOW-DAMAGE BUILDING STRUCTURES

Z. Zhang[1], A. Nema[2], G. Guerrini[3], U. Shakya[4], G. Tsampras[5], R. Fleischman[6], J. Restrepo[7], R. Sause[8], D. Zhang[9], J. Maffei[10], D. Mar[11], and G. Monti[12]

ABSTRACT

A new low-damage seismic system, the Inertial Force-Limiting Floor Anchorage System (IFAS), has been developed. The IFAS attempts to reduce building response in earthquakes by providing a deformable connection to the floor diaphragm. The IFAS development included: (1) creation and full-scale testing of IFAS prototypes; (2) an analytical parameter study to develop a design space for the IFAS; (3) a shake table test to demonstrate the IFAS concept. This paper presents a summary of selected research performed to develop the IFAS including: (1) key findings from the analytical parameter study that produced a feasible design range for the IFAS; (2) key results from the shake table testing; and (3) results from analyses of a calibrated model to clarify and augment the results of the shake table test. These results show the potential for the IFAS to be effective in reducing building response in an earthquake, including inter-story drifts and floor accelerations.

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ABSTRACT

A new low-damage seismic system, the Inertial Force-Limiting Floor Anchorage System (IFAS), has been developed. The IFAS attempts to reduce building response in earthquakes by providing a deformable connection to the floor diaphragm. The IFAS development included: (1) creation and full-scale testing of IFAS prototypes; (2) an analytical parameter study to develop a design space for the IFAS; (3) a shake table test to demonstrate the IFAS concept. This paper presents a summary of selected research performed to develop the IFAS including: (1) key findings from the analytical parameter study that produced a feasible design range for the IFAS; (2) key results from the shake table testing; and (3) results from analyses of a calibrated model to clarify and augment the results of the shake table test. These results show the potential for the IFAS to be effective in reducing building response in an earthquake, including inter-story drifts and floor accelerations.

Introduction

Current seismic design targets life safety and collapse prevention for building structures to permit occupants to survive the earthquake [1]. Structural elements are typically designed to dissipate

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seismic energy themselves, leading to unavoidable building damage in earthquakes. Recent large earthquakes has shown that the amount of building damage, economic loss due to downtime, and repair cost of structures may be unacceptably high even for countries with well-developed seismic codes [2]. As a result, the interest in developing new low-damage structural systems is increasing.

One such innovative low-damage system, the Inertial Force-limiting Floor Anchorage System (IFAS), has been developed [3-5]. The IFAS is designed to limit the inertial forces that develop in the floor diaphragm, thereby lowering floor accelerations and seismic demands on the building. This goal is accomplished by providing an engineered deformable connection between the floor system and Lateral Force Resisting System (LFRS) [3, 5]. The connection is designed with a lower strength than that is required for maintaining a conventional floor anchorage elastic in earthquakes. The connection deforms at this lower strength, transforming the diaphragm seismic demands into relative displacement between the floor system and LFRS. Earthquake energy in the building is dissipated in the IFAS when the relative displacement occurs.

The IFAS has the potential to improve structural seismic response with respect to a conventional structure (where the diaphragm-to-LFRS connection is typically near-rigid and strong by virtue of the use of the Ω_o factor in seismic collector design). The potential benefits of the IFAS include: (1) limiting building inertial forces, thereby reducing seismic demands, resulting in less damage to the structure; (2) lowering floor accelerations, leading to less damage to non-structural elements and building contents [6]; and, (3) limiting higher mode effects related to large story shear in the LFRS and large forces in the diaphragm [7], and thus potentially preventing failures associated with these actions.

The IFAS possess three main components. Each component acts between the floor system and LFRS: (1) force-limiting elements to limit the inertial forces in the floor system and dissipate energy; (2) elastic restoring elements (rubber bearings) to minimize residual relative displacement between the floor system and LFRS, and also brace the LFRS elements; and (3) re-engagement devices (bumpers) to limit the relative displacement between the floor system and LFRS, necessary for designs with lower IFAS strength. Development and demonstration of the IFAS consisted of three main research activities, in addition to insights and assistance from practicing seismic design consultants [8]:

(1) Development and testing of IFAS prototypes (Lehigh University). Two IFAS prototypes were developed [5,9], one with a friction damper (FD) as the deformable connection; the other a buckling restrained brace (BRB). Both prototypes were tested in full-scale at the NEES@Lehigh ATLSS Center. The test results showed that stable force-deformation hysteretic behavior can be provided from these IFAS prototypes. Supplemental testing investigating the force-deformation behavior of the bumpers under high loading rate was conducted after the shake table test.

(2) Analytical studies investigated the influence of different design parameters for the purpose of identifying a feasible design space. The effect of building height, IFAS characteristics (strength, energy dissipation capacity, initial stiffness, secondary stiffness), LFRS characteristics (overstrength and type), Gravity Load Resisting System (GLRS) characteristics (stiffness and strength) were investigated through nonlinear time history analyses (NTHA) on a two-dimensional

(2D) numerical model. The IFAS shake table test specimen design was based on this study.

(3) Demonstration of the IFAS through shake table testing. The test program, conducted at the NEES@UCSD Outdoor Shake Table, compared the IFAS to a conventional building. The test results showed that the IFAS significantly reduced most key building seismic responses with respect to a conventional structure. However, the floor acceleration reduction exhibited in the test was not as significant as expected. A three-dimensional (3D) numerical model was calibrated to the test results to investigate this unexpected behavior. This investigation provided compelling evidence for the experimental conditions that led to the lower than expected acceleration reduction.

This paper presents the: (1) analytical parameter study findings related to determining an IFAS design space for the shake table test specimen; (2) key shake table test results; and (3) analytical study results of the calibrated 3D model. These results show the potential of the IFAS in reducing building responses in earthquakes, including LFRS drifts and floor accelerations.

Analytical Parameter Study

Evaluation Structure

The evaluation structure for the analytical parameter study is a reinforced concrete (RC) structure. Figure 1a shows the typical plan of the evaluation structure. The structure is examined in the transverse direction only. The transverse direction LFRS is interior RC shear walls. The floor-to-floor height is 4.88m for the 1st story and 3.20m for upper stories. The seismic design of the evaluation structure is based on ASCE 7 [10]. Details of the design can be found in [11].

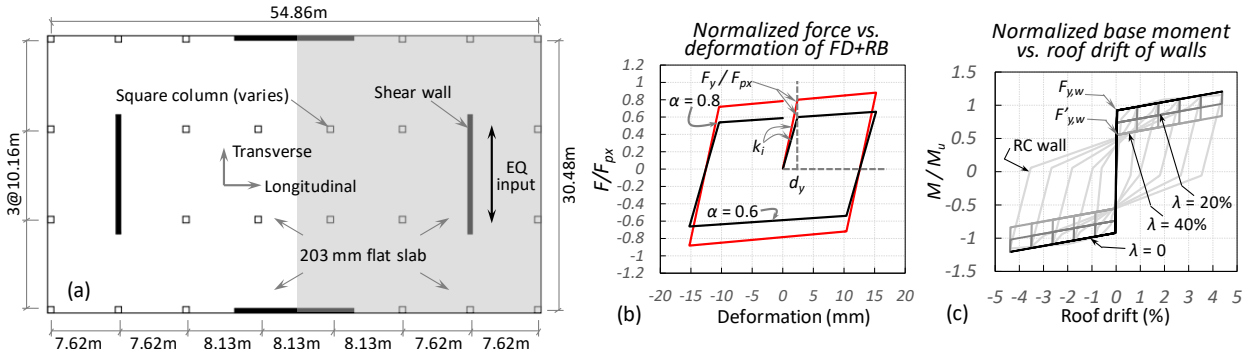


Figure 1. (a) Evaluation structure plan; Hysteretic characteristics: (b) FD + RB; (c) Shear wall.

Design Parameters: Analytical Study

The analytical study design parameters selected for presentation in this paper are: (1) IFAS strength α (defined as $\alpha = \sum F_y / F_{px}$, where F_y is the IFAS strength (See Fig. 1b), $\sum F_y$ is the total strength of the IFAS in one (lateral) direction for each floor; and F_{px} is the diaphragm design force from ASCE 7 [10]); (2) LFRS type, focusing here on conventional RC shear walls and rocking walls (See Fig. 1c); and, (3) LFRS overstrength (Ω_e), as defined subsequently.

The IFAS strength is the primary design parameter. The IFAS strength is varied from essentially full isolation to elastic in the study (See Table 1). The IFAS prototype used in the

studies presented in this paper consists of FD and low damping rubber bearings (FD + RB) [5]. Examples of the normalized IFAS force-deformation hysteresis is shown at two selected strengths (α = 0.6, 0.8) in Fig. 1b. Note: (a) the IFAS strength F_y is defined at a constant deformation (d_y = 2.4mm). Thus, IFAS initial stiffness, k_i, is proportional to F_y; (b) a 2% strain hardening ratio is assumed for each IFAS; (c) the IFAS strength is based on the maximum F_{px} at all floors and is kept constant along the structure height.

The analytical study results presented in this paper focuses on two LFRS types: RC walls (evaluation structure) and rocking walls (shaking table specimen). Different energy dissipation capacity is considered for the rocking walls representing different amounts of supplemental energy dissipation, as represented by λ, where $\lambda = (F_{y,w} - F'_{y,w}) / F_{y,w}$ (See Fig. 1c for λ = 40%).

The LFRS may often possess a larger strength (moment capacity) than required by the seismic design [10]. Displacement-based design can lead to an LFRS possessing lower moment capacity than the code required strength [12]. The effect of the LFRS strength is studied by using the LFRS overstrength (Ω_e), which is defined as the ratio between the expected moment strength (M_e) and the required design moment of the shear wall (M_u). Ω_e values are shown in Table 1.

Table 1. Design parameter values.

Design parameters		Values
IFAS	α	0.01, 0.1, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0, 1.2, 1.5, 2.0, 2.5, 3.0, Elastic
LFRS	Type	RC wall, Rocking wall (λ = 0, 20%, 40%)
	Ω_e	0.7, 1.0, 1.3, 1.6

Numerical Model

Two-dimensional (2D) models of an IFAS building were created using OpenSees (See Fig. 2a). The 2D model represents a half-symmetry model of the evaluation structure (shaded portion in Fig. 1a). The LFRS (shear wall) is modeled using a cantilever element with a base plastic hinge; the IFAS is modeled using nonlinear springs; and the GLRS is modeled as a frame with plastic hinges at the slab ends and column bases (See Fig. 2a). The model is analyzed in the structure transverse direction. The tributary floor (and column) mass is assigned to each GLRS beam-to-column joints; the structural wall mass is lumped at each level. Details of the model can be found in [11].

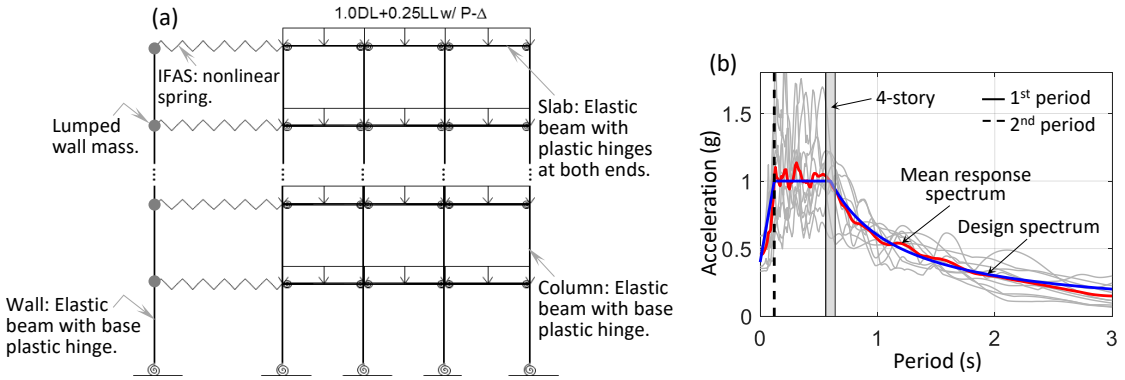


Figure 2. (a) Structure model; (b) Ground motion response spectrum (ξ = 5%), design spectrum.

Ground Motions

A suite of 10 ground motions are used in the study. The motions are scaled to match a 5% damped (ξ) design spectrum for a generic SDC D site at the design basis earthquake (DBE) level (Fig. 2b). The 1st (shaded) and 2nd (dashed line) mode periods for conventional structures at different Ω_e are indicated. Simulations are performed at DBE and maximum considered earthquake (MCE) level.

Parameter Study Results

The parametric results presented in this section are average values of the maximum structural responses from NTHAs using the 10 ground motions (refer to Fig. 2b).

Effect of IFAS Strength

The effect of IFAS strength on the 4-story RC wall structure MCE response is shown in Fig. 3. The floor acceleration decreases as α decreases, while some humps are observed (Fig. 3a). The LFRS drift decreases as α decreases (Fig. 3b). The GLRS drift and relative displacement increase as α decreases (Figs. 3b, c). Two design limits are used for limiting the relative displacement. The limits are shown in Fig. 3c: (1) conservative limit (101.6mm); (2) aggressive limit (203.2mm).

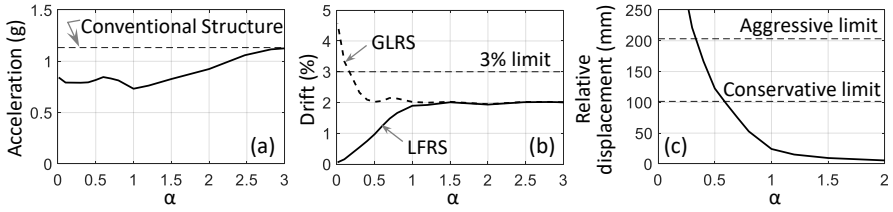


Figure 3. 4-story MCE response (Ω_e = 1.0): (a) acceleration; (b) drift; (c) relative displacement.

Effect of LFRS Types

The effect of different LFRS types on the 4-story structure (Ω_e = 1.0) response is shown in Fig. 4. Note that the rocking wall structure generates larger acceleration, LFRS drift, GLRS drift and relative displacement than the RC wall structure. Thus the results imply that the key response parameters decrease as the wall energy dissipation capacity increases.

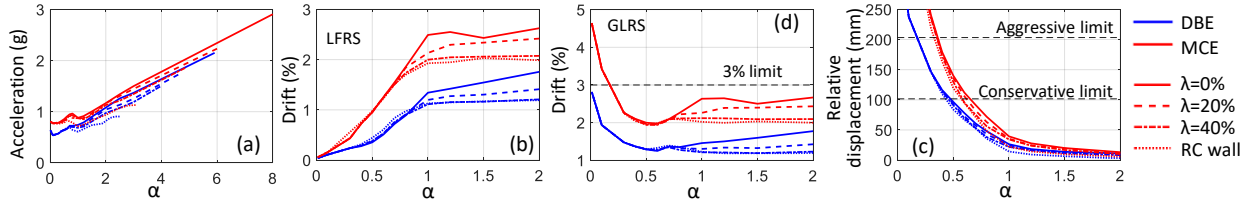


Figure 4. 4-story structures using different LFRS (Ω_e = 1.0): (a) floor acceleration; (b) LFRS drift; (c) GLRS drift; (d) relative displacement.

Figure 4c shows that a GLRS drift "valley" exists when the IFAS is designed at a certain strength range. This response implies that an IFAS designed within this strength range has the potential to produce smaller GLRS drift than the conventional structure.

Effect of LFRS Overstrength

The effect of different LFRS overstrength Ω_e is shown in Fig. 5. The response is shown for the 4-story rocking wall ($\lambda = 0$) structure under the MCE. The figure shows that each structural response with different Ω_e follows a similar trend as the IFAS strength varies. The floor acceleration (Fig. 5a) and relative displacement (Fig. 5d) increase as Ω_e increases. The LFRS drift (Fig. 5b) decreases as Ω_e increases. The GLRS drift is large and independent of Ω_e when α is small. The GLRS drift decreases as Ω_e increases when α is larger ($\alpha \geq 0.3$). The "valley" exhibited in the GLRS drift becomes more prominent as Ω_e decreases.

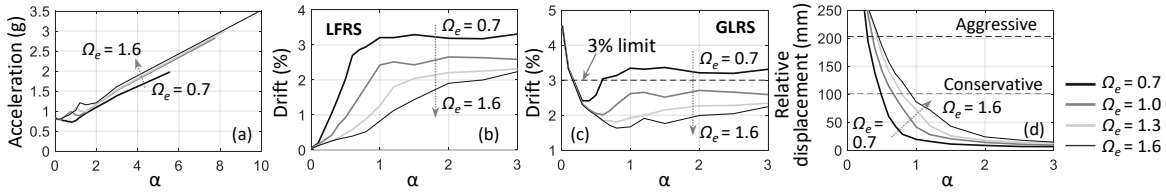


Figure 5. 4-story structure at different Ω_e under MCE: (a) floor acceleration; (b) LFRS drift; (c) GLRS drift; (d) relative displacement.

A 4-story structure was selected as the shake table test specimen. An IFAS strength range of $\alpha = 0.4$ to 0.6 was selected due to the good reduction in LFRS drift and floor acceleration, and the GLRS drift "valley" observed in this range from the parameter study. Re-engagement (bumper) devices were used in the test specimen for eliminating potential excessive relative displacement.

Shake Table Testing Program

A shake table test program was conducted to demonstrate the IFAS concept [12]. The test specimen was a 4-story RC building structure with precast rocking walls as the LFRS. The testing consisted of three phases. In Phase I, the structure contained the IFAS system, termed herein the IFAS structure. In Phase II, the floors were "locked" down to the walls to simulate the floor anchorage in a conventional building. This specimen, termed herein conventional structure, permitted a direct comparison with the IFAS structure. In Phase III, the rocking walls were "locked" into the foundations to simulate a fixed base RC shear wall structure in order to compare the response of a stiffer, stronger conventional structure. This paper will focus on Phases I and II.

The test specimen is shown in Figs. 6a, b. Precast hybrid rocking walls (PT wall) and special precast columns were employed in the test specimen for test repeatability purpose. A purposely eccentric wall layout was used to examine the IFAS in a torsionally-sensitive structure. This step also permits examining the IFAS in two directions on the unidirectional shake table. The force-limiting devices were friction dampers and buckling restrained braces (BRB) in the EW and NS directions, respectively. Rubber bearings were used for the restoring devices, and bumpers for the re-engagement devices. Full details on the test specimen are found in [12]. It is important to note that the LFRS was designed using displacement-based methods [12], and thus has a low overstrength (actually less than unity when compared to force-based design [10], refer to Table 1). The test specimen is modeled in 3D using ANSYS (See Fig. 6c) with details found in [11].

Four levels of earthquakes were applied in the testing: Seattle WA (SE) DBE, Berkeley

CA (BE) DBE, BE SVC (0.67 BE DBE) and BE MCE (1.5 BE DBE). SVC, DBE, MCE represent service level, design basis level and maximum considered level earthquakes.

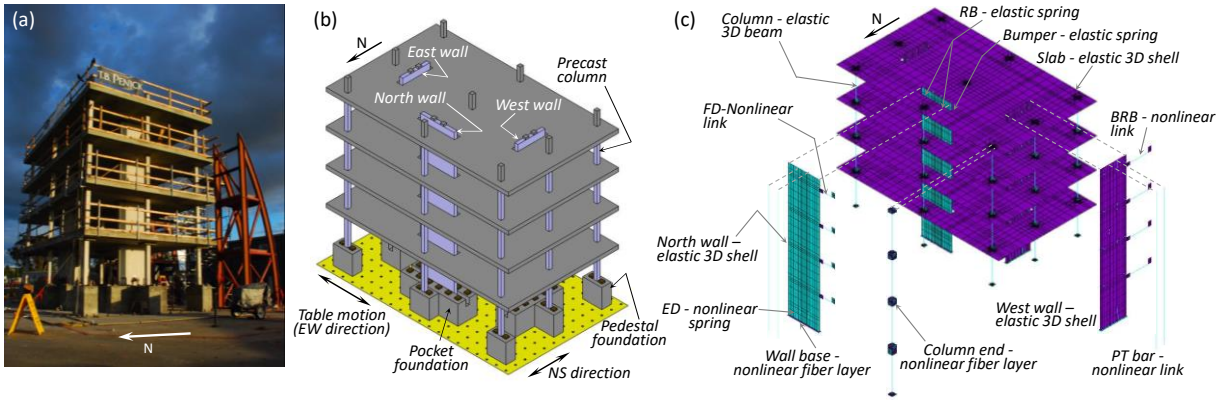


Figure 6. Shake table test specimen: (a) photo; (b) schematic drawing; (c) ANSYS model.

Test Results

Phase I and II results compare the IFAS to a conventional structure. Figure 7 shows the North and West wall base rotation (due to direct table motion and twisting) at different earthquake levels.

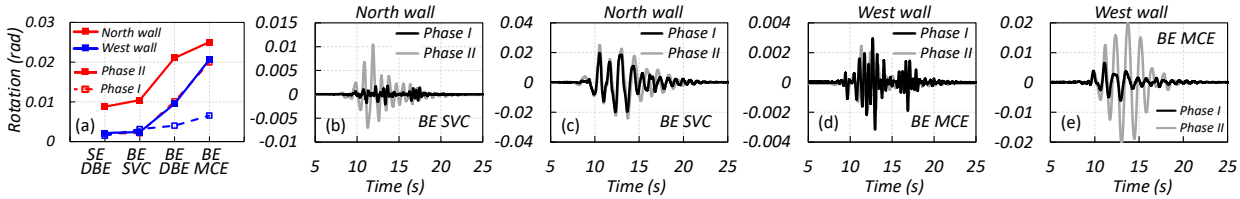


Figure 7. (a) Maximum wall base rotation; North wall, BE: (b) SVC; (c) MCE; West wall, BE: (d) SVC; (e) MCE.

Figure 7a shows the maximum wall base rotation at each test level. Significantly lower North Wall base rotation is observed in the IFAS structure relative to the conventional structure for the first three earthquake levels (Fig. 7a). However, the IFAS North wall response reduction in the BE MCE is not as significant (Figs. 7a,c). Figure 7a shows the opposite trend for the West Wall: similar transverse wall response for IFAS and conventional structures at lower demands, and a significant response reduction in the IFAS structure for the two stronger motions. Thus, the IFAS is seen to significantly reduce the LFRS response for all earthquake levels when considering total structure response, where the stronger earthquakes are dominated by a torsional mode. Figures 7b-e show the individual wall base rotation time histories at the BE SVC and MCE.

Figure 8 shows envelopes of the EW direction and total GLRS inter-story drift, $\hat{\Delta}_{\mathrm{GS}}^{\mathrm{EW}}$ and $\hat{\Delta}_{\mathrm{GS}}^{\mathrm{TOT}}$, for different seismic demand levels. As seen, the maximum GLRS drifts, both EW and total, are consistently lower for the IFAS structure than for the conventional structure. This positive result was not always anticipated in the analytical research used to develop the IFAS (refer to Figs. 3 – 5), where limiting amplified GLRS drift at very low α values was a major design constraint. A possible reason for this lower GLRS drift response was the use of a low overstrength low-rise rocking wall for the shake table structure. The "valley" in the GLRS drift seen in Fig. 5c becomes

pronounced for low LFRS overstrength, low-rise structures and for rocking wall structure, which all fit the description of the shake table test specimen. Additionally, cumulative damage in the specimen might be another reason for observing larger GLRS deformation in Phase II.

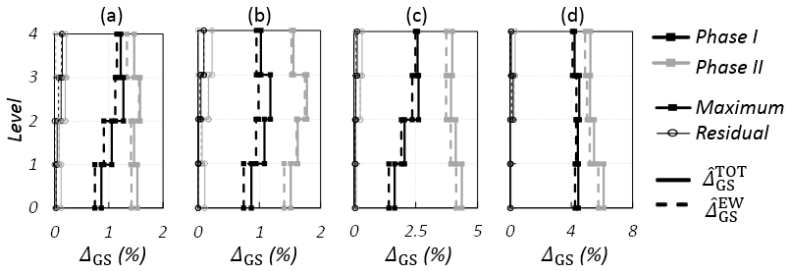


Figure 8. GLRS inter-story drift $\hat{\Delta}_{GS}^{EW}$, $\hat{\Delta}_{GS}^{TOT}$: (a) SE DBE; BE: (b) SVC; (c) DBE; (d) MCE.

Figure 9 shows the maximum EW direction and total floor accelerations $\hat{a}_{EW}$, $\hat{a}_{TOT}$ for different earthquake demand levels. The results indicate similar maximum floor acceleration in Phases I and II. This phenomenon was not anticipated in the paramedic study, where significant floor acceleration reduction was observed (refer to Figs. 3 – 5). This outcome may be due to: (1) the low overstrength of the PT wall used in the test; (2) unavoidable damage incurred in the test specimen between Phase I and II.

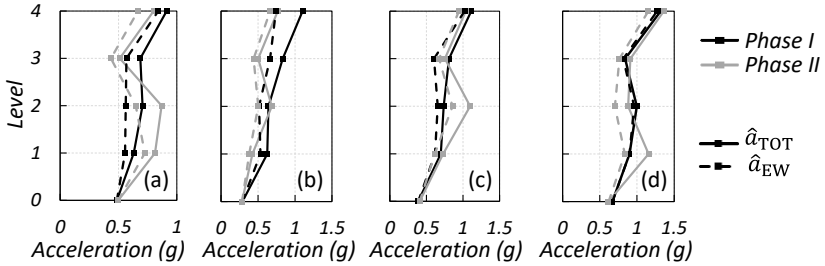


Figure 9. GLRS acceleration envelope: (a) SE DBE; BE: (b) SVC; (c) DBE; (d) MCE.

Post-Test Analytical Investigation

A 3D model of the shake table test specimen was used to investigate the results observed in the testing. Though every attempt was made in the testing to create a repeatable structure, the sequence of tests nonetheless incurs cumulative damage and thus, a modification to the structure properties. Thus, the 3D model calibrated after the testing permits comparison of "virtual tests" of "pristine" vs. damaged structures. Figure 10 shows numerical analysis results from the 3D model in Phase I (PI) with corresponding test results. The PI numerical model is pristine (no damage). The model matches the corresponding test, indicating the accuracy of the model.

The pristine PI model is modified to be analyzed as a pristine Phase II (PII, solid black) model. The results show that the pristine PII model produces larger floor acceleration than that of the pristine PI model (green to solid black in Fig. 11a), implying the effectiveness of reducing floor acceleration through using the IFAS for pristine structures. However, note that the pristine PII model does not match the related PII test results (solid blue).

Considering unavoidable damage that occurred to the test specimen, a PII model with built-

in damage (PII damaged) is analyzed (dashed black). This model is shown to match the PII test (blue to dashed black). Therefore, cumulative damage can be assumed as a reason for not observing larger accelerations in Phase II, an unavoidable reality of the testing. Figure 11b shows that the North wall drift was amplified in the test due to cumulative damage (black to blue). However, the IFAS still provides good drift reduction (black vs. green). Thus, the numerical analyses of the calibrated model show that the potential for the IFAS to reduce both floor acceleration and drifts.

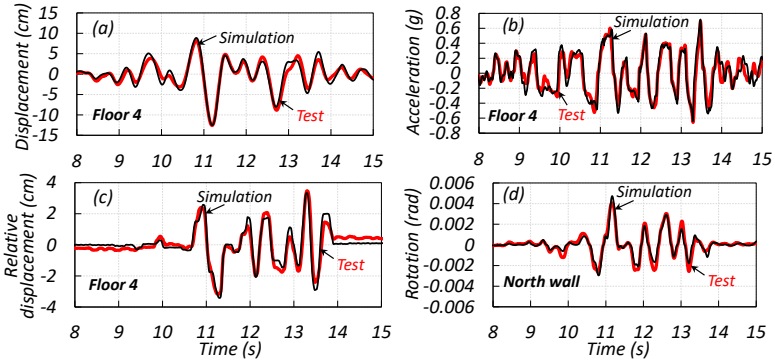


Figure 10. Responses: (a) floor displacement at southern of the specimen; (b) floor acceleration near middle of the west side; (c) relative displacement; (d) North wall base rotation.

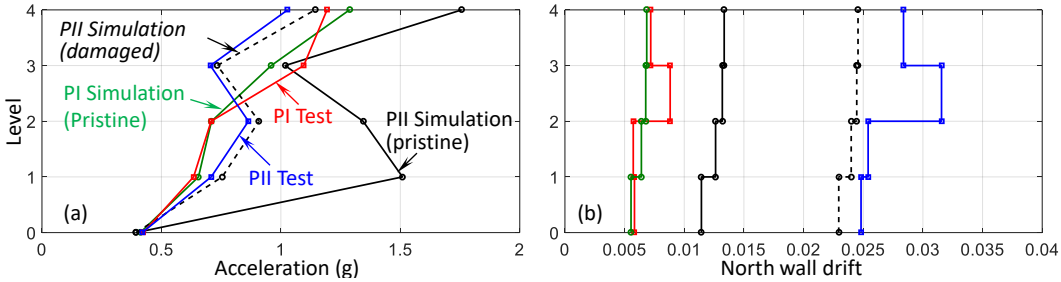


Figure 11. Shake table test specimen response: (a) floor acceleration; (b) North wall drift.

Conclusions

A new low-damage floor anchorage system, the Inertial Force-Limiting Anchorage System or IFAS, was developed. A design space for the IFAS was developed through an analytical parameter study using 2D models. The IFAS concept was demonstrated through a shake table test, and with supplemental information using numerical analyses on a calibrated 3D model. The following conclusions are drawn:

(1) The IFAS is shown to have a potential to reduce building damage under earthquakes. Both parameter study and shake table testing show that LFRS drift can be reduced through using the IFAS. The floor acceleration reduction observed in the parameter study was not observed in the shake table test. However, supplemental analytical studies of the calibrated model indicate that unavoidable cumulative damage led to lower floor accelerations for the conventional structure, thereby implying the potential of the IFAS in reducing floor accelerations under earthquakes.

(2) The parameter study shows that IFAS structure floor acceleration and relative displacement increase as the LFRS overstrength increases, while the LFRS and GLRS drifts

decrease; and overall responses (drift, acceleration, relative displacement) are larger in rocking wall IFAS structures than in RC wall IFAS structure, and depend on level of energy dissipation.

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