Rate Effects in Non-Ductile R/C Columns

A Prelude to Real Time hybrid Simulation

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Outline I

Motivation

Rate Effects in

- Concrete material: well established.
- Structural systems: indirectly investigated through shake table tests.
- Structural components: not sufficiently investigated.

Real Time Hybrid Simulation (RTHS)

- of reinforced concrete frames seldom/never investigated.
- Prior to its undertaking one must master control techniques for multiple degrees of freedom systems

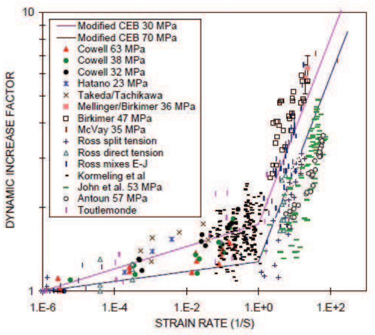
Objective Undertake a series of 10 tests of a non-ductile reinforced concrete columns in order to

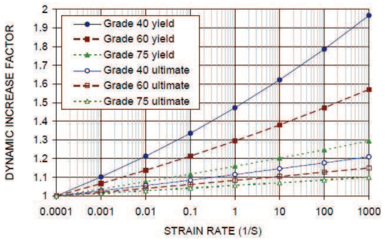
- Sharpen our skills prior to the undertaking of complex RTHS.
- Determine whether there is indeed a rate effect in reinforced concrete columns (currently not considered in ASCE 31/41)

Materials

Concrete Drastic increase in strain rate effect at 1.0 /sec (well beyond rates induced by earthquakes); Malvar (1998-1)

Reinforcement Noticeable increase; Malvar (1998-b)





Observations

- Several experimental investigations have been performed on RC beams and columns at seismically representative loading rates
- State of knowledge on loading rate effects on RC members is still in its infancy.
- Specimens need to be tested under more realistic loading protocols.
- To date all dynamic tests have used single-degree-of-freedom actuation (i.e., a single actuator or slaved actuators applying load in the same degree of freedom).
- Difficulties in controlling several actuators at high loading rates have so far hindered efforts to apply more realistic loading protocols.
- Our tests will address some of these limitations.

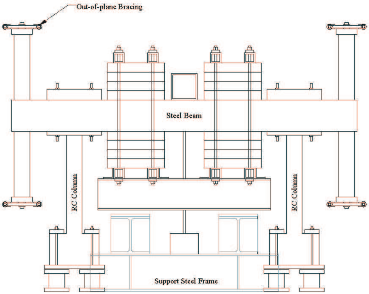
Background

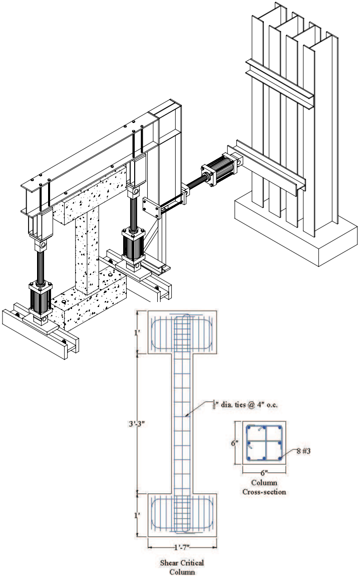
- Interest in tested column is three fold:
  1. Extensively tested in past investigations:
     - Varying pseudo static loading protocols (i.e., cyclic and monotonic) Lynn et al. (1996), Sezen and Moehle (2006), Shin (2007)
     - Frame sub-assembly (Elwood and Moehle (2008))
     - Full frame setup (Ghannoum (2007)
  2. Has a shear capacity that is only slightly larger than its flexural one making it an interesting candidate for studying failure mode shifts.
  3. Of interest to seismic collapse hazard mitigation as it belongs to a family of lightly confined RC columns that is vulnerable to collapse in earthquakes.
- Yields in flexure prior to failing in shear at lateral drifts only slightly larger than those causing flexural yielding. Flexure-shear critical (ASCE 41 (2007)).
- Dynamic loading effects observed in all dynamic tests: increased flexural yielding strength (up to 25%) and associated increases in shear demand. No shifts in failure modes were recorded due to dynamic loading.

Presented column tests were devised to shed more light into the dynamic behavior of this column type.

Test Setups: Components

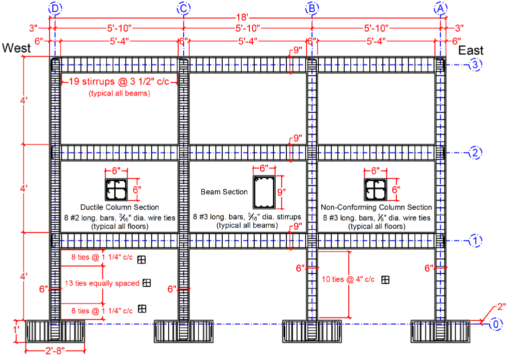
- Sezen (2000) Large scale static tests
- Shin (2007) Shake table tests to investigate the dynamic response of ductile and non-ductile reinforced concrete columns.





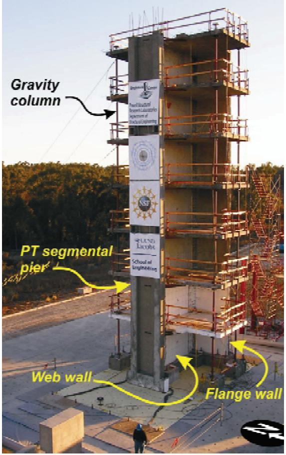
Shake Table Tests of Ghannoum

Ghannoum (2007) tested R/C frames with non-ductile columns



Column dimensions identical to those of Shin (2007), we will use same column design

Shake Table Tests at San Diego

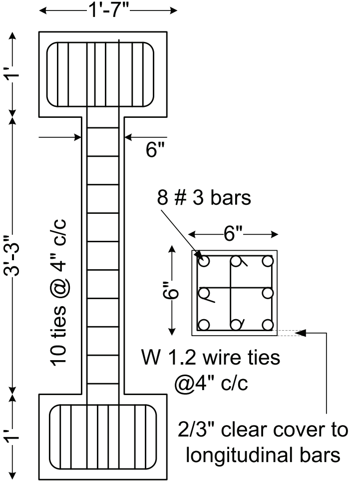


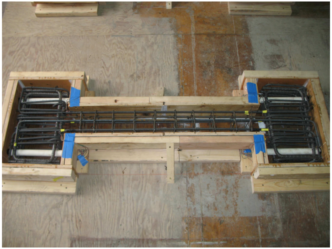
Panagiotu, Restrepo and Conte tested a slice of a 7 storey reinforced concrete building

Shake table tests represent actual structural performance quite well, however they do not lend themselves to parametric studies of RC element behavior at seismic loading rates (lack of causality), and are relatively expensive to conduct.

Reinforcement

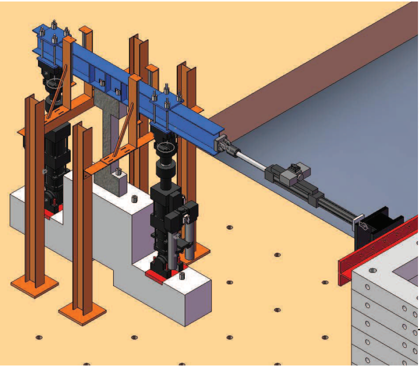
8#3 bars longitudinally and 1/8" ties spaced 4" on center, identical to the one tested by Shin (2007) and Ghannoum (2007)

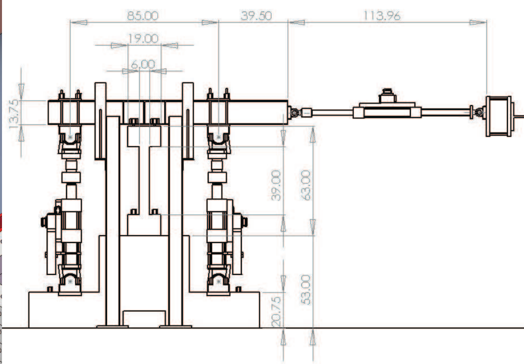




Actuators

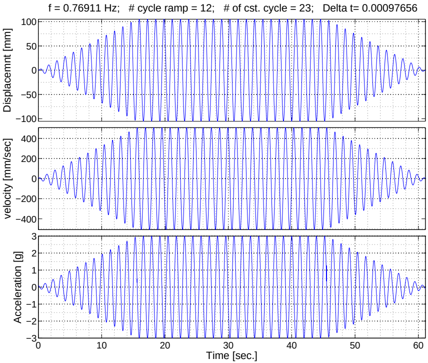
Dynamic Actuators: Vertical (X2 and X3): MTS 244.41S; 110 kip, 10 in. stroke and 20 in/sec. velocity); horizontal (X1): MTS 244.22 (22 kip, 24 in. stroke and 100 in/sec. velocity)



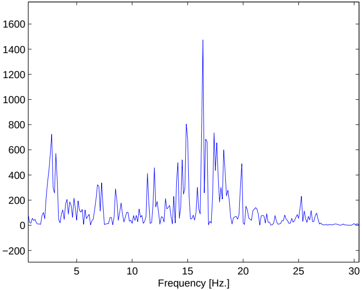


Load

- Axial load (X2, X3): 10% P_f^{axial}: 17 kips
- Peak displacement amplitude imposed through increasing fractions of first yield drift (1%).
- Care exercised in controlling velocity, but minimize acceleration (not not exceed load cell capacity)
- Maximum velocity 54 in/sec.



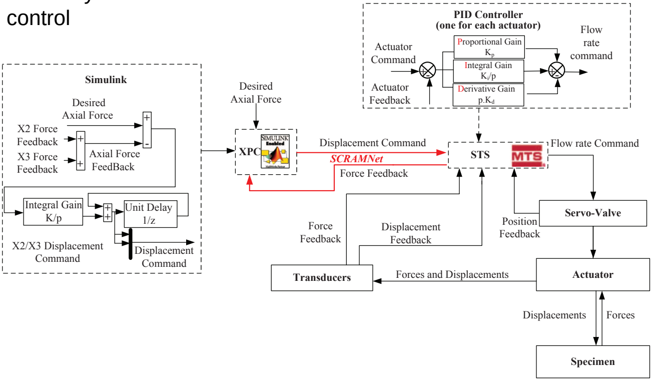
- Unwarranted vibrations observed around 16 Hz



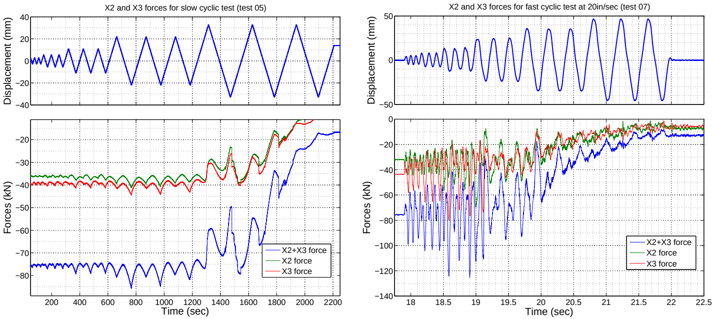
- Remedied by “stiffening the setup” (remove vertical leg of beam-rig.
- Implemented an on-line filtering scheme

Mixed Control System

- Three degrees of freedom Δ_h, Δ_v and θ:
  - Imposed displacement by X1
  - Zero rotation $\theta = 0$
  - Sum of forces in X2 and X3 constant.
- MTS STS control system can not handle this mixed control
- Use a Simulink based controller running on an xPC computer to drive through STS X2 and X3
- Lateral displacement directly controlled by STS



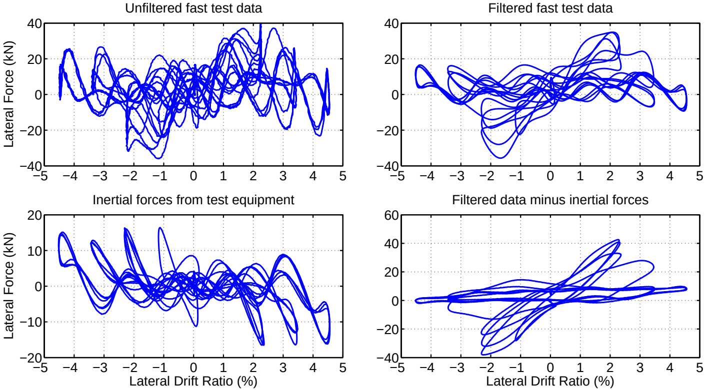
Controller Performance



- Axial load curve oscillated before failure (related to the horizontal displacements)
- Upon failure near end of test, axial load drops rapidly even though the PID controller continually pushes vertically downward in increasing amounts.
- For slow test, axial loading is maintained with less than 13 kN [3 kips] error until initiation of axial failure.
- During the fast cyclic test the PID controller does a less satisfactory job of

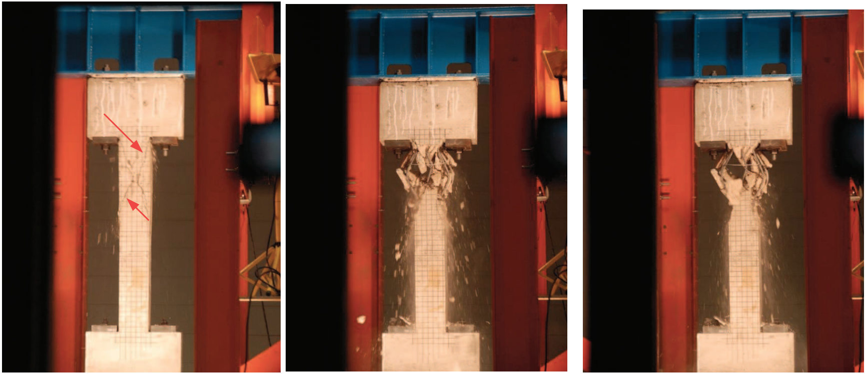
Inertia Force Removal

- Effective mass estimated from a linear regression analysis of force *vs* accelerations
- Implemented inside Simulink code to eliminate it



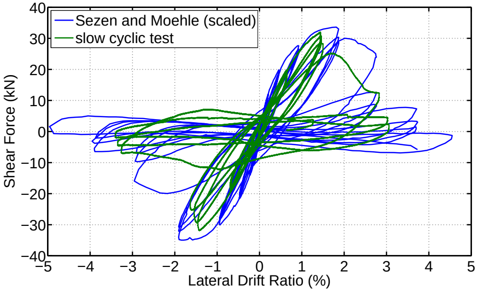
Failure Modes

Shear failure (one or two orthogonal inclined cracks close to flange), followed by compression failure (buckling of the longitudinal reinforcement)



Slow Cyclic Test Behavior

- Columns tested under a pseudo-static “slow” cylic protocol behaved as anticipated and compared well with full scale tests conducted by Sezen and Moehle (2006).
- A typical flexure-shear failure mode was observed whereas the column yielded in flexure at about 1% lateral drift ratio and subsequently sustained shear cracking that resulted in shear failure initiating at a lateral drift ratio of 1.75%.



- Axial failure followed at larger lateral drifts.

Rate Effects; Results

- 10 tests performed, 5 to “fine-tune” experimental setup; and 5 yielded proper results

Test	Maximum shear (kN) [kips]	Minimum shear (kN) [kips]	Drift ratio at max. shear (%)	Drift ratio min. shear (%)	Increase in max. shear from PS	Increase in min. shear PS
Pseudo-static slow cyclic (Test 5)	32.0 [7.2]	-32.0 [-7.2]	1.43	-1.41	N/A	N/A
Cyclic @ 254 mm/sec peak velocity (Test 9)	42.7 [9.6]	-38.3 [-8.6]	2.26	-2.24	33%	19%
Cyclic @ 508 mm/sec peak velocity (Test 7)	42.2 [9.5]	-39.1 [-8.8]	1.95	-1.69	32%	22%
Cyclic @ 1016 mm/sec peak velocity (Test 8)	40.9 [9.2]	40.0 [-9.0]	2.44	-2.31	27%	25%
Cyclic @ 1016 mm/sec peak velocity (Test 10)	40.9 [9.2]	-42.2 [-9.5]	2.32	-2.30	27%	32%

Rate Effects; Observations

Failure Modes

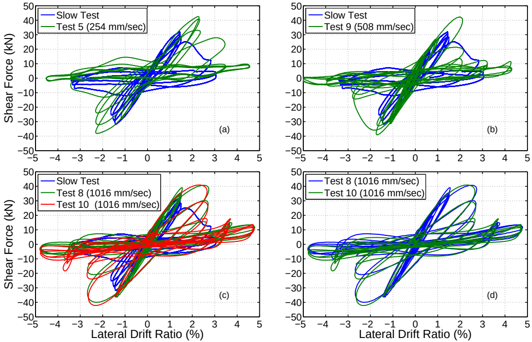
- In all cases a flexure-shear failure mode was observed, irrespective of load rate.
- Flexural yielding was followed by shear failure (inclined cracks) and then by axial failure (buckling of longitudinal reinforcement).

Maximum Shear Demand

- Faster loading rates increased maximum shears and moment in test columns (consistent with other experimental observations).
- Surprisingly, increase appears to be independent of the tested velocities.
- Since flexural yielding influences maximum shear demand in this type of column, an increase in longitudinal steel yield strength is a likely cause of increased shear values.
- Recorded max. longitudinal bar strain about 0.35/sec. (corresponding to a yield strength increase of $\simeq$35% (Malvar, 1998).

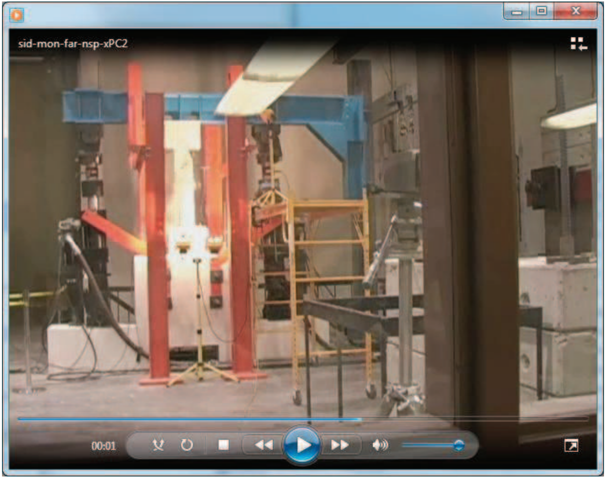
Others

- **Column Stiffness** Higher loading rates did not significantly affect column lateral stiffness prior to yielding.
- **Cyclic Loading Protocols** Loading history prior to longitudinal bar yield does not seem to affect shear failure response. This observation is consistent with pseudo-static cyclic loading observations.



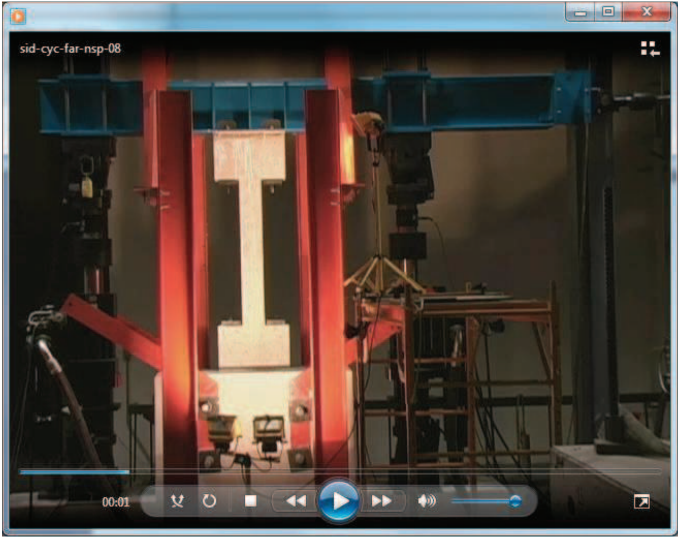
- **Response Envelopes** Higher loading rates seem to produce larger response envelopes than pseudo-static loading. However, higher loading rates appear to increase the rate of cyclic damage in columns as observed in larger drops in shear capacity per cycle in faster tests. At low damage levels, this indicates that once a shear crack forms, it degrades much faster at higher loading rates.

Monotonic, Real Time

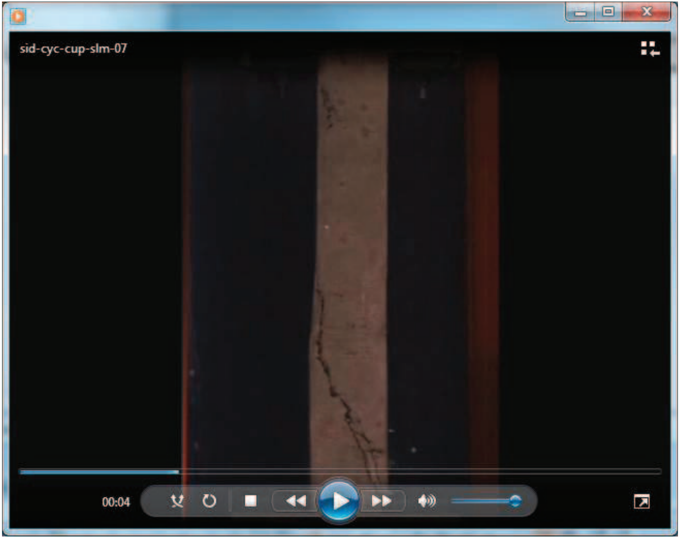


Monotonic, Slow Motion

Cyclic, Real Time



Cyclic, Slow Motion



Conclusions I

- Numerous pseudo-static tests and shake table tests are reported.
- Extraction of rate effects from shake table tests may be problematic as causality (direct assessment of causes on effects) is challenging.
- Few tests on reinforced concrete columns have been conducted at seismically representative loading rates; with all reported tests using single-degree-of-freedom actuation.
- This investigation
  - Was a prelude to real time hybrid simulation
  - Sought to quantify the effect of the load rate on the structural response of a non-ductile column.
  - was based on three independently controlled actuators.
- A number of experimental challenges had to be overcomed (in particular data filtering and elimination of inertia forces)
- Indications are that an increase in lateral load capacity of up to 33% may result if load rates are accounted for.

Conclusions II

- A significantly larger shear force versus lateral drift envelope can be attributed to higher loading rates.
- There are indications that cyclic damage and cyclic shear strength degradation can increase at higher loading rates.
- The observed strength increase is not insignificant, and if further validated by future tests, could have a profound influence on our seismic assessment of non-ductile reinforced concrete frames.
- By ignoring such an increase, codes are currently erring on the conservative side in strength assessment, but then costly repais/rehabilitation may not be justified by the outcome of this research.
- Further investigations are needed to corroborate conclusions.

Credit

Prof. Wassim Ghannoum	CO-PI, Data Analysis
Prof. Victor Saouma	CO-PI, Testing
Dr. Gary Haussmann	Development of Control Algorithms
Dr. Dae-Hang Kang	Development of Mercury Matlab, c++
Kent Polkinghorne	FHT Operator and DAQ
Michael Eck	FHT Operator
Etienne Burdet	Data Analysis
Casey Champion	Lab Assistant
Dr. Eric Stauffer	Technical consultant
Thomas Bowen	Laboratory Manager
NSF/PEER/UC Berkeley	Shake table tests
CU-NEES/NEESinc/NSF	FHT Equipment
State of Colorado	Financial support

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