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Sidesway Collapse of Deteriorating Structural Systems Under Seismic Excitations

Submitted to: NEES Inc.

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Abstract

An experiment was conducted in a joint effort between Stanford University & University at Buffalo to complete the first comprehensive collapse experiment. A four story two bay moment frame in one eighth scale made of aluminum, with steel dog bone connections. Is being used in a multi-step experiment including component and shake table testing to prove an analytical collapse prediction software package. The steel dog bone connections model that of moment connections used in the industry, these connections were tested monotonically and cyclically. The moment frame is attached to a mass simulator that employs the flagpole technique to simulate the weight of the structure. This complete structure was tested on shake table number one at the Structural Engineering Earthquake Simulation Laboratory with an earthquake record simulating that of the 1994 Northridge Canoga Park record. This was scaled and used in six levels of testing which inevitably ended with the correctly predicted collapse of the structure. A second round of shake table tests using a 1985 Chilean record was tested on an identical second frame to further verify the software package.

Introduction

An experiment was conducted in a collaborative effort between Stanford University and the University at Buffalo in the Structural Engineering and Earthquake Simulation Lab (SEESL) in order to verify a software package developed to predict collapse. The principal investigator (PI) and Co-PI on the project are Dr. Krawinkler from Stanford University and Dr. Whittaker from the University at Buffalo respectively. The PhD candidate working on the project, who played an integral part in developing the software package, was Dimitrios Lignos also from Stanford University. The package is designed to input a structure of any shape, and any earthquake record or records and predict the point at which the structure will collapse, or will loose the capability to support itself. The frame design chosen for the tests is a four story two bay frame designed in one-eighth scale with reduced beam sections (RBS). All of the beams and columns were fabricated in aluminum, and the dog bone sections that model different scaled moment connections are made of steel whose properties were determined using a tensile test.

Two frames were used in two separate series of testing which involved earthquake records. The tests took place on shake table #1 in the SEESL lab, and occupied the table for close to nine weeks. The frame was totally constructed and dissembled for both tests, along with the construction of the bracing systems and mass simulator which remained on the table through both series of testing. The first frame was subjected to six levels of testing all of which used the same earthquake record the 1994 Northridge Canoga Park. The intensity of the testing ranged from elastic testing levels up and to collapse. The second frame was only subjected to only four levels two of which were the Canoga Park

and the other two were a Chilean record Lolleo. For the testing there was over 300 channels of data acquisition, on six different types of instrumentation.

Other goals of the NEES Collapse project were testing the scaled moment connections with steel dog bone plates done at Stanford University using actuators. The experimental funding came from National Science Foundation (NSF), and the Network for Earthquake Engineering Simulation (NEES).

Theory

The manner in which a structure acts under ground accelerations is a complicated area of study in which there are new developments made everyday. Every structure is different and has its own unique properties. All seismic design stems from a basic understanding of structural dynamics and the equations of motion. There are two different types of loading static and dynamic or time varying load with respect to magnitude, direction, and position.

The amount of components that produce a displacement in the system in order to represent all forces is the number of degrees of freedom in a system (DOF). One of the key characteristics in a structural system are defining and determining the equations of motion. Equations of motion are mathematical expressions that identify dynamic displacements, by solving for these equations valuable information such as displacement histories can then be determined.

This particular system used a flagpole theory in order to simulate the mass to the frame. The frame is attached to four mass plates each weighing on the order of eight and a half thousand pounds, by using four horizontal links connecting each plate to the corresponding floor. The plates are connected to each other vertically through two links on each side, four total on each plate to allow the plates to move in the plane of motion. Lubrication also plays a vital part of the system to reduce friction damping in order to allow the system to move freely during ground accelerations which accounts to the structural properties.

These structural properties can become very involved calculations leading into finite analysis modeling. The basic theory for this finite modeling analysis comes from understanding the period, frequency, and system damping. Starting with the natural frequency of the system and damping coefficient.

$$\omega_n = \sqrt{\frac{k}{m}} \quad (1)$$

$$\zeta = \frac{\lambda}{2\sqrt{km}} \quad (2)$$

Where:

ω_n = Natural Frequency of the System

ζ = Damping Coefficient

λ = Dashpot Coefficient

k = Stiffness

m = Mass

These equations in addition to the damping natural frequency along with the period of the system, by utilizing all these equations the system properties can be found.

$$T = \frac{2\pi}{\omega_D} = \frac{2\pi}{\omega_n \sqrt{1-\zeta^2}} \quad (3)$$

$$\omega_D = \omega_n \sqrt{1-\zeta^2} \quad (4)$$

$$f = \frac{1}{T} \quad (5)$$

Where:

T = Period

ω_D = Damping Natural Frequency

f = Frequency

These are the basic principles needed to find the system properties to find a SDOF, in the case of the collapse frame many calculations involving MDOF systems were done to analyze the frames motion. These calculations are more involved than that of the REU's involvement this summer.

Ground Motions

For the experimental test setup it is extremely important to choose the correct ground motion in order to generate collapse. When deciding to choose which record the design spectrum of the structure was plotted against the different earthquake records. Before the 1994 Northridge Canoga Park record was chosen over 40 records were examined and plotted to see if they would comply. A second record of a Chilean earthquake Lolleo was also used in some levels of testing; the spectral accelerations also met the design spectrum for the structure. The following figures compare the spectral accelerations of both records to the design spectrum of the structure. These figures show the plot of spectral acceleration on the y-axis, and the x-axis has a plot of the period. When plotting against the period it normalizes the records so they can be compared to the design spectrum.

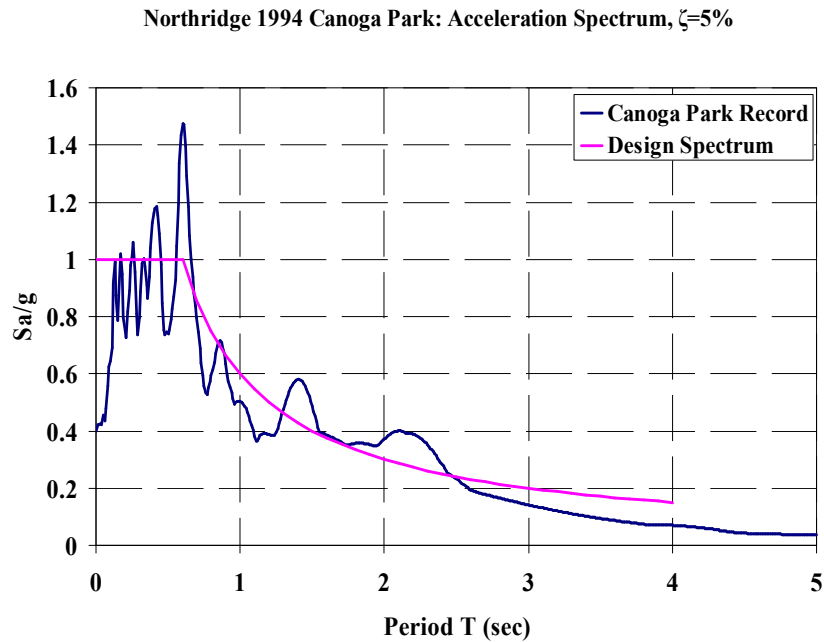


Figure 1: Canoga Park versus Design Spectrum

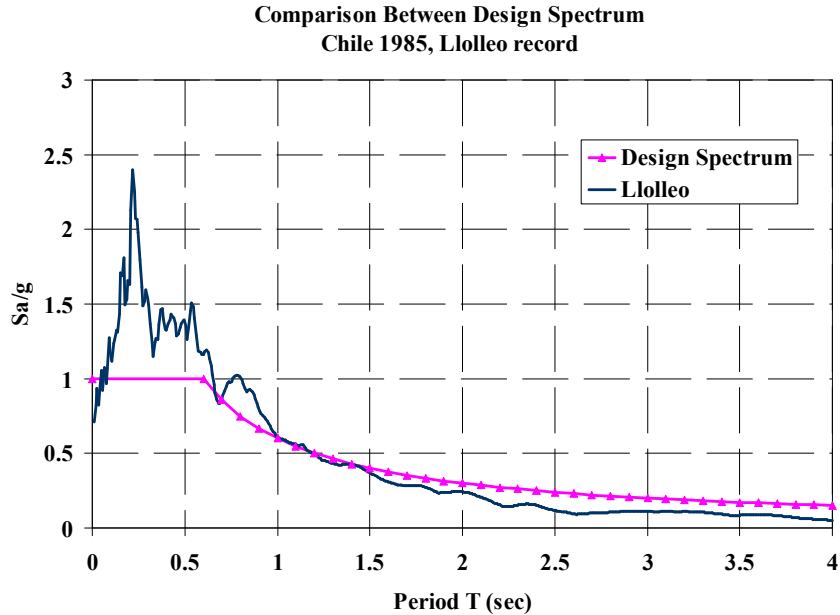


Figure 2: Lollo versus Design Spectrum

The Canoga park record is a better fit for the structure, while Lollo still has a close enough fit. As seen in both records the peak accelerations fall on the design spectrum before it begins to slope downward. Making both records an excellent fit for the four story two bay moment frame.

Experimental Setup

In the scaling of the structure, the dimensions of the beams and columns and other structural components is not the governing factor. Properties such as the strength and weight can govern the system. If a system is modeled to the perfect dimensions, it may only weigh a fraction of what a structure eight times its size constructed of steel might weigh. A similar problem happens with strength modeling; in order for the experiment to have any meaning the scaled structure must act the similar under scaled loading as the actual structure acts under actual loading. These issues are dealt with by modeling the scaled structure using the similitude rules, and a theory known as flag pole technique to simulate the mass.

There are three components the system being tested. First the frame is the actual one eight scaled structure that is being tested under the earthquake records. The second component is the mass simulator, buy employing the method know as flagpole technique four mass plates each weighing over eight and a half kips are held together using a sophisticated system of ball bearings, vertical, and horizontal links that employ a turnbuckle technique, the mass simulator stands up with the help of the frame. The third component of the system is the bracing for the frame and mass simulator, this system was

designed both to only allow unidirectional motion and shaking, but also to employ safety factors. During the collapse level testing without safety precautions forty thousand pounds could come crashing down onto the shake table or even worse people, or other lab equipment. A schematic of the system can be seen below in the following figure.

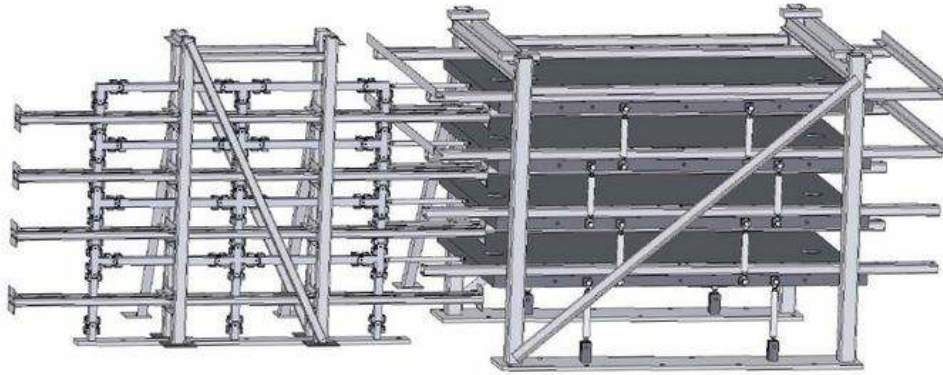


Figure 3: Schematic of System

Frame

The frame was designed based on a four story building located in the Los Angeles area. The beam sections were designed using reduced beam sections based on the FEMA-350 building codes and provisions. The scaled model was designed and fabricated using all aluminum beams and columns with steel dog bone plates creating the moment resisting connections. These components were based of a steel frame design as seen in the plan view of the prototype structure.

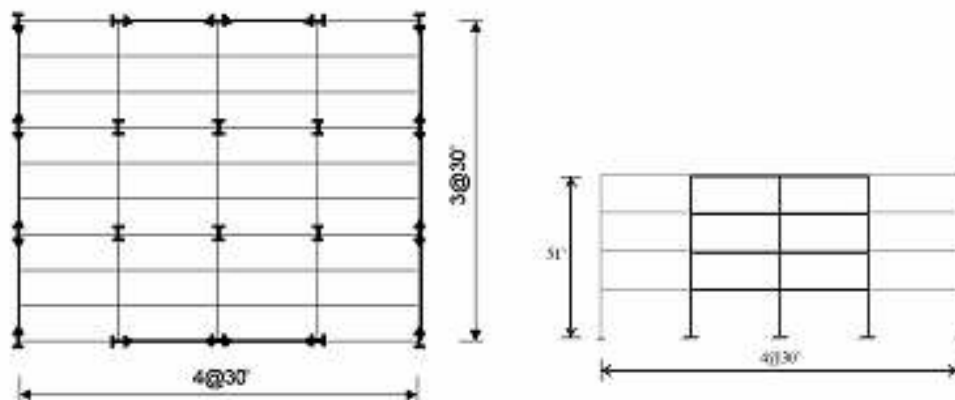


Figure 4: Plan View of Prototype Structure

The frame was tested in multiple levels of testing and was subjected to collapse twice. After the first collapse the aluminum members of the frame were not damaged, just the steel dog bone plates which were replaced for the second level of testing.

Mass simulator

The mass simulator's function was to subject the structure to the normal gravity loads that a four-story building of steel construction would usually be subjected to. Four mass plates of equal mass rest upon vertical links that act as turnbuckles for adjustment, and ball joints for motions from the seismic activity. A total of sixteen vertical links act to hold up the 4 mass plates weighing in total over thirty-five thousand pounds. In order to transfer this weight to the frame, a flagpole technique is employed, by using a system of four horizontal links one on each floor through a horizontal stiffness the gravity loads are transferred to the frame. This is called the flagpole technique because it is modeled as if the mass were straight down the connection in the horizontal links as if all the mass acted in a straight line directly down as a flagpole would.

Once the mass simulator was constructed, some unexpected problems arose. During some system properties white noise testing, the friction damping was much higher than expected, and was prohibiting the system from operating correctly. The solution was lubrication; heavy-duty axle grease was applied throughout the mass simulator which alleviated much of the friction in the system. The following figure shows an image of the mass simulator with the added fuchsia axle grease to prohibit the friction damping.



Figure 5: Mass simulator

Bracing System

The bracing system is painted in bright orange paint to show distinction between the frame and the mass simulator. The purpose of the bracing system is to prohibit the system from moving out of plane. The table is capable of moving in six degrees of freedom, but in this experiment the frame is only being tested in unidirectional motion. To avoid any movement in other directions the bracing system is both welded and bolted to the shake table in an effort to stop all other motion. The following figure shows the system as a whole including the frame, mass simulator, and bracing system.



Figure 6: Complete System Overview

Data Acquisition and Instruments

The experiment would mean nothing without a method to collect the results from the testing. In the SEESL lab there are a data acquisition systems, three were used in the NEES collapse project. The Pacific system collected the bulk of data and had over three hundred channels simultaneously collecting data. Another system that collected data was the Krypton; this is one of the three systems functioning in the United States that uses LEDs to collect data and then plot it to show relative motion in 3D and even rotation of a point. This particular Krypton system has a capability of forty LEDs to collect the data of these forty crucial points. One last system was used to manage all the recording video cameras that totaled over eleven.

While the Pacific system can obtain these three hundred plus channels of data it is not all coming from one specific instrument. A total of six different types of instruments were all collecting different data. The two most crucial instruments were the strain gauges, and the home made “clip gauges”. The homemade clip gauges were a fancy strain gauge

that would collect strains at points past the steel yielding; this was done by using a C shaped piece of steel, and applying the strain gauge to the top surface of the steel. A typical strain gauge works by reading an electrical signal from the tightly wound wires and converting the signal into a strain, which could then be converted to a displacement. An image of the clip gauge can be seen below.



Figure 7: Homemade clip gauge

Other instruments that played an essential role in collecting the data were string pots and accelerometers which both recorded acceleration. Also used were homemade load cells, which were essentially strain gauges, calibrated to measure a load, and video cameras along with a digital SLR camera to document the damage.

Testing Levels

Throughout the experiment there were two identical in plan scaled frames both tested under multiple levels of testing. The two frames were constructed and erected by the same plans, but different steel dog bones were used giving them slightly different structural properties. The first frame underwent a series of testing with six levels of the Canoga Park record and dozens of white noise property tests. All major testing on the first frame was done using only the Canoga Park record. Some of the white noise property tests varied in intensity and length, as well as sine sweeps were used in trying to find the period, resonance frequency, and the modes. The second frame also underwent the same property testing, but instead of just being subjected to the Canoga Park record a second Chilean earthquake record Lolleo was also used.

The first frames six levels of testing varied by intensity only. The scaled Canoga Park record's peak accelerations were just increase by different scaling factors in each level of testing; all other properties did not change including time and relative magnitudes. The first level of testing was white noise tests to find the system properties. The scaling factors for these tests were determined through the sophisticated analytical software package developed to predict collapse. The second level of testing was named the

service level (SLE) and was 0.4*Canoga Park, this earthquake has a probability of 50% in 50 years. The third level of testing was named the design level was 1.0*Canoga Park, and has a probability of 10% in 50 years. The fourth level of testing was the maximum credible earthquake (MCE) and was 1.5*Canoga Park, and had a probability of 2% in 50 years. The fifth and sixth levels of testing was the collapse level (CLE) and final collapse level (CLE-F) was 1.9*Canoga Park and 2.2*Canoga Park respectively. The probabilities of these earthquakes are part of the data that is trying to be acquired through this series of testing.

The second frame underwent only DLE, MCE, CLE and CLE-F testing levels along with property testing. The only differences were that the DLE and MCE testing used the Lolloo earthquake record.

Results

Each distinct level of testing brought new and important information about the structure itself, its movement, and its potential collapse. Data collected from each test was saved and documented and displayed in a post processor designed in Mat lab to view displacement histories, inter-story drifts, strains, acceleration profiles, joint rotations, and many other important plots. The most crucial part of the experiment was to validate the software package that could predict the collapse of a structure. The software would run consecutive levels of inelastic testing and then go on to predict the magnitude of the earthquake that would in effect put the structure past the point of supporting itself and into collapse.

Predicting something like collapse is not as easy as it seems, the software even being extremely sophisticated cannot predict everything, there is always some error involved in prediction. The program had ran the SLE, DLE, and MCE earthquakes in order to predict the scaling magnitude used in the CLE level test, but due to some strain hardening that was not expected the prediction was extremely close but did not collapse the structure. The next level of testing was the CLE-F which collapses the structure in the first cycle. The actual collapse level laid between the two tests at approximately 2.0*Canoga Park. A plot showing the comparison of the predicted analytical testing level versus the experimental testing is shown below.

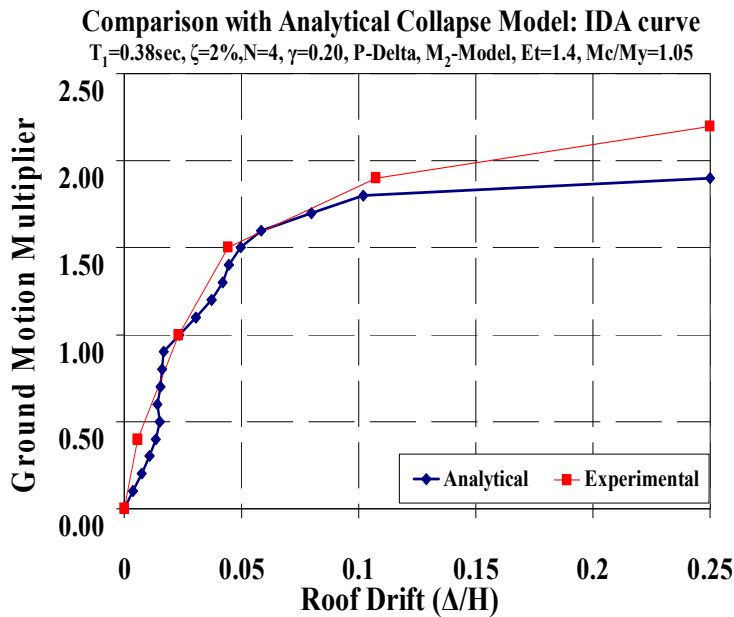


Figure 8: Analytical Results versus Experimental Results

By interpreting this plot it is seen that the first four levels of testing were almost precisely predicted, or having a small error within a 2-5% error when comparing with predicted roof drift. These testing levels included SLE, DLE, MCE, and CLE. The CLE-F test was slightly higher than predicted due to an unexpected gain in strength directly before collapse. This can be explained due to the steel plates all approaching failure at once, therefore all giving off a strain hardening affect great enough to save the collapse of the structure as a whole, even though displacement and drifts were at points where most full scale structures would have collapsed. This strain hardening was then discovered to be the factor when cyclic dog bone tests were looked back upon and seen a gain in strength close to the ultimate force and displacement values as seen in the figure below.

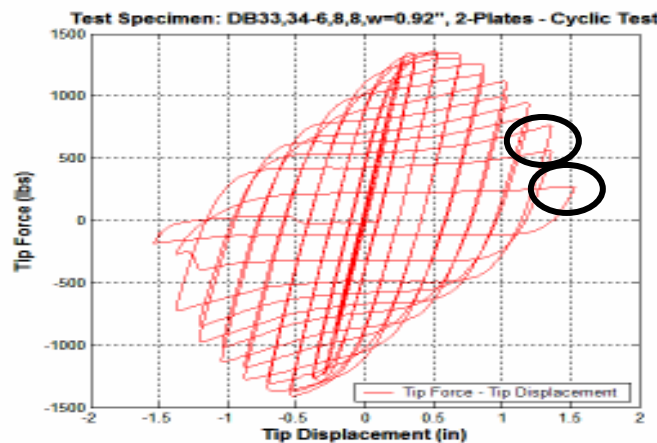


Figure 9: Dog Bone Cyclic Testing

When a structure collapses it fails in a certain manner, each structure has its own unique way to fail, and this is called the mechanism of the structure. For the frame in this experiment a static pushover analysis was done in order to determine the mechanism of this particular structure. This was done both by hand and using an analytical tool which can be shown graphically in the following figure.

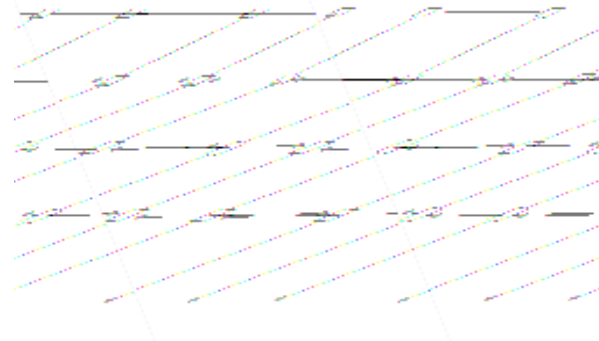


Figure 10: Analytical Prediction of Structural Mechanism

After the CLE-F level of testing, and the structure had completely collapsed it had become very clear that the analytical prediction of the mechanism was a perfect prediction of structure. All the dots in the figure above represent steel plates that had yielded, and in the actual structure there was damage at each of those plates. An actual image of the structure after collapse to show the actual mechanism can be seen in the figure below.



Figure 11: Structure after collapse

Although the structure did not collapse at the initial prediction, this is not an indication of the software working improperly. As seen before the mechanism of the structure was predicted flawlessly, and the collapse prediction was within a 2% error. More than just the collapse was predicted, as mentioned earlier after the CLE level the structure had experienced huge residual displacements and therefore experiencing large roof drifts. These peak displacements were also analytically predicted using the software package. When looking pack comparatively of the analytical predictions to the experimental results the predictions were all within a quarter to half an inch of what was predicted, and these were based on the floor of the structure. The following figure shows a plot of the peak residual displacements after testing to the analytical predictions.

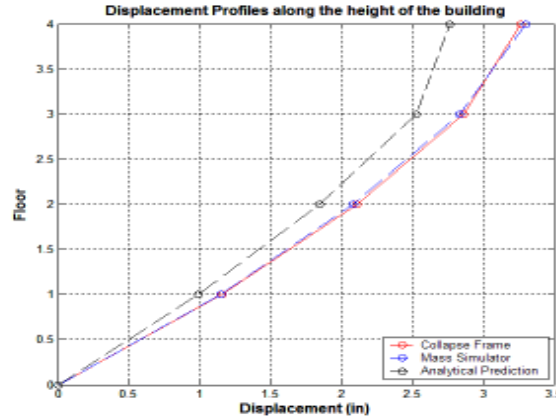


Figure 12: Displacement Profiles along the Building Height

Conclusions

The overall the experiment was considered to be a success, while there is still a very large amount of data to be reviewed and analyzed the immediate results were seen to be quite accurate in predicting the collapse of the structural system. The overall immediate conclusions before all the data could be analyzed were as follows:

- Although the structure did not collapse at the initial predicted scaling factor the prediction was within a 2% error
- This error in the prediction was due to a large gain in strength from all of the yielded plates strain hardening at the same time
- The analytical and experimental structural mechanisms were almost identical, therefore proving a perfect prediction of the mechanism
- The peak displacements were also predicted accurately to within a quarter of an inch
- While the predicted level of collapse was at 1.9*Canoga Park it was determined that the actual collapse level was 2.0*Canoga Park

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