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CYCLIC PERFORMANCE AND DAMAGE ASSEMENT OF STUCCO AND GYPSUM SHEATHED WALLS

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SUMMARY

In an effort to gain a better understanding of the seismic behavior of woodframe structures, the CEA (California Earthquake Authority) and CUREE (Consortium of Universities for Research in Earthquake Engineering) initiated a woodframe wall testing project at the University of California, San Diego. The project was conducted in two separate phases. Phase I investigated the response of woodframe walls having boundary conditions consistent with the first level walls of a two-story structure, and Phase II investigated the response of woodframe walls having boundary conditions consistent with a single-story structure.

Common construction techniques of the 1970s were targeted as the prototype test specimen since it is believed that this style of construction most consistently reflects the current majority of existing woodframe structures. A typical 7/8 in. three-coat Portland cement plaster system was used for the exterior wall finish and 1/2 in. gypsum wallboard was used as the interior wall finish. No structural sheathing was applied to the framing to increase the lateral resistance. Two separate wall configurations with openings were tested under reversed psuedo-static cyclic loading conditions. Damage thresholds were defined as the drift ratios associated with changes in structural performance and qualitative damage states. Drift levels of 0.2%, 0.4%, and 0.7% were determined as the drift ratios demarking the relevant performance regimes and damage states and were used as milestones in all tests for purposes of repair and performance assessment. The drift ratio associated with ultimate strength of test specimens was 1%-1.25% for all walls.

The documented repairs performed during testing effectively restored the original strength of the walls at comparable drift levels and a slight increase in ultimate wall strength was observed in some cases. Local variation of damage occurred and was dependent on the repair method, but the global crack patterns and residual widths were consistent. From the relationship between residual stucco crack width, residual story drift, and maximum story drift, a method was derived to asses the seismic damage to walls of similar construction and appropriately classify them according to the damage state.

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INTRODUCTION

BACKGROUND

On January 17, 1994 the Northridge Earthquake of moment magnitude 6.7 hit Southern California. In terms of economic loss, this earthquake ranks as the largest single natural disaster in United States history. The insured residential damage totaled $12.5 billion, almost all of which occurred in structures of woodframe construction (EERI [1]). In the months following the earthquake, engineers and trade professionals alike agreed that much research had to be conducted in an effort to relate visible damage to structural capacity of various woodframe wall systems, as well as relating corresponding visual documentation to various levels of structural damage.

Because of the relative lack of information and testing on the seismic response of woodframe structures, the performance levels of various woodframe systems is widely disputed. Much confusion also exists on how to properly design such systems considering the wide range of allowable design values used in practice over the years for the individual wall constituents (i.e. gypsum wallboard, cement-based plasters, etc). Because of this confusion, insurance company claim adjusters and engineers in the field commonly conflict on the assessment of damage sustained to a wall or home when making an insurance claim appraisal. Many buildings became total losses even though they had relatively minor damage, and in some cases, significant but subtle damage was not initially identified.

By the early 1970s, residential woodframe structures were generally built with a defined lateral force resisting system utilizing the finish materials (ICBO [2]). The widely varied installation techniques of the finish materials created varying performance levels and became more of a concern as the construction rate began to increase. A large portion of the existing woodframe construction in California can be attributed to the construction boom of the late 1960s to early 1980s. Because the rate at which new homes were being built was so high, more efficient building materials and finishes were sought out and used. The most common finish materials used in construction of woodframe residential construction became Portland cement plaster for exterior finish and gypsum wallboard (drywall) for interior finish.

PORTLAND CEMENT PLASTER CONSTRUCTION

Portland cement plaster, commonly referred to simply as stucco, is a cementitious material similar to mortar in composition. Advantages of stucco include versatility of design and aesthetic appeal, variety of finish styles and color, water resistance, good performance in a variety of climates, good fire-resistant properties, low maintenance and life-cycle cost ratio, and impact resistance. A wall system utilizing stucco is mainly comprised of four constituents: Portland cement plaster, reinforcing mesh, membrane, and structural framing, typically wood or steel studs (see Figure 1).

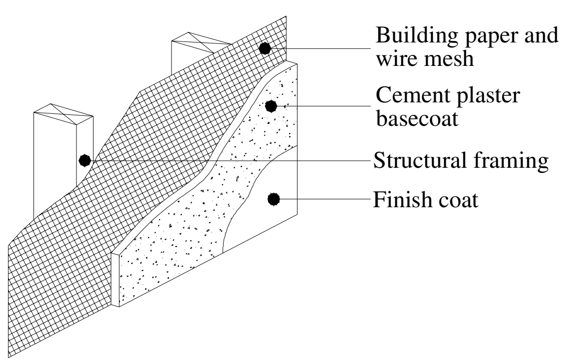


Figure 1: Open Stud Construction

Portland cement plaster is commonly applied in one to three coats. The three-coat system used in this study involves first, a 3/8-in. scratch coat, second, a 3/8-in. brown coat, and finally, a 1/8-in. finishing coat. In addition to providing tensile reinforcing of the stucco, the reinforcing mesh provides a means of securing the stucco and the wall-framing members via a variety of fastener options such as furring nails or staples. Varying sizes of wire openings and gages are available for the reinforcing mesh. The building paper membrane serves as a water barrier between the exterior stucco and the interior framing. Initially, the membrane material was commonly a heavy-duty material such as #30 felt, but due to the poor vapor permeability of felt, a Grade D type building paper has replaced the use of felt for the weather barrier. When properly applied, the membrane creates a weather resistive barrier preventing decay and other possible damage to the wood framing caused by water that penetrated the stucco. Self-furred, paper-backed lath is an alternative to the wire and paper membrane, however the purpose is the same. Another common feature of stucco walls is the implementation of weep screeds at the bottom perimeter, which allow for the exit of any moisture that penetrates the plaster and is intercepted by the building paper.

Because water is the catalyst for the cement curing process, shortening or shrinkage of the plaster will inevitably occur as the mixing water evaporates. This shrinkage will typically create randomly distributed hairline cracks in solid stucco panels. Where openings are present, the cracks will tend to emanate from the corners of openings in the stucco panels. Another common cause of non-structural cracking is due to the difference in the coefficients of thermal expansion between the plaster and the wood framing. Many new innovations have been proposed in order to reduce these cracks which include: the implementation of high-strength stucco, the use of fiberglass tape as a skin beneath the finish coat, small 1/2 in. fiberglass or polypropylene fibers introduced as an additive to the scratch coat, and acrylic additives introduced into the finish coat. Even though the cracks are non-structural, homeowners and insurance companies are very concerned with this level of cracking (Northwest [3]).

GYPSUM WALLBOARD CONSTRUCTION

Gypsum wallboard construction commonly referred to as drywall became popular in the 1950s, but it was not until around 1970 that nearly 90% of all new residential construction was built using gypsum wallboard as an interior finish material for both ceilings and walls. Drywall replaced the previously used gypsum lath and plaster. The latter method used a variety of lath materials and configurations to attach the plaster to the framing members. One of the main advantages of the lath and plaster method is the superior fire resistance. These systems are the best interior wall and ceiling finishes when considering long-term performance, durability and a truly monolithic surface, but gypsum wallboard is much quicker to install and more cost effective.

Often incorrectly referred to by the proprietary names “Sheetrock”, gypsum wallboard is a wall finish material that consists of a gypsum slurry solidified into panels of desired length and width, most commonly 4 ft by 8 ft. The basic gypsum wallboard system is comprised of the gypsum wallboard panels attached to the structural framing members using mechanical fasteners; often phosphate covered cooler nails or screws. At locations where individual wallboard panels meet, either paper or fiberglass joint tape and joint-type setting compound is used to finish the joint, rendering it unseen. The increased use of gypsum wallboard can be attributed to the inherent advantages such as sound control, speed and relative cleanliness of construction, availability of attractive and unique final finishes, and overall economy (Bureau [4]).

CEA/CUREE WALL TESTING PROJECT

As part of a research project funded by the Consortium of Universities for Research in Earthquake Engineering (CUREE) under contract to the California Earthquake Authority, a testing program to assess earthquake damage in residential buildings was initiated at the University of California, San Diego. The objectives of the research are as follows:

(1) documentation of typical patterns of seismic damage to walls with openings,

(2) determination of performance of various finish repair methodologies, and

(3) determination and documentation of correlation between story drift and qualitative damage states based on the visible condition of wall finishes.

The project was conducted in two separate phases. Phase I involved testing having boundary conditions consistent with the first level walls of a two-story structure. Phase II involved the testing of identically built walls as in Phase I, but having boundary conditions consistent with the walls of a single-story structure. In order to provide results consistent with the majority of existing construction, the scope of both Phases I and II focused on construction techniques commonly used in the 1970s.

DEFINITION OF DAMAGE STATES

One of the objectives of the study is to determine levels of drift associated with various levels of damage. In the project proposal, three damage states were qualitatively defined as follows.

<u>Stage 1 damage</u> is described as the wall having displaced through a near linear-elastic response, with minimal strength and stiffness degradation. New cracks may develop while the attachment of finish to framing remains sound with virtually no structural damage. Cracking of the joint compound around the edges of the fasteners, commonly referred to as fastener “popping”, may be associated with this damage state. All finish damage should be readily repairable.

<u>Stage 2 damage</u> is associated with a slight reduction in wall stiffness. Stucco cracks associated with Stage 1 damage state increase in length and width and new cracks branch from existing cracks. Wallboard damage is more readily apparent with the initiation of cracking along the corner bead at the window openings. Fastener popping and wallboard joint cracks and tearing are associated with this damage state. The damage should be readily repairable without requiring the removal of any portions of the finish.

<u>Stage 3 damage</u> is defined as the damage state associated with some softening or loss of stiffness. Significant finish damage is expected to occur and large crack widths and lengths will be evident on both the interior and exterior finish. Partial finish removal and replacement may be necessary nevertheless, the damage should be readily repairable.

The level of drift associated with failure will have significant strength degradation past the ultimate strength of the wall. Large crack widths of stucco and gypsum wallboard, spalling of stucco at window corners, relative rotation of gypsum panels and the cooler nails pulling through the wallboard are all associated with the failure damage state. Other forms of non-repairable damage may be apparent as well.

It should be noted that the previously defined damage states are subjective. The purpose of the definitions was as a guide for quantifying wall finish damage. Descriptions such as “minimal” and “slight” do not have values assigned to them, but are to be used along with engineering judgment to assign a level of drift to the definitions, which are unique to this report. Any non-seismic cracking of wall finishes should also be identified and is commonly caused by local variation in framing or stucco shrinkage or differential foundation settlement.

TESTING PROGRAM

INTRODUCTION

Twelve test specimens were constructed and tested for the CEA/CUREE Woodframe Wall Testing Project. All wall specimens were cyclically loaded to failure using the CUREE loading protocol for the testing of woodframe structures (Krawinkler [5]) and carried out under reversed pseudo-static cyclic loading. For testing purposes, failure is defined as the point at which the applied load drops for the first time below 80% of the maximum load developed.

The target drift levels for were determined from the initial testing of two walls after studying the visual and measured response and comparing the data with the qualitative definitions. For subsequent testing, at each of the defined damage state drift levels the walls were repaired. Once repaired, the walls were reloaded to the next larger drift level, starting from the beginning of the loading protocol. This process was repeated for each defined drift level.

TEST SETUP

A self-reacting steel frame capable of testing two specimens in parallel was used as the test setup. The frame was designed such that out-of-plane motion at the sill plate and double top plate was prevented. A 165-kip, ±6 in. stroke hydraulic actuator was used to load the specimens. Phase I of the project investigated the behavior of the wall specimens under two-story boundary conditions, and Phase II investigated the behavior of the wall specimens under single-story boundary conditions. The varying stiffness of boundary conditions was achieved by altering the applied dead load as well as the stiffness of the member dragging the applied force into the wall. The testing frame is shown in elevation in Figure 2.

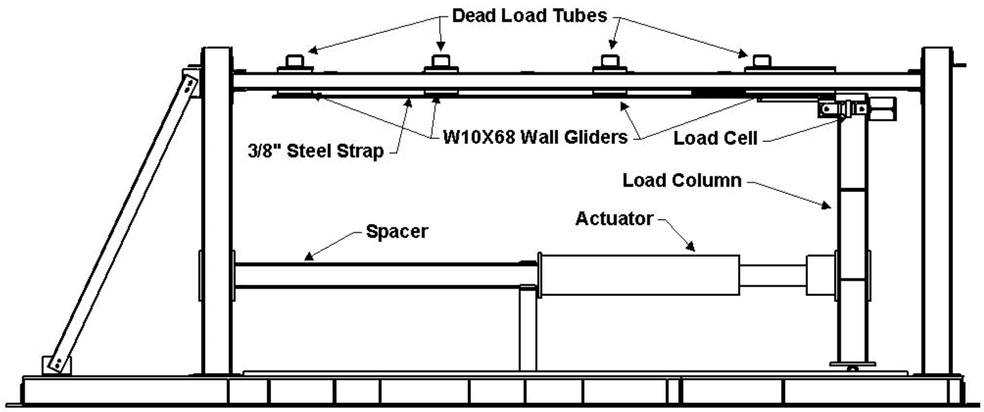


Figure 2: Testing Frame Elevation

WALL CONSTRUCTION DETAILS AND MATERIAL PROPERTIES

To simulate the performance of walls in an actual structure, various boundary conditions were implemented during the specimen construction. A 2 in. by 8 in. piece of lumber was added on the top of the double top plate so that a ceiling return was simulated for the gypsum wallboard. Typical corner stud construction was used at specimen ends to simulate the intersecting walls in an actual home. The interior finish of all test specimens was 1/2 in. gypsum wallboard fastened to the framing with 5d phosphate covered cooler nails spaced at 7 in. on center. The exterior finish was a three coat 7/8 in. Portland cement plaster. The Portland cement plaster application involved first the application of a 3/8 in. scratch coat followed by a 3/8 in. brown coat, and finally a 1/8 in. color or finish coat. Line wire, grade D building paper, 17-gage hexagonal wire lath, and furring nails spaced at 6 in. on center were also used to install the stucco.

Two separate wall configurations were built. One wall configuration had two-4 ft by 3 ft rough window openings, and the other configuration had one-4 ft by 3 ft rough window opening and one-2 ft by 8 in. wide by 6 ft by 10 in. door opening. No holdowns were installed at wall pier boundaries to provide uplift resistance and no structural sheathing was installed to the framing. All headers over wall openings were 4 in. by 6 in. and all anchor bolts were 1/2 in. diameter spaced at 72 in. on center to be consistent with the typical construction practice of the 1970s. All structural framing was nailed according to Table 23-II-B-1 of the 1997 Uniform Building Code [2]. The structural framing elevations for all test specimens are shown in Figure 3 and Figure 4. All gypsum wallboard was 1/2 in. 4 ft by 8 ft panels. The longer length was installed horizontally and all wallboard joints were staggered.

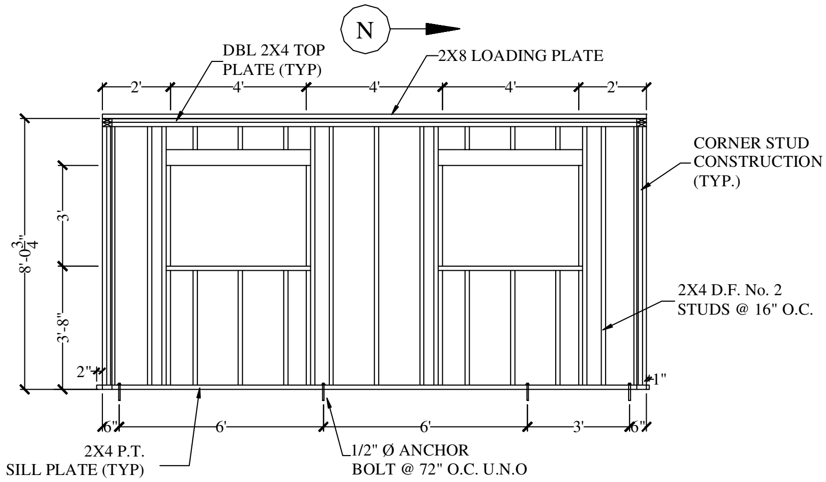


Figure 3: 2-Window Wall Configuration

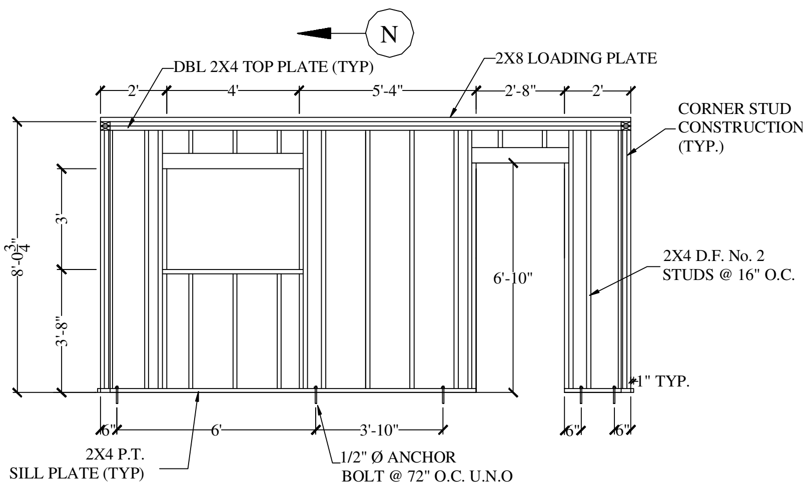


Figure 4: 1-Window 1-Door Wall Configuration

All the lumber used for the structural framing of the test specimens was Douglas Fir No. 2 structural lumber and the sill plates were pressure treated Douglas Fir No. 2. From ASTM D 4442-92 (ASTM [6]), the moisture content of the framing was taken from random stud samples after testing and was under the code maximum of 19% for all cases.

All framing was constructed using 16d common and 8d common nails where specified. Furring nails with a 3/8 in. cardboard wad were used for the stucco application spaced at 6 in. on center. The exterior finish material was residential grade, Portland cement plaster. The stucco boundaries were confined by a 7/8 in. Grade 10 stucco stop commonly referred to as “J” molding because of its shape. The common three-coat stucco procedure involves first the building paper and wire lath application followed by the scratch coat, the brown coat and finally the color or finish coat.

LOADING HISTORY

The CUREE Abbreviated Loading History for Ordinary Ground Motions (Krawinkler [5]), specifically developed for the testing of woodframe specimens, was used for this study. All tests were carried out under displacement control based on the deformation of a control wall. The opposite wall acted as slave test specimens. Initiation cycles begin the test and are intended to be used as an instrumentation check, and can also be used to check the response at small amplitude displacements representing small seismic events. The remainder of the cycles are symmetric primary cycles followed by a specified number of symmetric trailing cycles.

INSTRUMENTATION

An extensive instrumentation plan was used to capture localized effects in addition to the global response of the test specimens. A combination of displacement transducers, load cells, and inclinometers were placed in specific locations where the desired effect would be best exhibited. Load cells were attached to each of the anchor bolts used to secure the wall specimen to the testing frame, inclinometers were used to measure the stucco panel rotations and strain gage rosettes were attached to the stucco to measure shear strain. Linear potentiometers used to measured sill slip and sill uplift and string potentiometers (±7-1/2 in.) measured the global wall displacements and global wall shear deformations.

TEST RESULTS: TYPICAL WALL RESPONSE

PORTLAND CEMENT PLASTER RESIDUAL CRACK WIDTH AS AN INDEX

The cracks in the stucco were used to provide a baseline for comparison at different drift levels because the wallboard cracks were often difficult to measure and the damage to the wallboard was not as obvious at small displacements. Because of the large difference in the initial stiffness between the stucco and the gypsum wallboard, the stucco attracted the majority of the applied load at the small displacement cycles. As a result, the damage to the exterior finish was more readily apparent.

Maximum and residual stucco crack widths were measured at all drift levels associated with the prescribed loading protocol. The maximum stucco crack widths refer to widths measured while the test specimens were held at the peak displacement for each displacement level. The residual crack widths refer to widths measured once the walls were unloaded to zero force after each displacement level. The residual crack widths were used for comparison purposes because, after a seismic event, only the residual crack widths are measurable. Only the single largest crack width that occurred at each opening corner was measured. The measurement of all crack widths in the stucco would dilute the average width measured for each displacement level, since the cracks that formed at the openings corners were consistently the largest. The average was computed by taking the sum of the widths divided by the number of locations where a measurement was made.

The maximum imposed drift for each wall was plotted versus the average residual crack widths. The average residual crack widths were also checked versus the strength ratio for each displacement cycle to find a correlation between crack width and the developed load. The strength ratio is defined as the maximum force developed for each primary displacement cycle divided by the wall's ultimate capacity. A linear trend was assumed for both bases, which is reasonable based on the correlation coefficient computed for each least squares fit. The residual crack widths, the strength rations at each damage state drift level, and the relative magnitude of finish damage were consistent with the qualitative definitions.

DAMAGE STATE RESPONSE REGIMES: OBSERVED DAMAGE

A large volume of data were collected over the course of the test, including crack width measurements, visual examination of the condition of finishes and photo documentation at specific milestones in the test, as well as a continuous record of various transducer data. For ease of presentation, the response history of the walls has been divided into five regimes of behavior, identified by the end point of each regime as follows: 0.2% drift limit – 0.0% to 0.2% drift, 0.4% drift limit – 0.2% to 0.4% drift, 0.7% drift limit – 0.4% to 0.7% drift, ultimate strength – 0.7% to ultimate strength, failure – ultimate strength to failure.

0.2% Drift

Wall behavior up to 0.2% drift is characterized by a very stiff, nearly linear elastic response with minor cracking of finishes and not deterioration of behavior during trailing cycles. Stucco cracks initiated at the wall opening corners and propagated at near 45-60 degrees from the horizontal, depending on the opening location along the wall. Any stucco cracks that existed at wall opening corners before the testing began increased in length and width, which indicated that new damage had occurred. Some of the existing stucco cracks did not increase in length or width because they were not in a location of high stress under lateral loading, typically within the stucco piers away from the opening corners.

The gypsum wallboard finish sustained little damage after 0.2% drift. Small hairline cracks formed near the corners of the windows and along the edges of the corner bead at some locations. The early stages of joint tape damage was observed as well. Crack widths were only measured when a clearly defined width was obvious.

0.4% Drift
Wall behavior from 0.2% to 0.4% drift is characterized by some softening of the wall stiffness, extension of cracks in length and width, development of new cracks branching off primary cracks, and no deterioration of wall response during trailing cycles. After 0.4% drift, most stucco cracks that occurred during stage 1 increased in length and width. New cracks branched from existing cracks and at some locations the cracks propagated to the wall boundaries. The cracks that occurred at the upper window corners propagated vertically toward the wall boundaries at the edges of the solid pier widths. Some stucco cracks formed at the stucco boundaries at wall pier edges and propagated vertically. The stucco cracks that formed at the door opening corners were typically the largest due to the decrease is wall stiffness at that location caused by the large door opening.

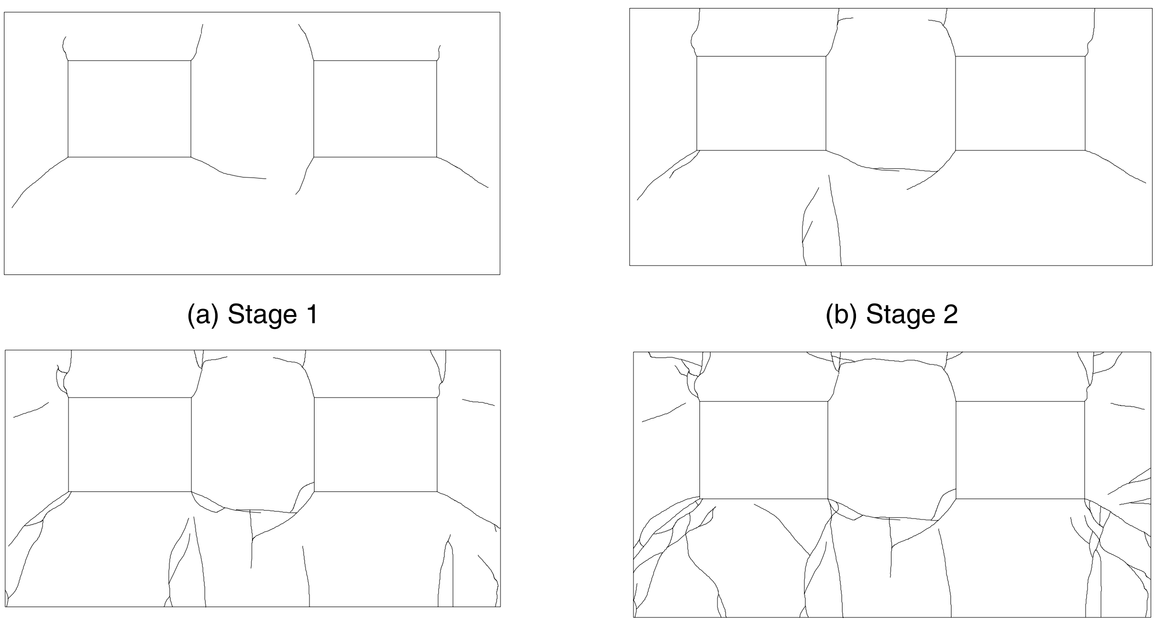
The gypsum wallboard cracking at all wall opening corners increased in length and width. The wallboard cracks propagated at near 45-degrees from the horizontal. Joint compound flaked off at some locations and fastener popping began at the bottom of the walls, and the joint tape damage that occurred during stage 1 increased in magnitude. Fastener popping initiated at wallboard panel edges and propagated vertically as the displacement level increased. The joint compound over the corner bead began to crack along the length under the windows.

0.7% Drift
Wall behavior from 0.4% to 0.7% drift is characterized by softening of the wall stiffness, extension of cracks in length and width, development of new cracks, and slight deterioration of wall response during trailing cycles. The stucco damage significantly increased in magnitude from stage 2 to stage 3, and the stucco crack widths were relatively large. Most of the stucco cracks that originated at the wall opening corners propagated to the stucco boundaries at the sill plate, the top plate, and corner studs. More stucco cracks initiated at the stucco boundaries at the wall pier edges, and all existing cracks increased in length and width. Nearly all the primary cracks had new cracks branch off from them and new cracks formed at the top plate stucco boundaries at the stucco pier edges. Stucco cracks that occurred at the wall opening corners at the edges of the interior stucco piers joined to create one large crack between adjacent wall opening corners and became large in width. Small relative stucco panel movement with respect to the wall framing was also noticed at this level of displacement.

The relative magnitude of damage sustained by the wallboard significantly increased with respect to the minor damage state drift since the gypsum wallboard panels contributed more to the performance of the wall system at higher levels of drift. Because of the relative stiffness difference between the Portland cement plaster and the gypsum wallboard, the stiffer stucco material attracted the majority of the lateral force at small displacement levels. As the stucco deteriorated at the larger displacement levels, the gypsum wallboard attracted more force, which is the reason for the large increase in visual damage between the minor damage state and the moderate damage state drift levels. An increase in the number of fastener pops was also observed as well as the relative magnitude of joint tape damage. The corner bead cracks increased in width and were observed to extend the entire length of the corner bead. At compression corners, the gypsum wallboard core crushed, which created distributed cracking or bulging in the wallboard. This effect was more obvious at larger displacement levels. The individual wallboard panels rotated relative to one another, which was evident from the joint tape tearing observed.

Ultimate Strength-Failure

The stucco cracking patterns for the wall configuration with two windows at all drift levels up to failure can be seen in Figure 5 and the relative magnitude between each drift level can be seen. The stucco damage patterns were similar for both wall configurations. Large crack widths that formed at wall opening corners and propagated to the panel boundaries produced individual stucco sections that rotated independently of one another. The cracking patterns observed follow the expected damage patterns for a wall with openings. Spalling of the stucco finish coat followed by crumbling of the brown and scratch coats at failure occurred at all opening corner locations at large displacement levels. The corner studs twisted at the wall ends, which created vertical cracking in the stucco along the corner rite reinforcement, causing the stucco to eventually deteriorate. Stucco movement relative to the framing as well as stucco separation from the framing was also observed, specifically at the sill plate.



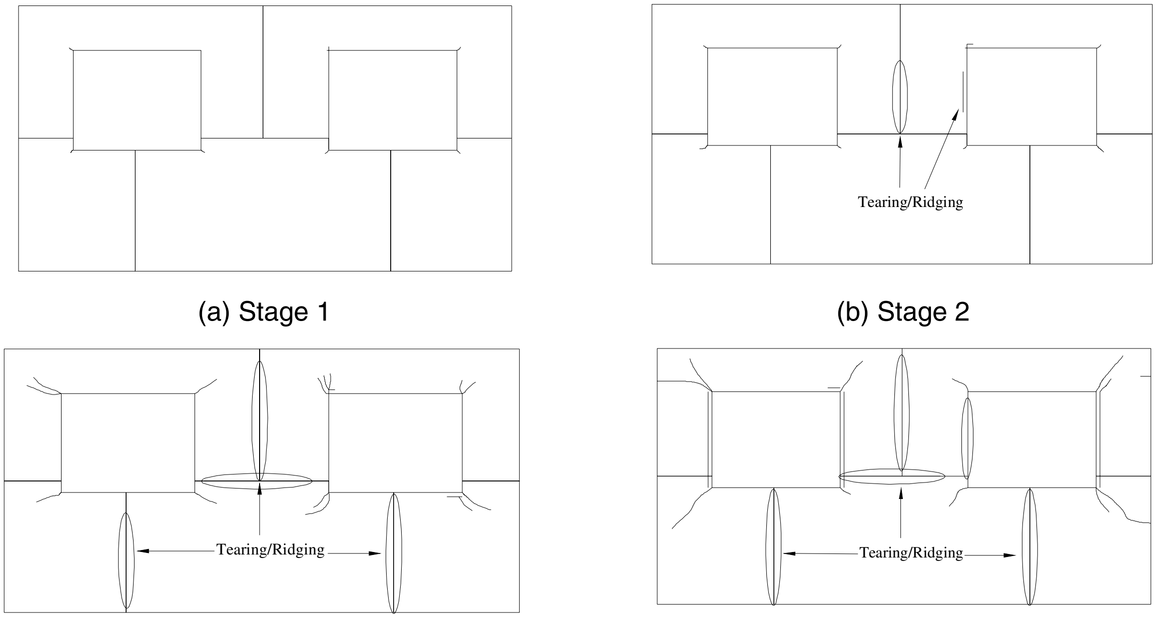
(a) Stage 1 (b) Stage 2

(c) Stage 3 (d) Failure

Figure 5: Stucco Damage Patterns

Once the testing was completed, various sections of the stucco was removed to investigate the building paper and lath. At locations where the stucco was removed the lath did not fracture at most of the opening corner locations, but building paper tearing did occur at all locations along the length of the stucco crack, however, it is unclear when the building paper tears occur. The gypsum wallboard was removed and the framing was observed to be in excellent condition At some locations, the furring nails were observed to pull out of the studs at locations where sufficient edge clearance was not attained into the stud.

The global crack patterns and wallboard damage observed up to failure is shown in Figure 6. Most of the wallboard joints were significantly damaged when the individual wallboard piers rotated relative to one another. Large crack widths and lengths were observed at all wall opening corners, and the cracks tended to follow a 45-degree path. The only deviation from 45 degrees was noticed at wall corners adjacent to a horizontal wallboard joint. For this case, the cracks began to level out horizontally and the majority of the damage was concentrated in the wallboard joints rather than at the wall opening corners. At wall returns, some ridging of the wallboard also occurred at large displacements and eventually resulted in large cracks. This occurred since the wallboard rotation was restricted at the wall returns unless the corner studs significantly deformed. Individual wallboard rotations were evident by the separation of the corner bead and the wallboard joint compound. Most wallboard joints sustained significant damage. As the wall displacement increased, the fastener popping became more obvious and was concentrated at the lower half of the walls.



(a) Stage 1 (b) Stage 2

(c) Stage 3 (d) Failure

Figure 6: Stucco Damage Patterns

DAMAGE STATE RESPONSE REGIMES: MEASURED RESPONSE

The typical global wall response can be seen in Figure 7 which also shows the points at which the response regime limits correspond on the force-deformation curve. The trend observed was that the anchor bolt forces continually increase up to a drift level of 1.5%, then the wall anchorage forces decrease as the wall displacement increases. This is caused by the different displacement mechanisms of the wall at different levels of drift. At lower drift levels, the walls rock more or less as a rigid body. The increase in overturning created an increase in anchorage force with increased wall displacements. Once the wall stiffness began to degrade, the damage was concentrated in other forms such as increased finish damage or damage at the sill plate level. Damage at the sill plate level inhibits the lateral force transfer to the anchor connections, thus lowering the developed force. The structure dead load, sill and stud uplift, and wall rotations and shear deformations all influence the development of anchor bolt uplift forces.

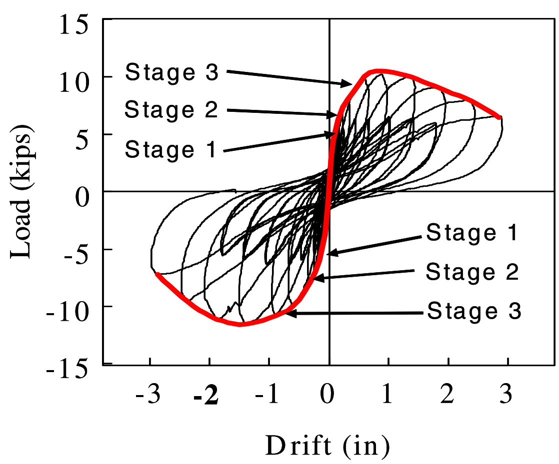


Figure 7: Typical Global Response

Inclinometers were placed at the mid-height of the wall piers at the wall mid-height to measure any rigid body rotation of the individual stucco wall piers. When the stucco panels rotated, the force distribution to the nails was more evenly distributed to the furring nails connecting the stucco to the framing. When the wall framing began to deform more in shear and rotate less, the forces were concentrated at wall boundaries, either the top plate or the sill plate. This created a larger force demand on the nailing at the sill plate level. If the amount of nailing to the sill could not adequately resist the developed forces, the nailing of the stucco to the sill plate failed and the stucco panels displaced relative to the framing.

Stud uplift was another displacement mechanism that was directly measured and represents the displacement between the top of the sill plate and the bottom of the studs. The stud uplift was calculated by subtracting the measured sill plate uplift from the stud uplift since both quantities were referenced from the testing frame. The uplift for the studs acting as wall pier bondary elements were consistently larger than the uplift for studs at all other locations.

The separation of the stucco cladding from the structural framing was measured at two locations above the sill plate along the length of each wall. The stucco separated most at the wall ends. The stucco movement relative to the framing was calculated by subtracting the measured sill plate movement from the measured stucco movement and increased as wall displacements increased.

String potentiometers were used to measure the shear deformation of each wall panel and the deformation contributing to the global wall displacement was calculated. The shear deformation contributes less to the overall deformation mechanism of the wall as the wall displacements increase. The stud uplift and wall rotations begin to contribute more to the total deformation response.

SPECIMEN REPAIR

INTRODUCTION

To determine the efficacy of the repair methodologies used at the various damage states, comparisons are made between the performance of the specimens tested without repair and specimens repaired at each stage of loading. Additionally, the performance of both the un-repaired and repaired condition is compared at the same stage of loading.

Each of the repair methods has inherent advantages and disadvantages and each is evaluated aesthetically and structurally. For structural evaluation, various structural properties such as lateral resistance and stiffness of the walls were investigated in accordance with localized effects exhibited at various wall locations. For aesthetic evaluation, the wall finishes at all repair locations were compared at the same drift levels.

Repair methods typical to common practice were used. Common stucco repair methods consisted of painting, stucco patch, stucco crack routing and filling, and fiberglass tape application along the lengths of the cracks after finish coat removal and acrylic bonder application. Additional screws were also added at the sill plate at the Stage 2 damage repairs to determine the effectiveness of reducing any stucco movement relative to the framing. Typical wallboard repairs consisted of the use of paper and fiberglass tape to cover any wallboard cracks as well as supplemental fastener application at locations of fastener popping. Where wallboard cracks were large, small portions of the wallboard were removed and replaced as well.

Performance Comparison

For Stage 1 damage, the repair methods used for both the interior and exterior finish are considered minor repairs. At such small displacements, all walls performed well. Less than a 5% lateral resistance reduction was observed between the original and the repaired walls at the 0.2% drift. A slight unrecoverable loss of stiffness was present, but the difference was considered negligible at this displacement level since the wall stiffness and resistance at the end of the Stage 1 drift level is nearly the same. The structural fasteners bearing against the finish materials and damaging the original bond caused the slight stiffness variation. Upon reloading, this difference is insignificant when considering the effect on the wall performance above 0.2% drift. The observed structural performance of the repaired walls with respect to the original walls was acceptable at this level of drift. The repair methods used at the Stage 1 damage state achieved a comparable structural performance level for the repaired wall specimens.

The repairs used at Stage 2 were similar to the repairs used for Stage 1. The walls performed very well after the repairs were implemented. The structural performance of the repaired walls is nearly identical to the original walls displaced up to 0.4% drift. Virtually no loss of stiffness or lateral resistance was observed. The exceptional performance of the repaired walls was due to the increased wallboard rigidity from the large number of supplemental fasteners added for the Stage 2 damage repairs. Supplemental screws were added at the sill plate level in the stucco and contributed to the global response more at larger displacements.

The extent of repairs necessary after the Stage 3 damage state level of drift was significantly greater than the extent of repairs at the Stage 2 damage state level of drift. The amount of necessary repairs was an indicator of the increased structural damage to the walls. The Stage 3 damage state repairs did not have an effect on the resistance for small displacement cycles. The repair increased the lateral resistance and stiffness of the walls as the displacements became larger than the Stage 2 damage state drift of 0.4%. The resistance of the original walls was effectively restored using the Stage 3 damage state repairs with less than a 10%-15% reduction.

The repaired walls were also loaded to failure and the results were compared. The observed damage to the stucco and the wallboard finishes closely followed the same patterns as the original un-repaired walls with slight local variation caused by the various repairs used. The repaired walls were actually stronger than the unrepaired walls with respect to the ultimate strength of the walls. This is not unexpected since the addition of the repair screws at the sill plate level significantly reduced and observed movement of the stucco relative to the framing. As a result, the overturning resistance was increased and was reflected in the anchorage uplift forces at equivalent drift levels. The tests have shown that if a wall has sustained damage consistent with the walls having developed forces up to 90% of the ultimate strength of the wall, that the original wall resistance and ultimate strength can be effectively restored using the prescribed methods at each damage state.

The global crack patterns were very similar with no significant change in behavior for all drift levels and repair methods. One of the main differences observed in the stucco behavior was the stucco panel movement relative to the structural framing was nearly eliminated for the repaired wall specimens. The reduced stucco panel movement allowed for very large cracks to form after the capacity of the wall specimen was reached, whereas the stucco panels only separated from the framing after large displacements for the unrepaired cases. After the capacity of the walls were reached, previously observed wallboard buckling of was eliminated by the addition of the supplemental fasteners. Again, the elimination of this damage caused very large cracks at the opening corner, which propagated up to the wallboard boundaries.

The crack patterns are nearly identical for the repaired and un-repaired walls. Aesthetically, the walls performed nearly the same for each repair method used. All stucco repair methods produced favorable results and can be considered effective for the repair of stucco at each drift level.

Repair Cost

The economic loss of structures plays a large role when making performance based engineering decisions. It is not uncommon that a structure, which did not sustain a significant amount of structural damage, was effectively a total loss due to the fact that the cost of repairing the aesthetic damage was determined to be greater than the value of the structure. Many factors affect the cost estimation for various repairs and the estimated cost can greatly vary between contractors. Factors that affect the total cost may include, geographic location of the structure, the ability to match the existing paint and texturing design, personal taste and acceptance levels, availability of materials, and the size of the structure and repair job.

In order to assign a relative cost to each damage state, a local contractor was consulted to evaluate and repair all finish damage after stages 1-3. Based on the cost of the purchased materials, the number of man-hours needed to perform all repairs, and a percentage for the contractors mark-up, a cost of each repair was calculated for each damage state. The repair costs were correlated with the maximum story drift associated at each damage state level of drift. An increase in cost with the increase in drift is observed. The material cost was insignificant when compared to the cost of labor which was the dominating factor contributing to the rise in the total repair cost. The total cost of repair versus the complete removal and replacement of wall finishes was found to be advantageous up to the Stage 3 level of repairs, where the removal and replacement of finish may be warranted versus repair.

WALL DAMAGE CLASSIFICATION

After the inspection of the exterior walls of a structure, the walls can be effectively placed into one of four categories based on limits defined by measured crack widths and residual drifts. The defined limits of each damage state are to be used as a guide and are not intended to represent absolute limits. The following method, along with experience and engineering judgment, must be used to properly categorize damage. Different walls of a structure may be placed into different categories because the level of damage sustained will vary depending on the geometry of the structure or the presence of any structural irregularities such as torsion, soft-story conditions, or large diaphragm openings. Again, engineering judgment must be used to classify the structure as a whole.

The average residual crack widths for each Stage of drift were determined from the recommended curve established in Figure 8. The measured average residual crack widths at Stages 1, 2, and 3 damage states are 0.004 in., 0.012 in., and 0.023 in., respectively. The limits shown for each damage state are designated by the vertical dashed lines in Figure 8 and represent practical limits for the average crack widths for each damage level.

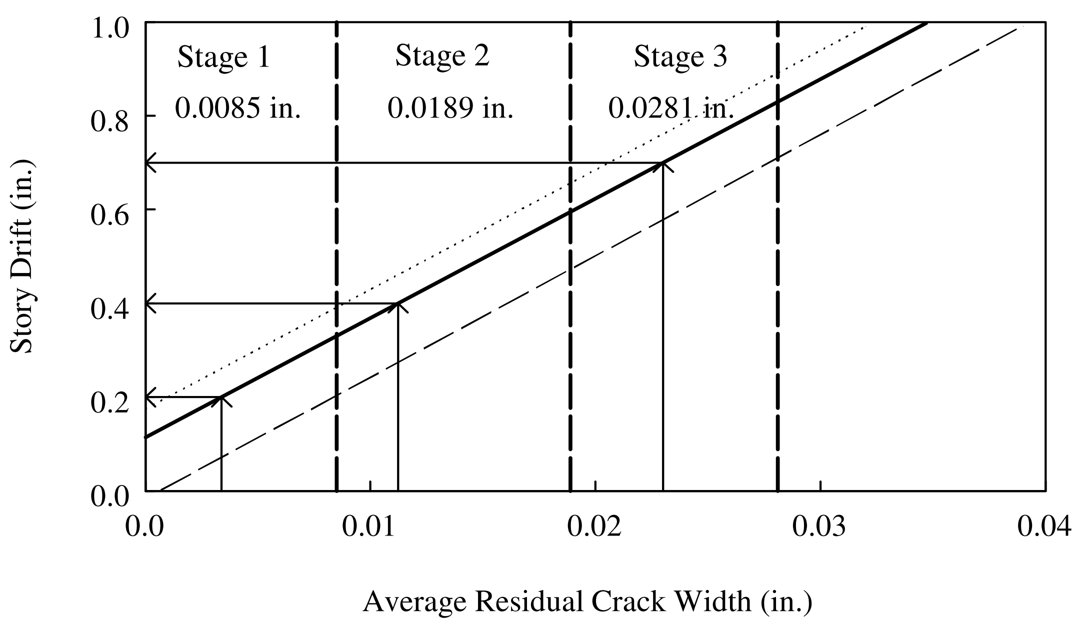


Figure 8: Crack Width (C_w) versus Story Drift (Δ_m)

Once an average crack width is calculated from the measured primary cracks at all opening corners of a wall, the approximate level of maximum story drift can be determined from the recommended curve (solid line). Once the maximum story drift is attained, an estimation of the expected residual drift of the wall can be found from Figure 9 and checked versus an actual measured residual drift of the wall. This may be an iterative process where engineering judgment and experience play a role until and accurate classification can be made. Once a reasonable estimate of the story drift experienced can be attained, it can be related to the strength ratio curve determined from testing seen in Figure 10. The strength ratio is defined as the wall force developed at a specified drift divided by the ultimate wall capacity and relates to the wall stresses developed in terms of wall capacity. At this point, the decision to repair an existing structure can be made based on the wall classification and the relative cost of the repair versus a total loss.

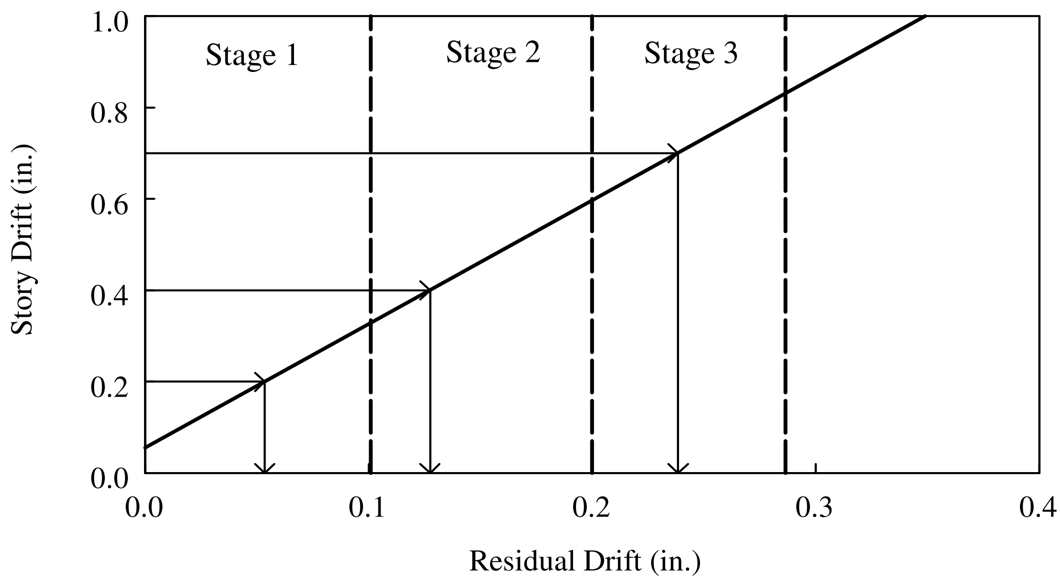


Figure 9: Residual Drift (Δ_r) versus Story Drift (Δ_m)

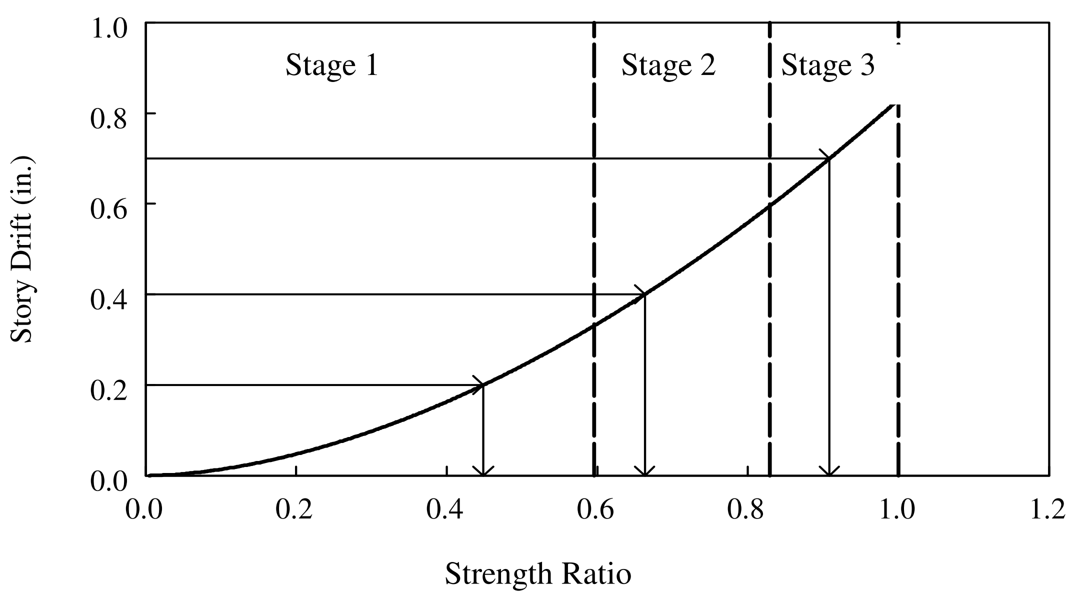


Figure 10: Strength Ratio (*SR*) versus Story Drift (Δ_m)

CONCLUSIONS

Wall Repairs

For the walls repaired at the Stage 1 damage level, some unrecoverable initial stiffness loss was observed upon reloading, but the original stiffness and resistance of the walls was nearly restored. Walls that have experienced drifts levels near 0.2% can be effectively repaired with a secant stiffness reduction of less than 5%. For the Stage 2 damage level, the repair methods used were very effective in restoring stiffness of the damaged walls at an equivalent level of drift. Walls that have experienced drift levels near 0.4% can be repaired with less than a 5% reduction of secant stiffness. For Stage 3 damage, the stiffness of the walls can be recovered with a secant stiffness reduction of less than 15% at this level of drift.

The ultimate strength and stiffness of the repaired walls was greater in the primary loading direction than the reference walls with an increase in ductility and less than a 5% reduction of the ultimate capacity in the secondary loading direction. The repair methods used can effectively restore both the stiffness and ultimate strength of walls subjected to near 0.7% drift which corresponds to a loading of near 90% of wall capacity.

Wall Damage Classification

By relating the residual stucco crack widths and the residual story drift to a maximum imposed story drift, the relative magnitude of the developed forces for structures of similar construction can be accurately determined after a seismic event. With proper engineering judgment earthquake damage to existing structures can be accurately classified and placed into one of the response regimes previously defined. Recommended values for average residual crack widths are as follows:

(1) Wall specimens experiencing roughly 0.2% drift had average stucco crack widths of near 0.004 in. and few greater than 0.01 in. Recommended limit is 0.0085 in. Damage is limited to small cracks originating at opening corners.

(2) Wall specimens experiencing roughly 0.4% drift had average stucco residual crack widths of roughly 0.012 in. and few greater than 0.025 in. Recommended limit is 0.0189 in. Some stucco cracks were observed to extend to the stucco boundaries. Primary cracks had new cracks branching off at wall opening corners. Cracks originating at adjacent wall opening corners exhibited a tendency to join in a near horizontal fashion.

(3) Wall specimens experiencing roughly 0.7% drift had average stucco crack widths near 0.023 in. and few greater than 0.05 in. Recommended limit is 0.0281 in. The stucco cracking patterns extended up to the stucco boundaries and most of the primary cracks originating at wall opening corners have one or more cracks branching from them. Finish coat flaking was also observed at various wall opening locations.

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